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Review Article

Carbon capture and storage: An evidence-based review of its limitations and missed promises

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Abstract

Despite over $40 billion invested globally, Carbon Capture and Storage (CCS) captures and stores less than 0.1% of annual global CO_2 emissions, raising serious questions about its efficacy as a climate solution. This review addresses the critical disconnect between modelled expectations and empirical outcomes of CCS, offering a comprehensive, evidence-based reassessment of its technical, economic, and strategic performance. The analysis integrates data from peer-reviewed literature, international reports (IPCC, IEA, Carbon Tracker), and investigative journalism, evaluating both failed and superficially successful projects, including Petra Nova, Gorgon, Sleipner, and In Salah. These case studies expose recurring patterns of cost overruns, suboptimal capture rates, geological uncertainties, and public liability transfer. Projects hailed as "successful" often fall short when scrutinized against durability, scale, and emissions offset claims. While these findings raise valid concerns, this review does not categorically dismiss CCS. Instead, it emphasizes the need for strategic deployment in specific, hard-to-abate sectors where alternatives are limited such as cement production or legacy infrastructure retrofits. Beyond critique, the review explores proven alternatives: renewables, bio-based removals, mineralization; that offer higher scalability and permanence with fewer systemic risks. A predictive evaluation framework is introduced to match/compare capture and mitigation/avoidance technologies to emission contexts using criteria such as CO_2 concentration, energy demand (2.5–8 GJ/tCO_2), cost ($50–600/t$CO_2$), scalability, and permanence. Ultimately, the findings underscore that continued reliance on CCS is a high-cost

gamble that risks delaying the deployment of truly effective climate solutions; yet, if strategized properly, 2026–2030 could still mark a decisive turning point in determining its role in the energy transition.

Previous Next

Keywords

Carbon capture and storage (CCS); CCS failure analysis; CO_2 storage risks; Carbon mitigation strategies; Climate policy assessment

Nomenclature

Agencies, Institutions, and Organizations

IPCC
: Intergovernmental Panel on Climate Change

IEA
: International Energy Agency

UNFCCC
: United Nations Framework Convention on Climate Change

DOE (US DOE)
: U.S. Department of Energy

NETL
: National Energy Technology Laboratory (U.S.)

CSIRO
: Commonwealth Scientific and Industrial Research Organisation (Australia)

MIT
: Massachusetts Institute of Technology

Global CCS Institute (GCCSI)
: International CCS research and advocacy body

IEEFA
: Institute for Energy Economics and Financial Analysis

Carbon Tracker Initiative (CTI)

Independent financial think tank focused on climate risk

1. Introduction

Climate change remains one of the most urgent global challenges, driven by escalating greenhouse gas emissions from energy production, industrial activities, and land use changes (Fan et al., 2025; Strack et al., 2025). Meeting international climate goals, such as those outlined in the Paris Agreement, demands rapid and sustained emissions reductions across all sectors. In this context, a wide array of mitigation strategies has been explored among which Carbon Capture, Utilization, and Storage (CCUS) is one of the technologies often cited as a potential contributor to deep decarbonization particularly in hard-to-abate sectors such as cement and steel production, and in retrofitting existing coal-based power infrastructure (Yu et al., 2025). Recent regional studies have explored the strategic deployment of Carbon Capture and Storage (CCS) in China's energy and industrial sectors, highlighting scenarios where it may support emissions reductions, energy security, and equity goals (Fan et al., 2023, 2025; Zhou et al., 2025). However, while these projections underline the theoretical value of CCS within broader climate action frameworks, there is a growing need to assess its real-world applicability using realistic technical, economic, and policy criteria.

First introduced during the Kyoto Protocol negotiations in the late 1990s and later endorsed by the Intergovernmental Panel on Climate Change (IPCC), Carbon Capture, Utilization and Storage (CCUS) or CCS in the particular context has been repeatedly positioned as a cornerstone of global climate mitigation strategies (de Medeiros Costa and Arlota, 2021; Reader, 2021). A brief overview of the timeline of CCS development and key milestones post Kyoto Protocol is depicted graphically in Fig. 1 (a). Beginning with its policy inception during the Kyoto Protocol and subsequent scientific recognition by bodies such as the IPCC, the timeline highlights the gradual integration of CCS into climate strategy frameworks (Dixon et al., 2013; Kheshgi et al., 2012). It reflects phases of both optimisms marked by pilot projects and scaling ambitions and challenges, including rising emissions and questions about technological reliability. The most recent entries, labelled 2023–2024, indicate a transitional phase, potentially signalling the emergence of new directions or technologies in response to growing concerns over CCS's efficacy and impact. The premise was simple, yet lucrative; humanity could continue burning fossil fuels, while capturing and safely storing the resulting carbon dioxide emissions underground. This framing allowed policymakers and industries to delay more disruptive transitions away from fossil energy, betting heavily on technological salvation.

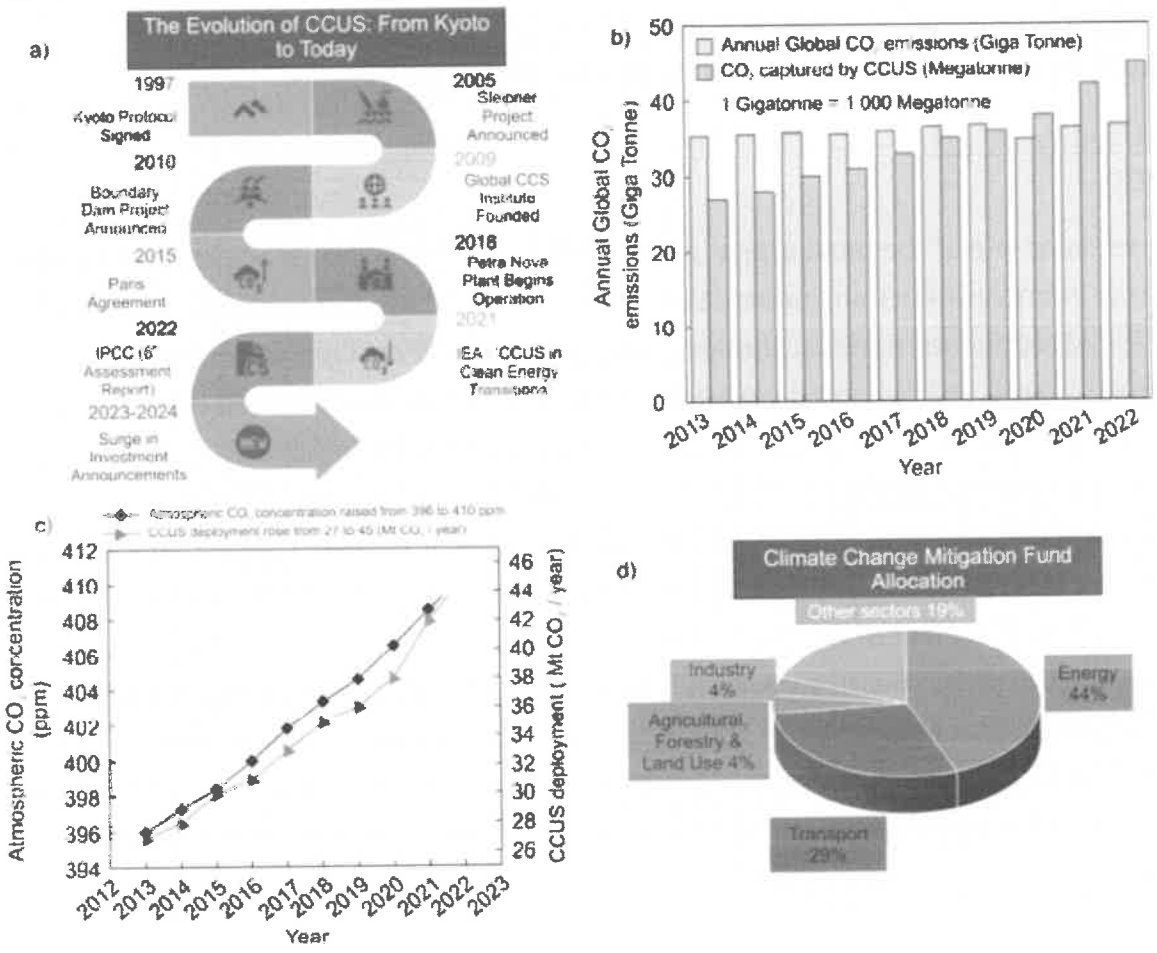

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Fig. 1. **a)** Timeline of CCUS development (Global CCS Institute, 2021), **b)** Global CO_2 Emissions vs. CO_2 Captured by CCUS (2013–2022) (International Energy Agency, 2020; Liu et al., 2024), **c)** Trends in Atmospheric CO_2 Concentration and CCUS Deployment (2013–2022) (Rui et al., 2025; Storrs et al., 2023), d) Climate mitigation finance (2021–2022) depicting strong emphasis on energy (44%) and transport (29%) sectors (International Energy Agency, 2021b).

More than two decades later, however, the record of CCS tells a different story. Despite billions of dollars in public and private investments, global deployment of CCUS remains staggeringly low, capturing less than 0.1% of total annual anthropogenic CO_2 emissions as depicted in Fig. 1(b) reported by the IEA in the annual report "CCS in Clean Energy Transitions" (2020) (IEA, 2020; Kapetaki et al., 2022). Fig. 1(b) provides a stark visualization of the disconnect between global climate goals and the actual performance of carbon capture technologies. While annual CO_2 emissions have consistently hovered above 33 gigatonnes over the past decade, the volume captured by CCS technologies remains marginal typically under 40 megatonnes per year (McLaughlin et al., 2023; Nath et al., 2024; Wang, 2024). This represents less than 0.1% of global emissions, exposing a vast and persistent shortfall. Although CCS deployment has shown modest growth, most of this capacity is theoretical or installed, not actively operational. Many high-profile

projects have faced technical setbacks, shutdowns, or failed to meet capture targets, raising doubts about the technology's real-world viability (Chrysostomidis et al., 2013; Dutton et al., 2022; Middleton and Yaw, 2018; Wang et al., 2021). Fig. 1 (as a whole) underscores that despite decades of research and billions in investment, CCS has yet to make a meaningful impact on global emission trends. It highlights how reliance on CCS as a cornerstone climate solution is deeply flawed, especially when more scalable and immediate strategies exist. Rather than serving as a bridge to decarbonization, current CCS efforts often act as a detour used to justify the continued operation of fossil fuel infrastructure (Durmaz, 2018; Mahjour and Faroughi, 2023; Simbeck and Beecy, 2011; Stephens, 2014). This disparity between promise and performance demands a shift in climate priorities, focusing on proven, scalable mitigation measures over speculative technologies (Cebrucean et al., 2014). Meanwhile, atmospheric carbon dioxide concentrations continue to climb, and fossil fuel production has expanded, not contracted. The IPCC's Sixth Assessment Report (AR6) explicitly acknowledges that while CCS may play a niche role, relying heavily on it carries high risks of locking in emissions and delaying systemic change (Kikstra et al., 2022; Lee et al., 2023).

Fig. 1(c) depicts the ineffectiveness of current carbon mitigation strategies, particularly CCS, by charting the parallel rise of global CO_2 emissions and atmospheric CO_2 concentrations over a decade (Latin, 2012; Somerville, 2020; Strachan and Usher, 2012). Despite increasing investments in carbon capture technologies, there is no observable deviation in the trajectory of atmospheric CO_2 levels, which continue to climb in lockstep with emissions (Hansson, 2012; Stenberg and Lawson, 2023). Moreover, the disproportionate allocation of climate mitigation funding toward CCS as shown in Fig. 1(d), despite its poor performance and limited scalability, raises serious concerns about the strategic priorities shaping global decarbonization efforts (Abdulla et al., 2020; Herzog, 2017). Public and private sectors have collectively invested over $20–30 billion into CCS technologies over the past two decades, much of it justified by the promise of deep emissions reductions (Boyd et al., 2024; Nath et al., 2024). However, as illustrated by current capture rates which are still under 0.1% of global annual CO_2 emissions, this investment has yielded negligible atmospheric impact. What's more concerning is that a significant portion of this funding continues to support projects tied to fossil fuel production, such as enhanced oil recovery (EOR), effectively subsidizing carbon-intensive industries under the pretense of mitigation (Marston and Moore, 2008). In contrast, sectors like renewable energy, public transport electrification, energy efficiency, and nature-based solutions, which offer more immediate, scalable, and cost-effective carbon reductions, often remain underfunded or politically deprioritized (Martini et al., 2023; Schilling and Esmundo, 2009; Upton and Snyder, 2017). This misallocation not only reflects technological bias and entrenched industrial influence but also delays systemic transitions by directing billions into speculative infrastructure rather than transformative change. Critically, continued reliance on CCUS as a funding magnet risk locking in carbon dependency, wasting precious time and resources in a decade where rapid emission cuts are most vital.

Given the scale of the climate crisis and the narrowing window for meaningful action, it is imperative that mitigation strategies are guided by evidence, not optimism. As nations commit

trillions to net-zero pathways, distinguishing between technologies that are genuinely scalable and those that merely appear promising on paper has never been more critical (Sovacool et al., 2023). This review seeks to contribute to that discernment by providing a grounded, cross-disciplinary reassessment of CCS; its realities, limitations, and potential niches while equipping policymakers, researchers, and investors with a framework to make more informed, impact-driven decisions. The goal is not simply to critique, but to redirect attention and resources toward solutions that are scientifically sound, socially responsible, and capable of delivering sustained climate benefits at scale. Also, it is imperative to point out here that the purpose of this review is not to negate CCS at all but to give a balanced bird eye view; that CCS can still be an asset in some industries, but its overall utilization must be strategized based on numbers rather than sheer optimism.

2. Review approach and structure

This paper employs a multi-scalar, evidence-driven review framework to critically assess CCS technologies across their full lifecycle from conceptualization and capture to long-term storage. Rather than relying on speculative modelling or idealized projections, the review draws from a wide body of real-world project data, institutional audits, regulatory analyses, and investigative journalism. Sources include major reports from the IPCC, IEA, Global CCS Institute, Carbon Tracker, and independent assessments by NETL, CSIRO, and Stanford University, as well as project-level evidence from Petra Nova, Gorgon, In Salah, Boundary Dam, and others. This ensures that the analysis remains grounded in operational outcomes and observed limitations, rather than aspirational narratives.

Though CO_2 capture logically precedes storage in the carbon management chain, we deliberately structured the paper to address storage first, as a matter of strategic emphasis. This reversal was intentional, grounded in the understanding that the long-term viability of CCS hinges not merely on capturing carbon, but on the credibility and permanence of its storage. Section 3 deconstructs the myth of permanent CO_2 storage, critically analysing geotechnical uncertainties, leakage risks, regulatory blind spots, and long-term monitoring burdens. Section 4 interrogates the technical performance of capture technologies, highlighting foundational constraints such as energy penalties, material degradation, and capture inefficiencies, with a focused study on membrane systems. Section 5 presents case studies of CCS project failures, revealing consistent patterns of underperformance, financial instability, and stakeholder resistance. It also points out the sectors where CCS can still be useful and hard to abate. Section 6 explores alternative strategies that offer higher scalability and lower risk, including direct air capture with mineralization, renewable energy expansion, and nature-based solutions etc.

To complement the qualitative critique, the paper concludes with a predictive evaluation framework; a decision-matrix model designed to score capture and alternative mitigations/avoidance technologies against key deployment criteria such as energy cost, scalability, permanence, and sectoral fit in section 7 versus emission sectors. This tool is used not to

rehabilitate CCS, but to reveal its poor contextual match in most real-world applications, offering a structured diagnostic lens to guide future investment, policy direction, and technology prioritization. Together, this hybrid review approach combining empirical critique with predictive analytics aims to challenge the strategic validity of CCS as a cornerstone climate solution and advocate for redirection toward more grounded, scalable alternatives.

3. Challenges and uncertainties in long term CO_2 storage

While much public and political attention has focused on capturing carbon dioxide at the source, an even more daunting challenge lurks in the second half of the carbon capture equation: permanent storage (Matter and Kelemen, 2009; Rasool ad Ahmad, 2023; Rasool et al., 2023). The assumption underlying most CCS strategies is deceptively simple; that CO_2, once injected deep underground, will remain safely sequestered for thousands of years. However, this presumption rests on models, simulations, and short-term pilot projects, not on empirical validation over the timescales required (Nordbotten et al., 2012; Rezk et al., 2023; Tadjer and Bratvold, 2021). The reality is that no CO_2 storage facility has yet demonstrated the ability to guarantee containment over centuries, let alone millennia. Geological formations are inherently dynamic, often compromised by natural faults or human-induced vulnerabilities, and the pathways for leakage, though slow, are numerous and poorly understood (Baines and Worden, 2004; Ogwu et al., 2023). Even with careful site selection and monitoring, the risks of migration, caprock failure, or leakage through abandoned wells cannot be eliminated but only managed with uncertain success (Fig. 2) (Anderson, 2017; Gholami et al., 2021; Harding et al., 2018; Song et al., 2023b). As more CCS projects are proposed and permitted based on theoretical containment promises, a profound question remains dangerously unresolved: Where will all this captured carbon truly go, and can it ever be kept away from the atmosphere long enough to matter? In this section, we critically examine why the dream of safe, permanent storage is largely an illusion built on shaky scientific, technical, and ethical foundations.

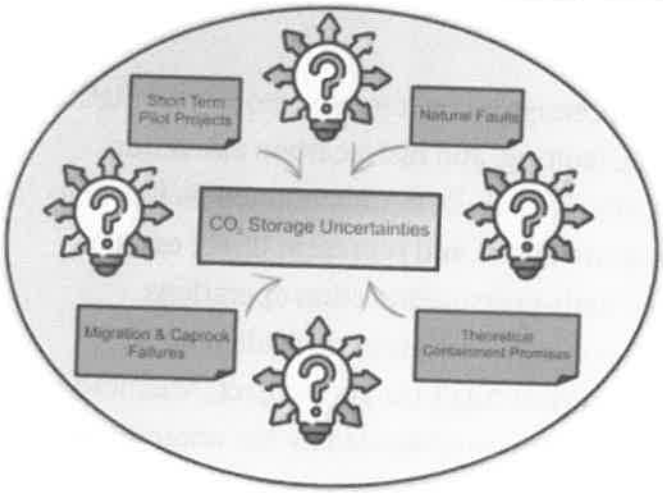

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Fig. 2. Aspects of CO_2 storage uncertainties.

3.1. Risk and realities behind permanent CO_2 sequestration

The notion of storing carbon dioxide underground for thousands of years is foundational to the CCS narrative, yet this promise remains largely theoretical (Anderson, 2017; Baines and Worden, 2004). Although flagship projects such as Sleipner and Gorgon have been operational for a few decades, their timelines are trivial compared to the geologic durations required for meaningful climate impact (Malek et al., 2004; Solomon, 2007). Even low leakage rates such as 1% per century can drastically erode the long-term efficacy of sequestration (Devi, 2024; Friedmann, 2006). Despite confidence projected by proponents, there is no empirical evidence that current storage strategies can maintain containment integrity over the timescales necessary for climate stabilization. As such, the assumption of permanence forms a fragile pillar of climate policy built more on optimism than on verified performance (Fig. 3).

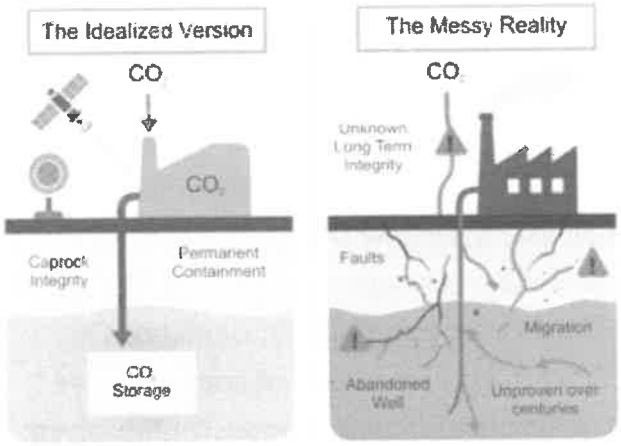

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Fig. 3. Reality vs idealized version of CO_2 storage.

The risks of subsurface leakage further destabilize this premise. Many targeted storage formations have already been compromised by decades of drilling, faulting, and hydrocarbon extraction, making them inherently vulnerable (Lee et al., 2017; Miocic et al., 2016). Abandoned wells often undocumented or poorly sealed are widespread in mature basins and represent direct escape pathways for stored CO_2 (Kopp et al., 2010). Moreover, high-pressure injection operations themselves can induce seismicity, caprock fracturing, or fault reactivation, as evidenced by shutdowns at Algeria's In Salah and operational delays at Australia's Gorgon project (Mathieson et al., 2011; Ringrose et al., 2013). These geomechanical risks are compounded by the unpredictability of plume migration and pressure build-up, revealing that even highly engineered sites remain exposed to systemic uncertainties (He et al., 2011; Muggeridge, 2023; Sun et al., 2023).

Beyond technical risks, long-term monitoring and governance present daunting practical and ethical challenges. Seismic and chemical monitoring tools degrade in reliability over time and require costly, continuous application for centuries far exceeding the duration typically mandated by regulatory frameworks (Peng et al., 2024; Valstar et al., 2024). Once storage operators exit, the financial and legal burden often shifts to the state, effectively privatizing short-term gains while socializing long-term risks. This introduces an element of intergenerational injustice, as future populations will inherit responsibilities and consequences without ever consenting to them. Meanwhile, current monitoring frameworks lack the granularity needed to detect micro-leaks or early signs of failure, leaving policymakers to navigate blind in the face of a centuries-long commitment (Dean and Tucker, 2017; Schloemer et al., 2013; Wiltshire and Roux, 2024).

In the subsequent sections, published evidence from review reports, investigative journalism and literature will be discussed to justify further the narrative presented in the preceding sections.

3.2. Published evidence on CO_2 storage failures

While carbon storage is often framed as the stable, long-term complement to CO_2 capture, a growing body of technical and institutional reviews reveals profound challenges in ensuring the integrity, scalability, and safety of geological CO_2 sequestration. Major reports from the IPCC (2022) and IEA (2022) warn that storage permanence is not guaranteed; many sites require ongoing monitoring for decades or even centuries, creating long-term liability and regulatory uncertainty. Studies by the Global CCS Institute and Stanford University further expose a systemic overestimation of storage capacity and underestimation of risks related to caprock failure, well leakage, and geological heterogeneity. The Carbon Tracker Initiative's financial analysis emphasizes that even if technically feasible, CO_2 storage remains economically unsustainable without heavy subsidies and is unlikely to scale cost-effectively (Carbon Tracker Initiative, 2022; Commonwealth Scientific and Industrial Research Organisation, 2023; Global CCS Institute, 2022; Intergovernmental Panel on Climate Change, 2022a,2022b; International Energy Agency, 2022; U.S. Department of Energy – National Energy Technology Laboratory, 2023; University of Edinburgh, 2022) (refer to Fig. 4 and supporting information Table S3).

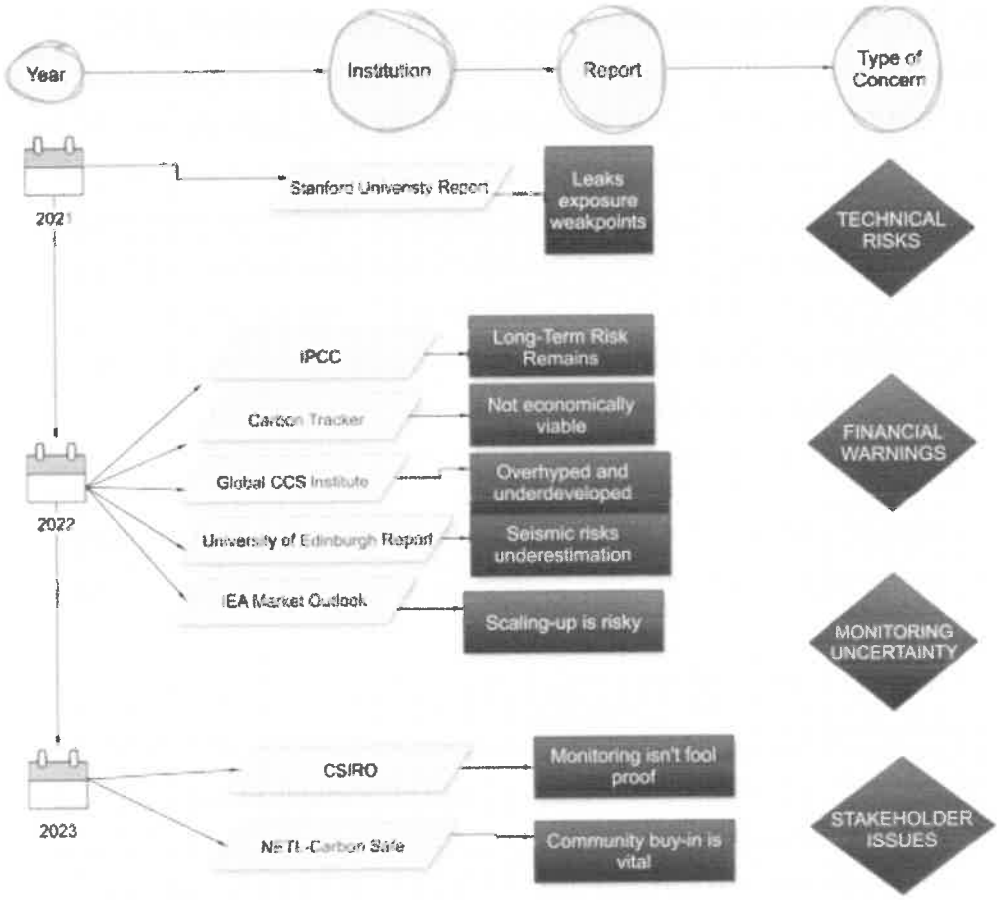

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Fig. 4. Evidence of CO_2 storage failures from published reports/reviews (2021–2023).

More recent assessments, including CSIRO (2023) and U.S. Department of Energy – National Energy Technology Laboratory's Carbon SAFE review (2023), reinforce these concerns with practical field insights. Monitoring technologies continue to lack the resolution needed to detect small-scale leaks, while public opposition and poor stakeholder engagement have delayed or derailed projects altogether. The University of Edinburgh (2022) adds further geological nuance, highlighting fault reactivation and seismicity as persistent threats to long-term containment, even in well-characterized formations (Fig. 4). Together, these reviews paint a sobering picture: far from being a reliable solution, CO_2 storage is riddled with unresolved scientific, regulatory, and operational uncertainties that make its large-scale deployment risky, expensive, and politically vulnerable.

While academic models and institutional projections often present geological carbon storage as a stable, scalable solution, real-world accounts reported by news outlets and investigative organizations paint a more sobering picture. Across diverse regions from Australia's Gorgon and Canada's Boundary Dam to the United States' Petra Nova, Summit Pipeline, and Carbon TerraVault projects have repeatedly underperformed, encountered regulatory roadblocks, or collapsed entirely due to cost overruns and technical or environmental failures. Investigations by *The Guardian*,

Reuters, *Financial Times*, and *Clarion Ledger* highlight recurring issues: caprock integrity concerns, pipeline ruptures, public opposition, and project cancellations tied to economic non-viability or political shifts. For instance, both the Petra Nova and ACTL projects have demonstrated an overdependence on oil market conditions, while others like the Polaris and White Rose projects were cancelled due to insufficient returns or loss of public funding (BBC News, 2022; Cato Institute, 2015; Center for Biological Diversity, 2024; E&E News, 2024; Guardian, 2015, 2021; IEEFA, 2023; IPCC, 2022a, 2022b; National Academies of Sciences, Engineering, and Medicine, 2019; NOS Dutch News, 2024; Pipeline & Gas Journal, 2024; Reuters, 2023a, 2023b, 2023c, 2024, 2025; Shift Action, 2025; The New York Times, 2025; Times, 2024; U.S. Department of Transportation, 2022) (refer to Fig. 5 and supporting information Table S4).

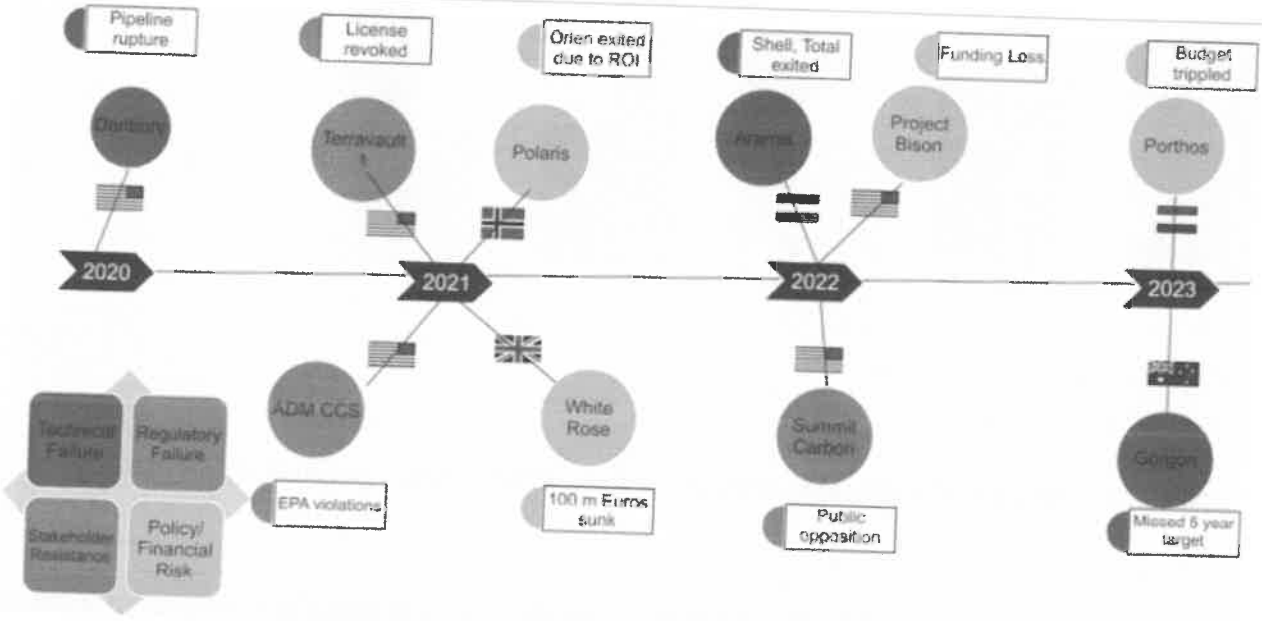

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Fig. 5. Evidence of CO_2 storage failures from investigative journalism.

These failures are not outliers but symptomatic of structural flaws: overestimated storage potential, underestimated risk, and poorly aligned incentives between public investment and private profit. Moreover, the frequent lack of community engagement and transparent risk communication has fuelled mistrust and regulatory backlash. Collectively, these journalistic accounts reinforce what many technical reviews also warn: CO_2 storage is not merely struggling to scale; it is being undermined by systemic technical, economic, and social vulnerabilities. As such, these failures serve as critical cautionary markers against overreliance on CCS in climate mitigation strategies without addressing its deeply embedded flaws.

The comparative analysis illustrated in Fig. 6 reveals a striking convergence between published review reports and media investigations on the systemic failure modes plaguing CO_2 storage projects. It can be concluded that technical and financial failures as the most dominant barriers to

effective and scalable storage deployment. These include persistent issues such as underperformance in injection targets, cost overruns, and project cancellations seen in both high-profile review assessments (IPCC, IEA) and project-level collapses like Petra Nova and FutureGen.

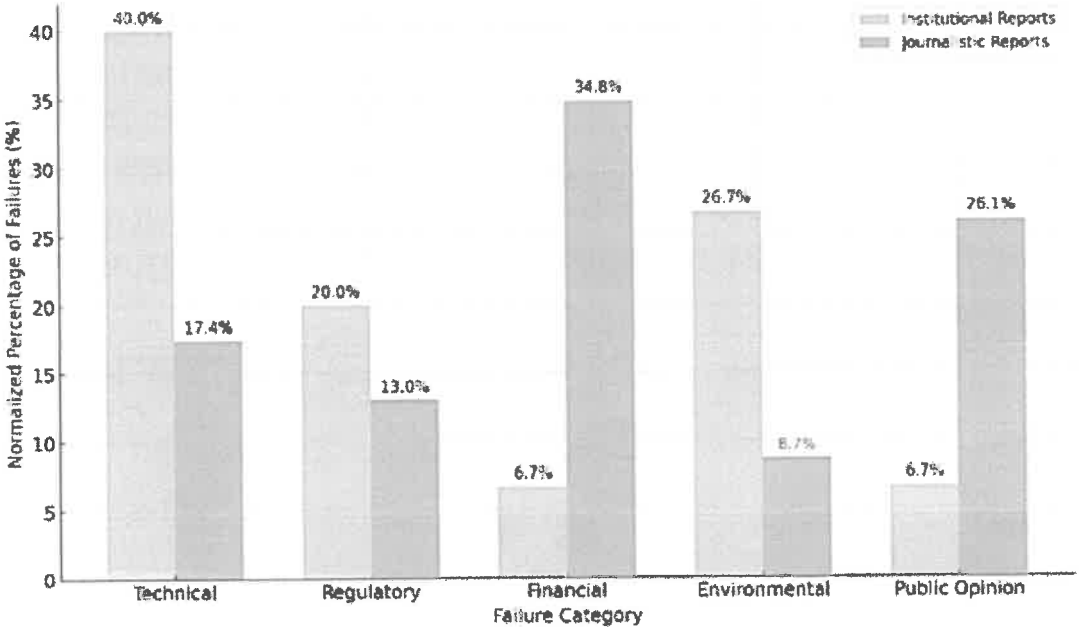

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Fig. 6. Comparison of factors affecting CO_2 storage projects derived from published reports and news articles.

Public opinion and environmental risks also emerge as a major concern highlight long-term leakage risks and the need for perpetual oversight. News outlets mirror this concern with real-world incidents like the Denbury pipeline rupture and ADM's paused injection due to EPA scrutiny. Regulatory and legal barriers, while more prominently emphasized in media coverage, are increasingly noted in institutional reports as key limiting factors due to permitting complexity, liability uncertainty, and poor stakeholder engagement. Meanwhile, public opposition, though often underweighted in academic literature, has proven decisive in the failure of projects such as the Summit Carbon Pipeline and Carbon TerraVaulthighlighting the importance of social license in deployment.

Altogether, Fig. 6 underscores that CO_2 storage challenges are not confined to theoretical risks or isolated failures they are deeply embedded and widely corroborated across both formal assessments and practical field outcomes. This convergence of evidence provides a robust foundation for critically reassessing the role of geological storage in future climate strategies.

The academic literature on CO_2 storage reveals a growing consensus that while CCS has theoretical potential, its real-world deployment is constrained by persistent technical limitations (Table 1). Studies such as Nooraiepour et al. (2024) document site-specific geological issues, including low

injectivity and salt-induced geomechanical weakening. These are not isolated anomalies but indicative of broader subsurface risks that jeopardize containment reliability. Larkin et al. (2019) further critiques in-situ mineralization approaches, showing that they are largely infeasible in the near term due to complex geochemical requirements. Collectively, these findings challenge the optimistic assumptions that CO_2 can be securely and uniformly injected across a variety of formations.

Table 1. Evidence from literature on CO_2 storage projects failures (2012–2024).

Title	Data	Critical Insight	Implication	References
A Review of CO_2 Storage in View of Safety and Cost-Effectiveness	Storage cost: \$20–\$80/tonne CO_2	Long-term liability risks and weak monitoring	Raises concerns over cost-effectiveness and safety	Cao et al. (2020)
Risk Assessment of the Geological Storage of CO2: A Review	Capacity overestimated by 30–50%	Flawed modelling assumptions and ignored leakage risks	National storage potentials may be exaggerated	Li and Liu (2016)
The Costs of CO_2 Capture and Storage	Costs may exceed \$100/tonne	High transport and compression costs	Financially impractical for many formations	Rubin et al. (2015)
Carbon Dioxide Capture and Storage: Issues and Prospects	Sleipner injected ~1 $MtCO_2$/year	Small successes don't scale globally	Niche projects won't offset global emissions	de Coninck and Benson (2014)
Potential and Challenges of Underground CO_2 Storage via In-Situ Mineralization in Switzerland	Infeasible near-term due to geology	Data and mineral accessibility barriers	Mineralization is not scalable everywhere	Martin et al. (2025)
Challenges and Enablers for Large-Scale CO_2 Storage in Chalk	Low injectivity in chalk formations	Risk of fracturing and poor suitability	Site-specific geological risk must be considered	Bonto et al. (2021)
Durability of Carbon Dioxide Removal is Critical for Paris Climate Goals	Requires >1000 years permanence	Short-term storage = ineffective mitigation	Need for robust permanence in policy frameworks	Brunner et al. (2024)
Assessing Salt Precipitation and Weak	50% strength loss near wells	Salt crystallization weakens geology	Storage integrity threatened over	Nooraiepour et al. (2024)

Title	Data	Critical Insight	Implication	References
Acid Interaction in Subsurface CO_2 Injection			time	
The Feasibility of Reaching Gigatonne Scale CO_2 Storage by Mid-Century	Max capacity: 16 $GtCO_2$/yr (60% USA-dependent)	Limited global feasibility due to geology/infrastructure	Unrealistic to meet global mitigation targets	Zhang et al. (2024)

Economically, CCS storage remains precarious. Cao et al., (2020) estimate storage costs between $20–$80 per tonne, while Rubin et al. (2015) warn that costs can exceed $100/ton when transport and compression are included. This wide cost variability reflects a broader uncertainty in CCS's financial viability. Without strong carbon pricing, tax credits, or government subsidies, storage alone is rarely commercially attractive. Moreover, financial risk is exacerbated by the lack of scalable business models, especially outside enhanced oil recovery (EOR) contexts, where the stored CO_2 has no intrinsic economic value.

Regulatory frameworks and capacity projections have also come under scrutiny. Li and Liu (2016) warn that geological storage capacities may be overestimated by 30–50%, primarily due to flawed modelling assumptions that ignore leakage pathways and overestimate injectivity. Such discrepancies suggest that national storage strategies may be built on overly optimistic geological data, which risks future underperformance and public mistrust. Furthermore, many of these models lack robust uncertainty margins, undermining their credibility for long-term planning and cross-national comparisons.

Strategically, the literature points to a troubling disconnect between CCS promises and its planetary impact as tabulated in Table 1. Brunner et al. (2024)rgue that to be aligned with climate targets, CO_2 must be stored for over 1000 years yet current monitoring and liability frameworks are not designed for such durations. Liu et al. (2024) adds that nearly 60% of projected global storage capacity is concentrated in the United States, revealing a geographical imbalance that challenges global equity and scalability. These insights suggest that while CO_2 storage may be part of the climate solution toolbox, its limitations must be transparently acknowledged and its role carefully constrained within broader mitigation strategies.

Fig. 7 effectively distils the four critical dimensions of CO_2 storage failure; technical, financial, regulatory, and strategic underscoring why geological sequestration remains a deeply flawed mitigation pathway. From a technical perspective, persistent injectivity issues, salt-induced weakening, and site-specific geological incompatibilities such as near-well mineralization losses illustrate the mismatch between modelled assumptions and subsurface realities. Financially, the wide variability in storage costs ($20–$100/ton) and the added burden of transport and compression reveal an uneconomical architecture that struggles without subsidies. Regulatory

shortcomings, such as overestimated national storage capacities and inadequate leakage modelling, further erode the credibility of current policy frameworks. Strategically, the mismatch between CCS deployment and climate timelines especially the >1000-year permanence required by the Paris Agreement and over-reliance on U.S.-based storage capacity for global scaling highlight systemic vulnerabilities (Dimitrov, 2016). Collectively, these layered failures challenge the core premise of CCS as a scalable, durable climate solution and suggest that continued reliance on it could be a costly diversion from more viable mitigation pathways. In the subsequent section all these factors will be evaluated critically to determine how do they actually affect the feasibility and deployment of any CO_2 storage related project.

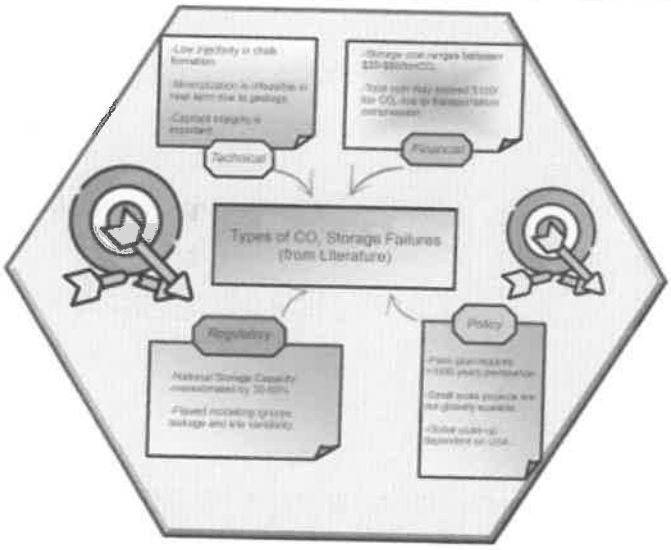

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Fig. 7. Factors contributing to CO_2 storage failures gathered from literature.

3.2.1. Technical failures

Technical failures in CCS storage projects often arise from the mismatch between theoretical modelling and subsurface realities. One of the most critical issues is poor injectivity, where the target formation cannot accept CO_2 at the anticipated rates without exceeding fracture pressure. This is particularly common in low-permeability formations or those with heterogeneous lithofacies that cause uneven fluid distribution. In such cases, CO_2 injection induces pressure build-up, which may lead to hydraulic fracturing of the caprock or lateral migration of CO_2 into unintended zones. These migration paths, often undetected in initial models, can breach the containment envelope, leading to leakage and loss of storage integrity (Carroll et al., 2017; Raziperchikolaee et al., 2013).

Another major technical vulnerability is caprock failure. While caprocks are selected for their low permeability and sealing capacity, they are not immune to stress perturbations induced by injection operations (Shukla et al., 2010; Song and Zhang, 2013). Pore pressure elevation, thermal expansion,

and chemical interaction with CO_2-saturated brine can all compromise the caprock's mechanical properties. In formations with existing faults or fractures, the risk is further exacerbated; even previously inactive faults may be reactivated under altered stress conditions, creating new pathways for leakage (Börner et al., 2015; Mortezaei et al., 2018). This is often underestimated due to the oversimplification of stress regimes and mechanical heterogeneity in reservoir models (Fig. 8).

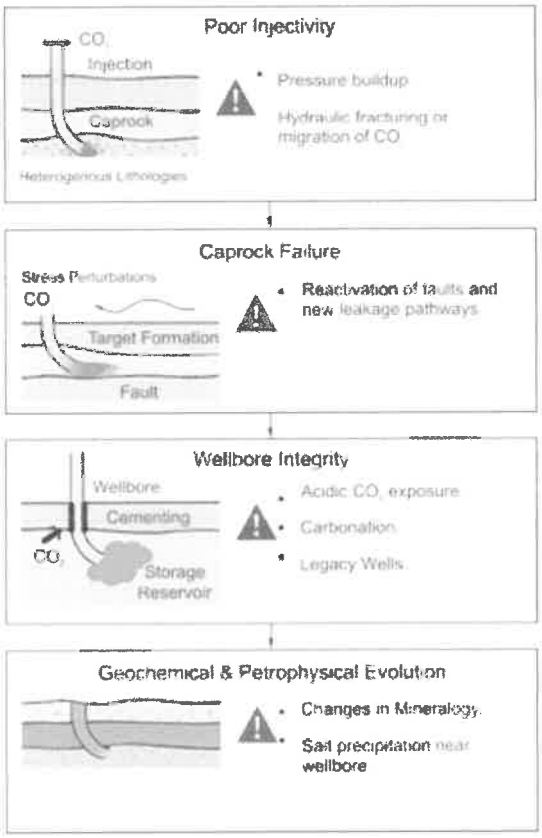

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Fig. 8. Possible technical failures during underground CO_2 sequestration.

Wellbore integrity is another critical weak point. Cement sheaths and casing materials are exposed to acidic fluids, cyclic loading, and thermal gradients during and after injection (Bachu and Watson, 2009). Over time, this can lead to micro-annuli formation, debonding, or cement carbonation, all of which compromise zonal isolation. Legacy wells that intersect the storage reservoir pose an even greater risk, especially if their location, condition, or construction history is poorly documented (Arbad et al., 2024). Such wells act as potential leakage conduits that bypass the primary seal entirely, making them one of the most difficult technical challenges to mitigate in mature basins (Fig. 8).

Finally, geochemical and petrophysical evolution of the storage formation during injection is often overlooked (Fentaw et al., 2024; Harvey et al., 2012; Hawkes et al., 2004). Continuous CO_2 exposure can alter mineralogical composition, reduce mechanical strength, and precipitate salts near the

wellbore, leading to formation plugging or damage to near-wellbore rock. These phenomena are not instantaneous and often emerge as long-term degradation mechanisms, making them harder to predict and manage. When compounded, these technical issues transform even well-planned projects into costly liabilities, emphasizing the need for real-time diagnostics, adaptive reservoir modelling, and conservative safety margins in design and operation.

3.2.2. Regulatory limitation

3.2.2.1. Institutional and legal uncertainty

One of the most paralyzing regulatory failures in CO_2 storage is the absence of a clearly defined liability regime. Once injection ceases, the long-term burden of monitoring and ensuring containment often enters a legal vacuum. In many countries, legislation lacks a designated timeline or mechanism for transferring responsibility from private operators to the state, leaving operators exposed to indefinite post-closure liability. This not only deters private investment but creates uncertainty for insurance underwriting, financing, and risk-sharing mechanisms. Furthermore, regulatory jurisdiction is often fragmented environmental, energy, and geological authorities may each hold partial oversight with no single accountable body. As a result, the regulatory apparatus is often unprepared to handle disputes, leak investigations, or liability claims. This legal ambiguity creates a structural weakness in the CCS chain: storage projects may fail not due to leakage, but due to the inability to legally govern that leakage (Fig. 9) (Dixon et al., 2015; Marston and Moore, 2008).

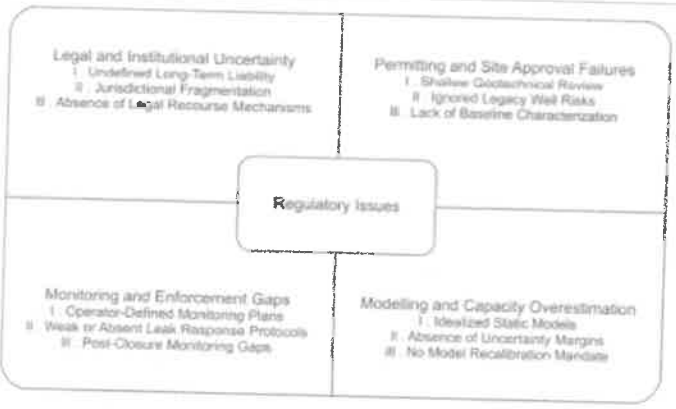

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Fig. 9. Regulatory barriers for CO_2 storage related projects.

3.2.2.2. Permitting and site approval failures

Permitting processes in many CCS jurisdictions exhibit a dangerous tendency toward overconfidence, approving projects based on modelled compliance rather than empirical certainty. This is particularly evident in the approval of sites with poor injectivity, faulted structures, or proximity to legacy wells. Permits are often granted on the basis of theoretical containment models that lack adequate site-specific data, especially in deep saline aquifers or structurally complex

formations. Critically, regulations in many regions do not mandate comprehensive inventories or sealing of legacy oil and gas wells, which may act as vertical conduits for CO_2 escape. In practice, this has led to significant post-approval surprises projects delayed, paused, or reengineered once unexpected geological features or flow behaviours emerged. Permitting is further weakened by the absence of baseline geochemical and seismic monitoring; without it, future CO_2 plume migration or leakage signals cannot be meaningfully detected or attributed. As a result, poorly designed permitting systems risk certifying geologically unsuitable sites and institutionalizing high-risk storage (Lee et al., 2013).

3.2.2.3. Monitoring and enforcement gaps

Even when a project is permitted and operational, systemic failures in monitoring frameworks allow risks to go undetected or unaddressed. Many regulatory regimes lack prescriptive standards for monitoring tools, duration, and spatial resolution, relying instead on operator-defined plans. This allows companies to minimize cost by deploying low-resolution seismic or pressure monitoring systems that may miss early warning signs of leakage or fault activation. Moreover, detection of anomalies often leads to bureaucratic stalling rather than enforcement with unclear thresholds for intervention, a discovery may trigger technical reviews but not operational suspension or remedial actions. Compounding this, few regions have well-defined post-closure monitoring requirements extending beyond a few decades, despite CO_2 needing containment for millennia. In effect, many CO_2 storage projects are regulated to a standard that ensures non-detection is the norm, creating a false sense of security (Balaji et al., 2019; Park, 2019).

3.2.2.4. Overconfidence in modelling and capacity estimation

Regulatory agencies routinely accept optimistic geological modelling from project proponents as the basis for approval, despite a track record of overestimating storage capacity by 30–50% in national inventories. These models often assume uniform porosity, perfect caprock integrity, and homogenous pressure behaviour, with little sensitivity analysis or empirical validation. As a result, storage estimates baked into national carbon budgets are frequently inflated, giving policymakers the illusion of mitigation potential that may not exist. Worse, most regulatory frameworks do not require model recalibration during operations, meaning early-stage assumptions may persist even in the face of divergent field data. This regulatory dependence on static, optimistic models undermines the credibility of both national CCS roadmaps and international climate targets (Middleton and Yaw, 2018).

3.2.3. Policy failures

3.2.3.1. Mismatch between climate ambition and deployment capacity

A major policy failure in CO_2 storage stems from the unrealistic assumption that large-scale deployment can match the timelines and volumes outlined in climate roadmaps. Many national

decarbonization strategies rely heavily on geological storage to meet net-zero targets yet overlook the fact that project development timelines (permits, construction, public buy-in) typically span 5–10 years, while modelled scenarios often compress this into half that time. Additionally, physical infrastructure for transport and storage pipelines, compressors, injection networks is severely underdeveloped, particularly in non-OECD nations. This creates a credibility gap: while CO_2 storage is positioned as a cornerstone of emissions mitigation, the policy tools needed to scale it like industrial clustering, spatial planning, and grid integration remain missing or underfunded (Fig. 10) (Lipponen et al., 2017; Stigson et al., 2012).

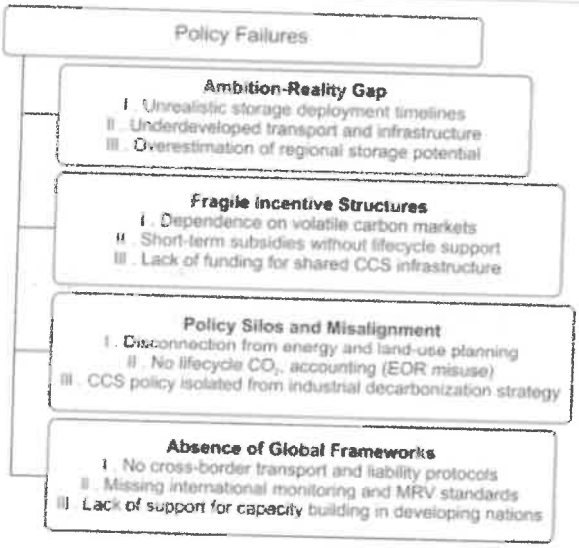

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Fig. 10. Policy failures for CO_2 storage related projects.

3.2.3.2. Overreliance on market incentives without structural policy

Many CCS-supporting jurisdictions lean heavily on carbon pricing, tax credits, or voluntary offsets as the primary means of incentivizing CO_2 storage. While these instruments can initiate projects, they do little to secure long-term operational stability. The volatile nature of carbon markets, shifting political priorities, and complex subsidy frameworks mean that project cash flows remain uncertain beyond short-term investment cycles. Moreover, storage is treated as a passive endpoint rather than an active part of decarbonization infrastructure, there is minimal policy support for shared infrastructure, knowledge transfer, or cross-sector integration. As a result, storage projects become siloed, commercially fragile, and heavily dependent on continued fiscal incentives that are politically vulnerable (Dapeng and Weiwei, 2009; Price and McLean, 2014).

3.2.3.3. Inadequate integration with broader energy and land-use policy

CO_2 storage policy is often developed in isolation from national energy, land-use, or industrial strategies. This fragmentation leads to practical misalignments such as storage targets being set in regions with no accessible geological formations, or CO_2 pipeline corridors clashing with land

zoning or agriculture priorities. More critically, many CCS policies ignore the rebound effect: captured CO_2 used in enhanced oil recovery (EOR) or tied to fossil fuel infrastructure may undermine net climate benefits, yet this is rarely constrained by law or policy. Without full lifecycle accounting and harmonization with sustainable energy goals, CO_2 storage policy risks becoming a decarbonization illusion rather than a durable mitigation pathway (Dixon et al., 2015; Dosumu et al., 2024).

3.2.3.4. Lack of global governance and cross-border frameworks

Despite CO_2 storage having global relevance especially for nations with shared sedimentary basins or transboundary reservoirs international governance is virtually absent. There is no unified protocol for CO_2 transport across borders, harmonized monitoring standards, or shared liability arrangements. This hinders investment in offshore or multi-country storage hubs and creates legal risk for early movers. Furthermore, developing countries with significant storage potential often lack the regulatory and financial tools to engage, and current policy mechanisms do little to support international cooperation or capacity building. In the absence of binding multilateral frameworks, global CCS policy remains fragmented, inequitable, and geopolitically constrained (de Coninck et al., 2009; Krüger, 2017; Maher and Symons, 2022).

3.2.4. Financial failure

3.2.4.1. Unviable unit economics

One of the most fundamental financial failures in CO_2 storage is the poor alignment between cost structures and revenue models. The cost per tonne of stored CO_2 can range from $20 to over $100, depending on depth, pressure, distance to injection site, and infrastructure availability. Yet, in many regions, carbon pricing or storage credits remain far below these levels, making projects economically unviable without permanent subsidies. Unlike capture, storage does not produce a marketable commodity it is a cost centre. As a result, private developers are reluctant to commit capital without guaranteed returns or long-term purchase agreements. Even where tax credits or compliance markets exist, they are often too volatile or short-term to underwrite the multi-decade operations required for geological storage (Fig. 11) (Mikhelkis and Govindarajan, 2020; Sowinski, 2022).

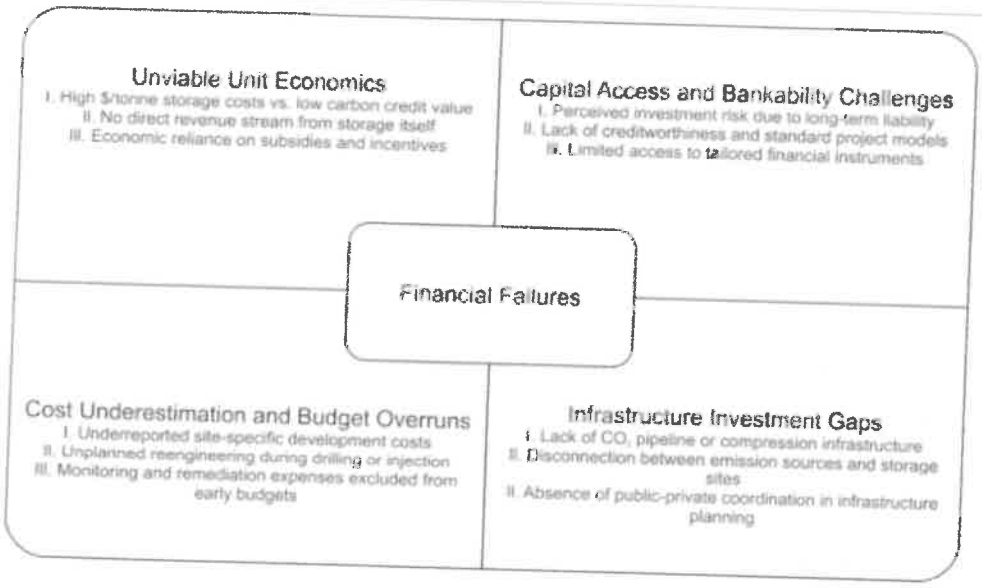

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Fig. 11. Financial constraints for CO_2 storage related projects.

3.2.4.2. Capital access and bankability challenges

CO_2 storage projects face an acute problem of bankability; the ability to secure investment under terms acceptable to institutional lenders. Unlike renewable energy projects, which offer clear revenue streams and standardized risk assessments, CCS storage is perceived as high-risk, capital-intensive, and governed by uncertain regulation and long-term liability. Many projects fail to reach final investment decision (FID) because they cannot de-risk their storage component sufficiently to attract investors. The lack of dedicated financial instruments such as CCS green bonds, pooled infrastructure funds, or public-private guarantee mechanisms has left a financing vacuum, especially in developing economies or frontier markets where capital cost premiums are already high (Comello et al., 2022; Davies et al., 2025; Hetland, 2014).

3.2.4.3. Cost underestimation and budget overruns

Another common failure is the chronic underestimation of capital and operating costs during the project planning stage. Budget projections often fail to account for site-specific complications like unexpected geology, pressure behaviour, or wellbore modifications, which result in cost escalations during drilling, compression, or monitoring. Notable CCS projects have seen costs double or triple due to reengineering, regulatory delays, or failed injection tests. This not only undermines investor confidence but also drains public funding, leading to project downsizing or cancellation. Moreover, cost models often ignore the need for decades-long monitoring and potential remediation, which are not optional but regulatory obligations in most jurisdictions (Eckhause and Herold, 2014; Shackley and Evar, 2012).

3.2.4.4. Infrastructure investment gaps

Even when project-level funding is secured, many CO_2 storage initiatives fail because the supporting infrastructure is missing or misaligned. Storage sites require dedicated pipeline networks, compression hubs, injection wells, and monitoring systems, none of which are cheap or plug-and-play. In many regions, the lack of investment in this foundational infrastructure means that storage-ready formations remain physically disconnected from CO_2 sources. This creates stranded potential viable geological sinks that cannot be used due to absence of CO_2 transport corridors or grid interconnections. The absence of coordinated infrastructure funding strategies at the national or regional level effectively raises the cost of entry and makes individual project economics infeasible (Oda and Akimoto, 2011; Stigson et al., 2012).

3.3. Stakeholder acceptance and public opinion

Beyond regulatory compliance, policy ambition, and financial modelling, one of the most decisive and often underestimated determinants of CO_2 storage success is public acceptance. While geological storage is a technical process, it unfolds in social and political landscapes that are far more volatile than reservoir pressure gradients. A storage project may meet all engineering and economic benchmarks, yet still collapse under the weight of community resistance, land-use conflict, or distrust in institutional actors (Brunsting et al., 2011; Mabon and Littlecott, 2016; Terwel et al., 2011).

The failure to meaningfully involve stakeholders particularly local communities, landowners, and Indigenous groups in the early planning stages remains a recurring oversight. Public opposition is often dismissed as uninformed or irrational, yet many concerns stem from legitimate fears: CO_2 leaks, seismicity, groundwater contamination, or long-term environmental liability. These are amplified by the invisibility of the process (underground injection), lack of tangible community benefits, and prior negative experiences with extractive industries. When engagement occurs late, or is limited to one-way "information sessions," it reinforces perceptions of procedural injustice and exclusion.

Furthermore, the "Not in My Backyard" (NIMBY) dynamic frequently derails project siting. Even when public opinion polls show general support for CCS as a climate solution, localized resistance emerges when injection wells or pipeline routes are proposed near residential or agricultural land (Braun, 2016, 2017; Selma et al., 2014). This spatial dimension of public opposition is particularly difficult to overcome once trust is broken. In several high-profile cases, public backlash has led to permit denials, legal challenges, and political withdrawal of support, regardless of the project's technical merits.

Crucially, public opinion is not a static variable; it evolves in response to transparency, institutional behaviour, media narratives, and perceived fairness. Therefore, stakeholder engagement should not be viewed as a checkbox exercise, but as a core component of risk management and social license to operate. CO_2 storage may be a geoscientific challenge, but its feasibility is ultimately determined

above ground in town halls, tribal councils, and legislative chambers (Saito et al., 2019). The industry must invest in co-created governance, community benefit-sharing mechanisms, and long-term trust-building if it hopes to scale storage projects beyond pilot phases.

4. The technological failures of carbon capture: a critical appraisal

Since its early political endorsement under the Kyoto Protocol and its subsequent inclusion in IPCC mitigation pathways, carbon capture technology has been promoted as the keystone for reconciling fossil fuel use with climate targets (Hashmi et al., 2024; Osman et al., 2021; Wilberforce et al., 2021). Advocates positioned it as the vital enabler for continued industrial activity, proposing that CO_2 emissions could be captured at source whether from power generation or industrial processes and safely stored without disrupting economic growth. However, decades of empirical data now suggest that this optimism was unfounded (Abdulla et al., 2020; Von Hirschhausen et al., 2012). Despite extensive funding and research, carbon capture technologies have failed to deliver scalable, cost-effective, or operationally robust outcomes (Scott et al., 2013; Wang et al., 2021). Theoretical models continue to outpace reality, with fundamental barriers in energy efficiency, materials stability, and economic feasibility remaining unresolved. The distance between promise and performance is not narrowing it is expanding, particularly as systems scale up and confront the unpredictability of real-world industrial conditions.

The maturity of carbon capture systems can be further contextualized by examining their Technology Readiness Levels (TRLs), which range from 1 (basic research) to 9 (fully operational systems). Post-combustion amine capture technologies, such as those deployed at Boundary Dam, are among the most advanced, typically reaching TRL 8–9, though their field performance remains inconsistent and energy-intensive (Hekmatmehr et al., 2024; International Energy Agency, 2020). In contrast, membrane-based capture systems, while widely studied in laboratory settings, remain at TRL 5–6 due to persistent scaling challenges, fouling issues, and limited real-world validation (Hekmatmehr et al., 2024; U.S. Department of Energy, 2021, 2025). Geological storage infrastructure generally operates between TRL 6 and 8, but subsurface monitoring and leakage detection technologies often remain in the TRL 4–6 range, with no systems yet validated for the century-scale durability needed to meet Paris Agreement goals (Zhuo-Ni et al., 2022). Meanwhile, emergent options such as DAC remain largely pre-commercial, with TRL estimates typically between 4 and 6 (United Nations Environment Programme Copenhagen Climate Centre, 2023). A summary of these TRL classifications is provided in Supplementary Table S5.

A key technical flaw lies in the intrinsic energy penalty associated with carbon capture. Post-combustion systems, for example, often consume 20–30% of a plant's output simply to operate the capture process; an issue well documented by MIT and IEA analyses (Bhown and Freeman, 2011; Klass and Wilson, 2009). This parasitic load not only reduces net energy efficiency but paradoxically increases upstream emissions by requiring more fossil fuel combustion. The case of Boundary Dam in Canada exemplifies this dilemma. Despite a retrofit investment exceeding $1.5 billion, the project

struggled with frequent shutdowns and operational inefficiencies driven by the energy demands of the capture system (Larkin et al., 2019; Preston et al., 2018). Rather than mitigating emissions, such setups risk entering a circular trap burning additional carbon to manage carbon.

Real-world capture rates also deviate sharply from the oft-cited 90% efficiency benchmark. Petra Nova, one of the most publicized projects globally, consistently underperformed, managing only around 70% capture efficiency during stable operation and eventually ceasing operations in 2020 due to financial and technical difficulties (Kristoff, 2020; Varro, 2017). Australia's Gorgon project, despite its status as the largest CCS initiative globally, missed its five-year capture targets by nearly half due to persistent subsurface and infrastructure issues. These headline failures are not isolated anomalies but indicative of systemic flaws: industrial-scale CCS suffers from high solvent degradation, equipment corrosion, and declining efficiencies under variable gas compositions; none of which are adequately captured in pilot-scale studies (Kristoff, 2022; Marshall, 2022). Worse still is the strategic misapplication of capture technology. Instead of prioritizing sectors where carbon abatement is technically challenging such as cement or steel production CCS has overwhelmingly been deployed in oil and gas operations (De Ras et al., 2019; Hills et al., 2016). The application of capture to "blue hydrogen" production offers another cautionary tale: while CO_2 is removed during steam methane reforming, the process remains fundamentally dependent on natural gas, reinforcing rather than disrupting fossil fuel pathways (Schlissel and Juhn, 2023).

This misalignment between technical promise and real-world application has led to what systems theorists refer to as "technological lock-in." Instead of enabling a transition away from fossil fuels, carbon capture frequently delays it preserving aging infrastructure and diverting attention and funding from renewable alternatives. The IPCC's Sixth Assessment Report explicitly warns that overreliance on CCS risks entrenching carbon-intensive systems, rather than enabling their phaseout (Lucas, 2021). In this light, carbon capture is less a mitigation tool and more a mechanism of deferred accountability; a technological placeholder that sustains business-as-usual under the pretense of innovation. If climate urgency is real, then reliance on unscalable and misapplied technologies must give way to proven, immediate solutions.

The growing body of evidence reveals a troubling consensus: CCS is largely failing to deliver on its climate promises. The MIT Energy Initiative's 2019 analysis flagged significant energy penalties (20–30%) and persistent gaps between laboratory results and field performance, setting the tone for scepticism around CCS viability (Table 2). This scepticism deepened with the IEA's 2021 global review, which reaffirmed that CCS remains cost-prohibitive and technologically immature, casting doubt on its scalability in real-world transitions. The Global CCS Institute's 2022 report dealt a further blow, showing that despite years of investment, current CCS infrastructure captures less than 0.1% of annual CO_2 emissions a figure that underscores its negligible climate impact.

Table 2. Recent review reports on carbon capture failure.

Review/Report	Organization/Publisher	Focus/Scope	Main Findings	Remarks
MIT Energy Initiative	Massachusetts Institute of Technology (MIT) (2019)	Analysis of carbon capture technologies; energy penalty, cost, and feasibility	Energy penalties (20–30%) undermine CCS practicality; lab-to-field performance gap	Foundational work exposing technical flaws of capture technologies
IEA CO_2 Capture Review	International Energy Agency (2021a)	Global review of CCUS status, potential, challenges in energy transitions	CCS remains expensive, underperforming; major scaling hurdles persist	Key benchmark for CCS policy debate; highlighted scalability doubts
Global CCS Operations Overview	Global CCS Institute (2022)	Annual global report on operational CCS capacity and trends	Global CCS captures <0.1% of annual CO_2 emissions; negligible climate impact	Demonstrates actual impact vs. political promises mismatch
CCUS in Blue Hydrogen – IPCC AR6 WGIII (Intergovernmental Panel on Climate, 2022a)	Intergovernmental Panel on Climate Change (IPCC) (2022a)	Assessment of CCUS's role and risks in hydrogen and energy transition	Blue hydrogen risks locking in fossil dependency rather than decarbonizing	First major IPCC acknowledgment of lock-in risk via CCS
IEEFA CCS Critical Review	Institute for Energy Economics and Financial Analysis (2022)	Critical review on financial viability and real-world performance of CCS	CCS economically unsustainable; repeated financial failures documented	Exposes CCS as a diversion from real decarbonization efforts
New York Times Investigative Report	The New York Times (2025)	Investigation into U.S. public funds spent on failed CCS projects	USD $1.1 billion wasted on failed DOE-backed CCS projects; minimal CO_2 captured	Spearheaded public scepticism about CCS funding and priorities

More critically, the IPCC's Sixth Assessment Report introduced the notion that CCS especially in blue hydrogen production may reinforce fossil fuel dependence rather than disrupt it, signalling a major shift in narrative from cautious optimism to structural concern. The IEEFA's 2022 review intensified the critique, portraying CCS as economically unsustainable and increasingly disconnected from practical decarbonization pathways. Finally, the New York Times' investigative report added a political dimension, revealing $1.1 billion in wasted U.S. public funds on failed CCS ventures, thereby amplifying public distrust. Taken together, these findings paint a damning picture: CCS, once considered a bridge to net-zero, is instead proving to be an expensive detour with little to show for decades of effort (Table 2).

While academic literature and institutional reviews offer structured analyses of carbon capture technologies, journalistic investigations and news reports provide an unfiltered look into the operational, political, and economic realities of these projects. A growing number of high-profile media and watchdog organizations including *The New York Times*, *Financial Times*, *Reuters*, and *BBC* have independently documented repeated failures, delays, and safety hazards associated with Carbon Capture, Utilization, and Storage (CCUS) initiatives (Table 3). From abandoned projects like Project Bison in the U.S. and Planetary Technologies in the U.K., to multibillion-dollar infrastructure collapses like the Summit Carbon Pipeline and Shell's withdrawal from the Aramis CCS project, these reports expose a troubling pattern: CCS is frequently plagued by unrealistic expectations, inadequate oversight, regulatory pushback, and financial instability (Table 3).

Table 3. Recent news reports on carbon capture failure.

Article/Report	Publisher/Platform	Main Focus	Main Findings	Remarks
New York Times – $1.1B Wasted on Failed CCS Projects	The New York Times (2023)	Investigation into US DOE funding wasted on CCS	Over $1.1 billion wasted; projects failed to capture meaningful CO_2	Increased public scepticism towards CCS funding and deployment
Financial Times – Summit Carbon Pipeline Setbacks	Financial Times (2023)	Reporting on major permit denial and financial risks for Summit pipeline	Project investments at risk; route deemed not viable; opposition strong	Highlighted regulatory, landowner, and financial hurdles
Reuters – Shell and Total Energies Exit Aramis Project	Reuters (2023b)	News about Shell and TotalEnergies pulling out from Aramis CCS project	Private companies exited due to poor economic feasibility	Private sector unwilling to bear CCS financial risks

Article/Report	Publisher/Platform	Main Focus	Main Findings	Remarks
NOS Dutch News – Porthos CO_2 Storage Project Costs Triple	NOS Dutch News (2023)	News about huge cost overruns at Porthos CCS project	Porthos project budget nearly tripled; raises economic concerns	Financial viability of CCS offshore storage deeply questioned
The Guardian – Project Bison DAC Collapse	The Guardian (2022)	News about collapse of a major Direct Air Capture (DAC) startup project	Project Bison shut down; DAC commercialization unviable	Exposed fundamental commercialization limits of DAC
BBC News – Planetary Technologies Pilot Failure	BBC News (2022)	News about failure of ocean alkalinity CO_2 removal pilot	Pilot deemed commercially and scientifically infeasible	Brought attention to ecological and practical limitations of ocean CDR
Clarion Ledger – Denbury CO_2 Pipeline Rupture	Clarion Ledger (2022)	Incident report of CO_2 pipeline rupture causing public health emergency	Pipeline accident exposed serious safety hazards in CO_2 infrastructure	Safety risks associated with CO_2 transport highlighted by real-world event
Carbon Tracker Initiative – Busted: Financial Reality of CCS	Carbon Tracker Initiative (2022)	Critical financial review of global CCS investments and failures	Massive financial waste; CCS unlikely to deliver climate targets cost-effectively	Documented systemic financial failures across global CCS investments

Several projects faced shutdowns due to cost overruns, public opposition, or technical failure despite significant public funding and government endorsement. Others, like the Denbury CO_2 pipeline rupture, underscored the serious health and safety risks inherent in large-scale CO_2 transport infrastructure. These real-world stories paint a far grimmer picture than what is often portrayed in promotional material or speculative modelling studies. Critically, many of these failures were not isolated anomalies but indicative of systemic issues: underestimation of costs, overestimation of capture potential, and a persistent misalignment between technological maturity and policy ambition. Together, these news accounts provide indispensable evidence that CCS, as it stands today, is not simply underperforming; it is failing across technical, financial, and societal dimensions. They offer a necessary counterbalance to institutional optimism, reminding policymakers and researchers alike that public trust, project viability, and environmental integrity cannot be engineered through funding alone. A critical discussion on capture failures highlighted in Table 2, Table 3, will be carried out in subsequent sub-sections.

4.1. Performance gaps and deployment challenges

At the heart of carbon capture's systemic failure lies not only the logistical challenges of transportation and storage, but also deep-rooted technical deficiencies in the capture process itself (Bowen, 2011; Lin et al., 2022). Despite decades of aggressive funding and research through initiatives like the U.S. Department of Energy's Carbon Capture Program, European Framework Programs, and countless private sector ventures carbon capture technology has consistently underdelivered relative to its promises (Folger, 2014; Litynski et al., 2006). Existing systems, whether based on amine scrubbing, cryogenic separation, or more experimental approaches, remain plagued by excessive energy consumption, high operational costs, material degradation, and scalability issues. Post-combustion capture, the most widely deployed method, demands between 20 and 30% of a power plant's energy output simply to operate the capture machinery, as extensively documented by the Massachusetts Institute of Technology (2019) and confirmed in subsequent IEA analyses. This parasitic energy penalty directly undermines the environmental and economic viability of the technology (Kheirinik et al., 2021; Lamberts-Van Assche and Compernolle, 2022; Olabi et al., 2022). Even where capture systems achieve laboratory-grade efficiencies, real-world conditions including fluctuating flue gas compositions, impurities, operational disruptions, and mechanical wear consistently erode performance. The technical literature is replete with small pilot success stories, yet industrial-scale deployment exposes crippling maintenance, fouling, and cost challenges that research publications often gloss over.

4.2. Performance limitations of membrane-based CO_2 capture

Among the many carbon capture technologies positioned as future cornerstones of climate mitigation, membrane-based separation has attracted a notable level of attention and investment. On the surface, the appeal is intuitive. Membranes offer a conceptually simple approach: materials selectively permeable to carbon dioxide that allow CO_2 to pass through while blocking nitrogen and other gases. This setup promises a low-maintenance, modular system with minimal moving parts and no need for chemical solvents (Luis et al., 2012; Roussanaly and Anantharaman, 2017; Roussanaly et al., 2016).

Driven by this appeal, global research efforts have accelerated rapidly. Between 2010 and 2023, more than 3.5 billion dollars were invested in membrane-related research and development. Over 2500 scientific publications emerged in that period, many highlighting laboratory-scale membranes with high permeability, strong selectivity, and apparent chemical stability. At first glance, experimental results are promising, with some membranes achieving CO_2 permeance values exceeding 2000 GPU and selectivity ratios above 50 under controlled conditions (Norahim et al., 2018).

Yet when these technologies move beyond the lab, the narrative begins to fall apart. No membrane system to date has demonstrated economically viable carbon capture performance at the scale required for commercial power generation, heavy industry, or direct air capture. The reason lies in a

fundamental performance constraint known as the Robeson Upper Bound (Comesaña-Gándara et al., 2019; Rowe et al., 2010). This trade-off dictates that as membrane permeability increases, selectivity typically decreases (Park et al., 2017). Membranes that can process large volumes of gas often allow unwanted components like nitrogen or oxygen to slip through, reducing purity. Conversely, membranes that are highly selective tend to process gas slowly, requiring larger surface areas and more stages to be effective. This results in bulkier systems, higher energy input for gas compression, and increased capital and operational costs.

In industrial environments, these challenges multiply. Membranes must operate under harsh conditions, with flue gases containing water vapor, sulphur oxides, particulates, and other contaminants (Iulianelli and Drioli, 2020; Pasichnyk et al., 2023). These impurities lead to membrane fouling and rapid performance degradation. A 2022 DOE pilot test in Alabama, for example, observed a 35 percent drop in capture efficiency within six months due to exposure to sulphur compounds. In such settings, the touted simplicity of membranes turns into a liability, as frequent maintenance or replacement becomes unavoidable (Alptekin, 2022).

To address these limitations, researchers have proposed hybrid configurations, combining membranes with solvent-based absorption or cryogenic cooling (Bhattacharyya, 2022). While theoretically offering improved separation performance, these hybrid systems introduce new layers of complexity. They require additional compressors, heat exchangers, and gas pretreatment units, along with increased parasitic energy loads. A 2021 comparative assessment by the International Energy Agency concluded that membrane systems, when deployed at scale, could consume 20 to 40 percent more energy per ton of CO_2 captured than advanced amine-based capture systems. Moreover, cost projections further erode the case for membranes. A comprehensive techno-economic review by the National Energy Technology Laboratory in 2023 concluded that membrane systems are unlikely to reach cost competitiveness, defined as below 60 dollars per ton of CO_2 captured, unless there are fundamental breakthroughs in materials science (Kamolov et al., 2023; Zhu et al., 2024). These breakthroughs remain speculative, with no commercially available material offering the required combination of durability, selectivity, and permeability.

In short, membrane-based carbon capture represents a classic case of promise inflated beyond performance. Laboratory results, while encouraging, fail to survive the transition to real-world applications. The underlying material science faces physical constraints that cannot be engineered away with incremental tweaks. While the concept of membrane separation is elegant, the practical reality is one of complex engineering challenges, unmanageable maintenance demands, and prohibitive costs.

The result is a technological mirage. Membranes appear to offer a clean and efficient path to carbon capture, but as efforts move from bench-scale to industrial deployment, the vision evaporates. What remains is not a solution, but another detour consuming valuable time, resources, and public attention in the race to decarbonize.

4.3. Misalignment between research and reality

The continued emphasis on developing advanced membrane materials, despite clear and well-documented industrial limitations, illustrates a deeper structural dysfunction within the carbon capture research ecosystem. At the core of this issue lies a misalignment between academic incentives and real-world engineering demands. University laboratories and material science departments often prioritize novelty, surface-level breakthroughs, and publishable metrics such as a 10% gain in CO_2 selectivity or marginal increases in permeance (Nawaz et al., 2022). However, these studies rarely tackle the hard engineering challenges that determine whether a technology can survive outside the lab, such as resistance to chemical fouling, maintenance frequency, or total lifecycle cost.

A survey of the scientific literature from 2010 to 2022 shows that over 70% of membrane research papers focus on optimizing performance under ideal gas conditions, often using binary gas mixtures of CO_2 and N_2 in controlled settings. In contrast, fewer than 5% of these studies address real-world contaminants like sulphur oxides, moisture, and particulates, which are ubiquitous in flue gas streams. This gap in relevance leads to a growing corpus of promising laboratory results that fail to translate into scalable, bankable industrial solutions (Mondal et al., 2012; Yu et al., 2023).

The problem is compounded by the use of simplified techno-economic models that assume membrane lifespans of over five years, membrane module costs under $50 per square meter, and capture efficiencies above 85%. Yet actual pilot data shows that membranes deployed in industrial environments degrade in performance by up to 35% within the first 12 months, often requiring partial replacements or cleaning every few hundred operating hours. Such operational realities are rarely integrated into research frameworks, creating an illusion of progress that is not matched by commercial viability.

This disconnect is not merely academic. Political and economic structures further entrench this misalignment. Research agencies, venture-backed startups, and national laboratories all face pressure to appear innovative and forward-leaning. Consequently, funding continues to flow toward membrane technologies even when fundamental thermodynamic and engineering limits, such as the Robeson upper bound or compressor energy penalties remain unresolved. Between 2015 and 2022, over $1.2 billion globally was allocated to advanced membrane research for carbon capture, yet not a single full-scale, economically viable deployment has emerged from these efforts.

What emerges is a feedback loop in which lab-scale "breakthroughs" are celebrated, investment is renewed, and industrial deployment remains stagnant. The result is a growing body of scientific literature and political rhetoric that is increasingly detached from operational needs. The conversation surrounding membranes becomes dominated by performance metrics that cannot survive contact with industrial complexity, regulatory scrutiny, or basic economic calculus.

For carbon capture technologies to meaningfully contribute to climate mitigation, research must be reoriented toward engineering realism. This means designing for the environments in which

systems will actually operate, prioritizing durability over novelty, and integrating techno-economic and lifecycle assessments into the core of R&D strategy. Without this recalibration, the promise of membranes will continue to exist primarily on paper—polished, precise, and fundamentally impractical.

The persistent investment into novel membrane materials, despite clear industrial limitations, reflects a broader structural problem in carbon capture R&D. Academic research incentives prioritize novelty and incremental performance improvements over systemic feasibility or deployment readiness. As a result, an enormous body of literature exists reporting modest improvements in membrane selectivity or permeability, but very little work addresses the fundamental engineering bottlenecks of scaling, fouling resistance, or lifecycle cost. Laboratory conditions, using purified gas streams, fail to simulate the abrasive, dirty, volatile environments that real power plants and industrial facilities operate under. Consequently, published results consistently overstate membrane performance while ignoring the brutal operational realities that doom these systems at commercial scale. The technological discourse becomes decoupled from deployment needs, perpetuating a cycle where "breakthroughs" on paper fail to materialize into viable industrial solutions.

Moreover, political and economic structures further distort research trajectories. Agencies and private firms seeking to appear forward-thinking and innovative continue to fund advanced materials development even when the underlying physical and economic limitations are well-understood. This flow of funding, in turn, reinforces an academic ecosystem that optimistically pursues ever-smaller efficiency gains in laboratory membranes, while the industrial sector quietly recognizes that membranes remain unfit for real-world carbon capture deployment.

4.4. Foundational barriers to scalability

Carbon capture technologies suffer from an endemic tendency to overpromise and underdeliver, a pattern rooted not only in logistical and economic barriers, but in deep technological limitations. While laboratory-scale results offer brief flashes of optimism, the leap to industrial reality reveals profound, often unresolvable weaknesses excessive energy costs, operational fragility, chemical degradation, and scaling difficulties. Membrane-based capture, a field that has absorbed billions in research funding, exemplifies this cycle of misplaced hope: a seductive theory undermined by brutal engineering and physical constraints. Instead of confronting these limitations head-on, much of the research community, encouraged by funding structures and political pressures, continues to chase marginal improvements in systems that are fundamentally misaligned with the requirements of industrial-scale, economically viable, sustainable carbon capture.

If technological optimism in carbon capture persists, it must be tempered with a hard reckoning: no material breakthrough, no marginal efficiency gain, no clever system hybridization has yet overcome the brutal realities of industrial physics and economics. To persist in promoting carbon

capture without this acknowledgment is not scientific rigor, it is technological denialism dressed as innovation.

5. Case studies of CCS failure: lessons learnt

Several real-life case studies pertaining to storage projects failures have been discussed in this section and also summarized in Fig. 12(a–c).

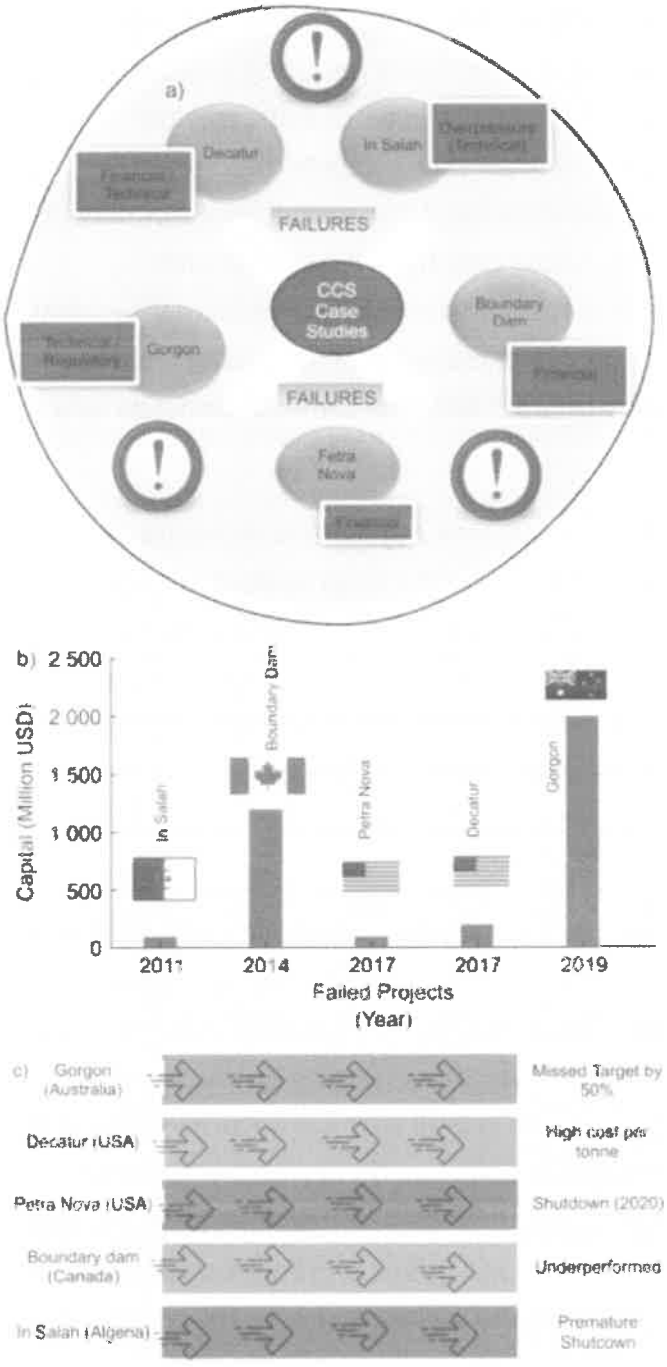

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Fig. 13. Radar map of 'successful' CCS projects evaluated on parameters like storage, transferability, economic independence, monitoring readiness and public funding dependency.

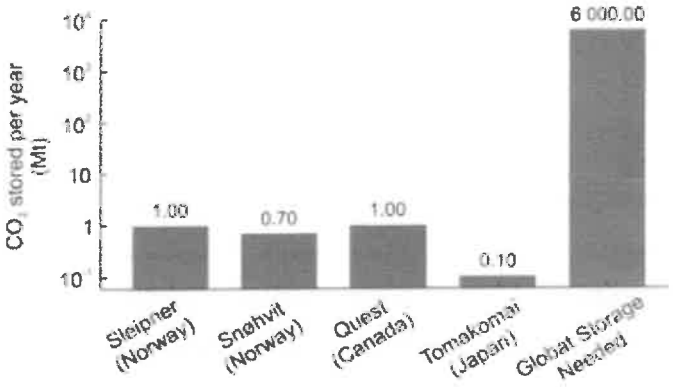

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Fig. 14. Global CO_2 storage needed vs CO_2 stored in 'successful' CCS projects.

5.6.2. Snøhvit (Norway)

Snøhvit, also operated by Equinor, began operations in 2008 as part of a liquefied natural gas (LNG) development in Norway's Barents Sea. The project captures CO_2 from natural gas processing and injects it into the offshore Tubåen sandstone formation. Initially heralded for its innovation and integration into offshore infrastructure, Snøhvit experienced a significant operational hurdle in 2011 when pressure buildup forced a temporary pause in injection. Nonetheless, the project was adapted and injection resumed, showcasing the value of responsive monitoring and reservoir management. Though smaller in scale than future targets demand, Snøhvit contributes to the growing evidence that offshore saline formations are viable storage options, particularly when integrated with existing energy infrastructure (Eiken et al., 2011).

5.6.3. Quest (Canada)

Shell Canada's Quest project began injecting CO_2 in 2015 from hydrogen production at the Scotford upgrader facility in Alberta. With over 6 million tonnes of CO_2 stored to date in a deep saline aquifer, Quest has become a model for operational transparency, robust monitoring, and third-party auditing. The project benefits from strong public funding roughly $800 million of the $1 billion total cost was covered by the Canadian and Alberta governments which insulated it from the economic risks that have undermined other CCS ventures. Quest consistently meets its capture, and storage targets and publicly shares detailed performance data, making it one of the most instructive case studies in the field. However, its success is closely tied to policy-driven funding, raising questions about replicability in market-driven contexts (Bourne et al., 2014; Rock et al., 2017).

5.6.4. Tomakomai (Japan)

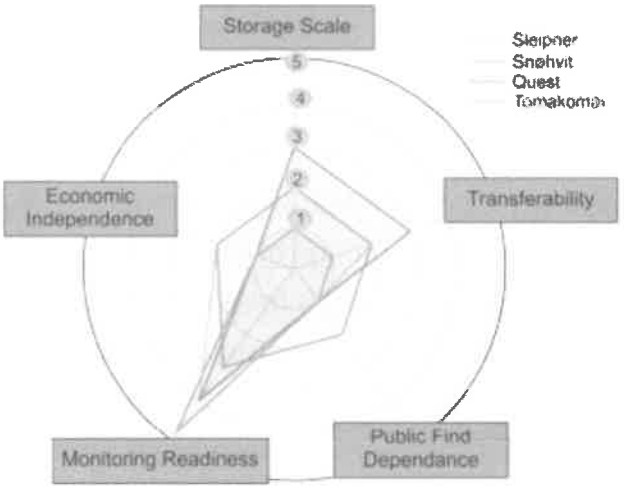
investigate potential subsurface movement underscoring ongoing operational and regulatory challenges (Reuters, 2024). Though less high-profile than Petra Nova or Gorgon, Decatur reinforces the pattern: technical, geological, and financial challenges repeatedly emerge even in "successful" pilot projects (Finley, 2014; Finley et al., 2013; Greenberg et al., 2018).

5.6. Are successful CCS projects really successful?

While a handful of CCS projects are often showcased as success stories, a closer inspection reveals that these claims rarely hold up under real-world scrutiny. Many of these projects, when evaluated beyond pilot-scale metrics or controlled conditions, fail to meet fundamental criteria for long-term scalability, economic viability, and climate relevance. Operational inconsistencies, low capture efficiencies, high costs, and dependency on enhanced oil recovery (EOR) undermine their credibility as climate solutions. The disconnect between what is defined as "successful" in industry reports and what is actually impactful in reducing global CO_2 emissions continues to widen raising a critical question: are these projects truly successful, or are they symbolic wins masking systemic inefficiencies? Some of the 'success' stories are discussed in the subsequent sub-subsections.

5.6.1. Sleipner (Norway)

Launched in 1996 by Equinor, the Sleipner project remains the world's first and longest-operating commercial CO_2 storage site. Situated in the North Sea, Sleipner injects approximately one million tonnes of CO_2 annually into the Utsira saline sandstone formation. This project stands out for its early adoption of high-resolution seismic monitoring and its integration into an existing gas processing platform, significantly lowering infrastructure costs. Funded and motivated by Norway's robust carbon tax regime, Sleipner demonstrated that geological CO_2 storage could be technically feasible and publicly acceptable albeit at a relatively small scale. While its success is undisputed, the project's size and reliance on national policy incentives make it less representative of the scalability challenges facing global CCS efforts (Fig. 13, Fig. 14) (Ringrose, 2018; Singh et al., 2025).



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Chevron's Gorgon project, located on Barrow Island in Western Australia, was supposed to be a flagship example of large-scale CO_2 sequestration. Designed to capture around four million tonnes of CO_2 per year from its liquefied natural gas operations, the Gorgon CCS facility is one of the largest and most expensive CCS projects globally, with costs exceeding $3 billion AUD. Yet despite its scale and prestige, Gorgon faced massive operational failures almost immediately. Delays in getting the injection wells ready, unexpected geological issues, and mechanical problems resulted in the project missing its legally mandated storage targets by nearly 50% over the first five years. Investigations by the Australian Clean Energy Regulator revealed that the project captured far less CO_2 than planned, even as the associated LNG facilities continued to emit large volumes of greenhouse gases. Chevron was forced to purchase carbon offsets to meet its emissions obligations; a humiliating outcome for a project intended to showcase geological storage. Gorgon starkly illustrates that even when backed by the world's largest oil companies and massive investment, CCS projects can underdeliver dramatically, raising serious questions about scalability, reliability, and regulatory oversight (Afagwu, 2024; Paz, 2021; Quinn, 2022).

5.4. In Salah (Algeria): premature shutdown

The In Salah project in Algeria, operated by BP, Statoil, and Sonatrach, was one of the earliest commercial CCS demonstrations, injecting CO_2 into a gas reservoir from 2004 to 2011. Initially, In Salah was celebrated for its technical sophistication, with extensive seismic monitoring designed to track the injected CO_2. However, within a few years of operation, InSAR monitoring detected surface uplift linked to subsurface pressure increases, raising caprock-integrity concerns and leading to cessation of injection in 2011. In Salah's premature shutdown provided an early, critical warning: subsurface environments behave unpredictably under high-pressure CO_2 injection, and engineering models are often insufficient to predict real-world outcomes. The project stands as evidence that even carefully planned CCS operations can fail when geological realities do not cooperate (Lanabi, 2024; Mathieson et al., 2010; Vasco et al., 2018; Vilarrasa et al., 2015).

5.5. Decatur (Illinois, USA): early plume migration and economic question marks

The Illinois Industrial CCS project at Decatur, operated by Archer Daniels Midland (ADM) with support from the U.S. Department of Energy, was designed to demonstrate the feasibility of injecting CO_2 into deep saline aquifers. Injection began in 2011, with a target of storing one million tonnes of CO_2 over three years. However, early in the project's operation, unexpected plume migration and pressure anomalies were detected, requiring significant operational adjustments. While the project ultimately met its injection volume targets, the technical difficulties encountered reveal the challenges of working with heterogeneous and complex subsurface environments. Furthermore, Decatur's economics remain questionable. The project benefited from substantial public subsidies and operated at a cost per tonne captured that is economically unsustainable without ongoing government support. However, Decatur achieved its 1 Mt demonstration goal and extensive monitoring reported no leakage as of 2015; however, subsequent EPA findings (2024)cited permit violations related to a corroded monitoring well, and ADM paused injection later that year to

Fig. 12. Case studies of failed CCS projects, a) various aspects of CCS projects failures, b) capital invested in failed CCS projects globally, c) reasons of CCS projects failures.

5.1. Petra Nova (Texas, USA): a $1 billion disappointment

When the Petra Nova project in Texas launched in 2017, it was hailed as a landmark achievement in commercial carbon capture. Developed jointly by NRG Energy and JX Nippon, it received substantial public funding, including a $190 million grant from the U.S. Department of Energy. The project was designed to capture 90% of CO_2 emissions from a coal-fired unit and use the captured carbon for Enhanced Oil Recovery in the West Ranch oil field. In promotional materials, Petra Nova was framed as a scalable model for retrofitting existing coal plants around the world. However, the reality soon diverged sharply from the narrative. Even under ideal operating conditions, Petra Nova failed to consistently meet its capture targets, often achieving below 70% capture rates. The economics of the project were tethered to high oil prices, without which the captured CO_2 could not generate sufficient revenue through oil production. Petra Nova was idled in 2020 after oil-price collapse and performance shortfalls, then restarted in Sept 2023; over its first three years it captured ~3.8 million short tons vs ~4.6 million expected. Far from proving the viability of CCS, Petra Nova exposed how fragile carbon capture economics are when decoupled from fossil fuel market dynamics. A project that cost nearly $1 billion produced no lasting climate benefit and now stands as a monument to technological overreach and misplaced public trust (Jenkins, 2015; Raven et al., 2016).

5.2. Boundary Dam (Saskatchewan, Canada): a high-cost underperformer

Another often-cited case study is the Boundary Dam project operated by SaskPower in Canada. Boundary Dam Unit 3 was retrofitted in 2014 with a carbon capture system, costing around $1.5 billion CAD. It was marketed as the world's first fully integrated post-combustion carbon capture power plant, with bold promises of capturing up to 90% of the unit's emissions. However, internal performance reviews and external audits paint a far bleaker picture. Capture rates fluctuated between 40 and 65% depending on plant conditions, maintenance needs, and mechanical failures. Furthermore, persistent operational issues, including compressor malfunctions and corrosion in the capture plant, resulted in frequent downtimes. The captured CO_2, again, was largely used for Enhanced Oil Recovery, creating a questionable net emissions profile. Financially, Boundary Dam has been a drain on public resources, requiring ongoing government subsidies to remain operational. Performance has been uneven over the project's life, with notable outages and variability; however, SaskPower reports its strongest calendar year to date in 2024 (≈848 kt captured; 85% availability). Independent assessments still question cost-effectiveness (Manuilova et al., 2014).

5.3. Gorgon CCS (Western Australia): the billion-dollar storage blunder

The Tomakomai CCS project, operated by Japan CCS Co. with support from METI, ran from 2016 to 2019 and demonstrated offshore CO_2 storage in a complex geological environment. Over the course of the project, approximately 300,000 tonnes of CO_2 were successfully injected into two separate sandstone formations beneath the seabed. What distinguished Tomakomai was its advanced seismic and microseismic monitoring systems, which provided high-resolution data on plume migration and reservoir response. Though limited in scale and designed purely for demonstration, Tomakomai's precision and comprehensive risk management make it a standout example of what well-funded, technically meticulous CCS deployment can achieve. Its main limitation lies in its non-commercial nature and lack of scalability evidence (Yamanouchi et al., 2011).

Fig. 13 compares Sleipner, Snøhvit, Quest, and Tomakomai across five critical dimension storage scales, transferability, public funding dependence, monitoring readiness, and economic independence, highlights fundamental weaknesses beneath their technical achievements. While these projects demonstrate competent monitoring systems and operational continuity, they score poorly on economic viability and scalability. All four projects rely heavily on public subsidies and operate under niche geological or regulatory conditions that are difficult to replicate globally. Their apparent "success" is largely conditional made possible only through controlled environments, generous funding, and minimal commercial risk (Tanase et al., 2013).

Most damning, however, is the stark disparity shown in the bar chart comparing annual CO_2 storage of successful projects to global climate needs (Fig. 14). Projects like Quest and Sleipner store around 1 million tonnes of CO_2 per year impressive in isolation, but insignificant next to the 6000 million tonnes per year the IPCC says we must store to stay below 1.5 °C warming. This reveals a scale gap of over 6000 times between current capacity and climate necessity fig. Even if these projects were flawlessly executed, they are not operating on a level that meaningfully contributes to climate goals. Instead, they function more as technological showcases than as climate solutions.

The subsidy wheel further underlines this point. All of the successful projects received between 70% and 100% of their capital funding from government sources. This indicates that private investment in CCS remains hesitant Fig. 15, if not entirely absent, due to the technology's poor return on investment and long-term liability concerns. These projects have not attracted scalable commercial finance because the economics simply do not work under current market conditions. If CCS were a truly viable climate solution, we would expect to see a robust pipeline of privately driven projects scaling up across diverse sectors and geographies. Instead, what we see is state-sponsored experimentation an expensive insurance policy against emissions with questionable payback (Sawada et al., 2018; Tanaka et al., 2014).

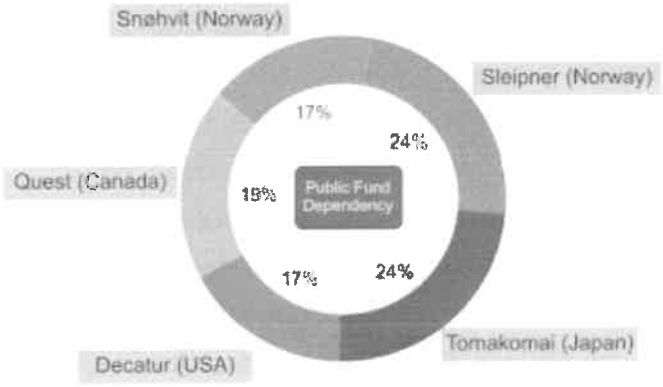

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Fig. 15. Public fund dependency of CCS projects.

In combination, Fig. 14, Fig. 15 convey a sobering message: CCS has not failed technically, but it has failed in its promise to scale, to finance itself, and to deliver measurable impact at the level required. The projects celebrated as "successes" are more accurately described as subsidized pilots, enabled by ideal conditions and narrow design scopes. They provide useful lessons and valuable datasets, but they do not prove that CCS is ready for global deployment. Without breakthroughs in cost, monitoring, and regulatory architecture and without drastic reductions in reliance on public subsidies CCS remains a fragile solution to a far more systemic problem.

5.7. Conditional applicability of CCS in specific scenarios

While this review and the case studies so far have rigorously documented the failures, misuses, and systemic risks associated with CCS deployment, it is neither the intent nor the position of this work to dismiss the technology in its entirety. Rather, our central thesis is that CCS is not, and should not be, treated as a universal climate solution. The current policy and investment narrative surrounding CCS suffers from overgeneralization, treating it as a one-size-fits-all answer to emissions mitigation. This framing has enabled large-scale misallocations of capital and policy focus. However, amid this overreach, it is crucial to distinguish between strategic misapplication and targeted, justified use. There exist narrow, well-defined scenarios in which CCS may hold residual utility not because it is efficient or cost-effective, but because the absence of alternatives creates a unique constraint space. In these cases, CCS may serve as a bridge, not a cornerstone, provided that its deployment is subjected to rigorous thresholds of technical, ethical, and economic scrutiny.

5.7.1. Industrial process emissions

Certain industrial sectors emit carbon dioxide not as a by-product of combustion but as an inherent result of chemical processes. Cement production, for instance, releases CO_2 during the calcination of limestone, accounting for over 60% of total emissions from the sector. Similar process-related emissions occur in steel manufacturing (especially via blast furnaces) and the chemical and

fertilizer industries (Hunt et al., 2010). In these cases, CCS represents a potential interim solution not because it is optimal, but because the technological maturity of low-carbon alternatives remains insufficient for immediate substitution (Jenck et al., 2004). However, even in these applications, capture efficiency, cost competitiveness, and secure storage access must be met before CCS can be considered viable. Without those conditions, CCS in these sectors risks becoming a costly delay tactic rather than a climate imperative.

5.7.2. Asset stranding and brownfield retrofits

A second domain often cited in defence of CCS is the challenge of avoiding premature decommissioning of high-emission industrial assets, particularly in developing economies or regions with limited fiscal capacity (Fischer and Baron, 2015; Paletta et al., 2025). In these cases, CCS is framed as a means of preserving economic utility while mitigating emissions. However, this logic is deeply fraught (Decleir, 2019). First, it implicitly normalizes long-term fossil fuel dependence under the guise of technological decarbonization. Second, brownfield CCS retrofits are rarely cost-competitive, typically facing parasitic energy penalties of 20–30%, high capital outlays, and logistical constraints in integrating capture systems into aging infrastructure (Jones, 2024). More importantly, most retrofits are financially feasible only when tied to enhanced oil recovery (EOR), directly undermining their climate benefit (Liu and Ettehadtavakkol, 2022). Therefore, while the political economy of asset stranding may justify temporary CCS deployment in select cases, these must be treated as exceptional and time-bound interventions not climate solutions.

5.7.3. Bioenergy with CCS (BECCS) and waste-to-energy

Among the most touted applications of CCS is its pairing with bioenergy systems or municipal waste incineration, where the captured CO_2 is theoretically "biogenic" and therefore net-negative. While BECCS features prominently in IPCC and IEA decarbonization scenarios, real-world deployment remains negligible. Critical challenges include land-use competition, feedstock sustainability, transport infrastructure, and the same storage and monitoring risks described earlier. In waste-to-energy plants, while flue gas composition is more stable, capture costs remain high, and emission factors vary widely. Thus, while CCS may enhance the climate profile of such facilities, it does not redeem them as systemic climate solutions. These use-cases must be re-evaluated against a full lifecycle carbon accounting framework and should not be used to justify expansion of combustion-based waste management or bioenergy capacity (Materazzi et al., 2024; Pour et al., 2017; Silveira et al., 2023).

5.7.4. Offshore storage in known hydrocarbon basins

Offshore CCS in legacy hydrocarbon fields (e.g., Sleipner, Snøhvit) is often considered a lower-risk storage option due to decades of geological data. However, these cases benefit from unique geographic, regulatory, and political alignments, including robust CO_2 taxes, strong public funding, and integrated infrastructure. Their apparent "success" is not replicable at scale. Moreover, even in

such well-characterized formations, plume behaviour remains unpredictable, and long-term monitoring remains unresolved. While these projects may serve as experimental case studies, they should not be treated as blueprints for global deployment, especially in jurisdictions lacking stringent regulatory oversight (Ciotta et al., 2021; Li et al., 2013). The existence of narrow use-cases for CCS does not invalidate the broader concerns presented throughout this paper. On the contrary, it reinforces them. That CCS must be so heavily caveated, technically constrained, and policy-supported to function even in its best-case scenarios illustrates the depth of its limitations. These applications should be viewed as niche patches, not scalable strategies, and only deployed when no superior mitigation alternative exists.

In sum, acknowledging these constrained scenarios does not contradict the central argument of this review. Rather, it underscores the importance of precision, evidence-based deployment, and the urgent need to avoid strategic overreliance on a technology whose systemic shortcomings remain unresolved. For CCS to have any credible role in climate mitigation, it must be reframed not as a pathway forward, but as a containment strategy for specific dead-ends.

6. Alternative proposed solutions and technologies

This section explores alternative technologies and strategies for combating climate change, presenting them as more viable or scalable options compared to conventional carbon capture and storage (CCS) approaches.

6.1. Direct air capture coupled with permanent mineralization

While carbon capture at industrial flue stacks has repeatedly failed to deliver scalable or cost-effective results, Direct Air Capture (DAC) technologies offer a more promising, although still emerging, alternative, particularly when paired with permanent mineralization. Unlike conventional CCS systems that remain tied to fossil fuel infrastructure, DAC systems remove carbon dioxide directly from ambient air (Fig. 16) (Castro-Munoz et al., 2022; Custelcean, 2021). This approach offers true negative emissions potential regardless of the original emissions source. Companies such as Climeworks and Carbon Engineering have already operationalized DAC facilities that demonstrate this capability. As of 2024, Climeworks' Orca and Mammoth plants in Iceland collectively remove approximately 6000 tonnes of CO_2 per year, while Carbon Engineering's modular plant designs aim for future capacities exceeding 1 million tonnes per year. Despite this potential, DAC still faces significant technological and economic barriers. Current DAC systems require between 1.5 and 2.0 MW-hours of energy per tonne of CO_2 captured, which translates into operational costs ranging from $400 to $600 per tonne. These figures are based on publicly reported data from Climeworks and Carbon Engineering (Ozkan, 2021). To achieve a gigatonne-scale impact, global DAC capacity would need to increase by more than 100,000 times its current installed base. Achieving this goal will require substantial reductions in both energy consumption and capital costs.

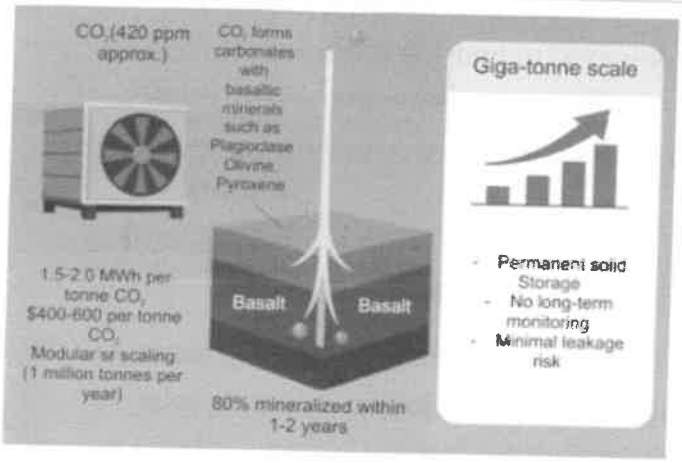

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Fig. 16. DAC coupled with in-situ mineralization.

One of the most compelling advantages of DAC lies in its potential integration with geological mineralization. This process, exemplified by the CarbFix project in Iceland, involves injecting CO_2 dissolved in water into basaltic formations (Rasool and Ahmad, 2023; Raza et al., 2022). There, it reacts with calcium, magnesium, and iron silicate minerals, forming stable carbonates. Unlike storage in depleted oil or gas reservoirs, which depends on maintaining caprock integrity for thousands of years, mineralization converts CO_2 into solid rock within one to two years. CarbFix has demonstrated that over 80 percent of injected CO_2 was permanently sequestered within two years, removing the need for long-term monitoring and sharply reducing leakage risks.

Scalability challenges for DAC with mineralization are real. They include the need for low-carbon energy sources, such as geothermal, hydropower, or renewables, to ensure cost-effective and emissions-free operation. In addition, the availability of suitable ultramafic or basaltic rock formations is geographically limited, found mainly in regions like Iceland, parts of Oman, and select volcanic zones worldwide (García del Real and Vishal, 2016). Moreover, even with these hurdles, the scientific and technical risks associated with DAC combined with mineralization are lower compared to those linked to conventional CCS. Conventional systems often suffer from chronic underperformance, high maintenance costs, and reliance on fossil-tied applications such as Enhanced Oil Recovery (EOR). In contrast, DAC offers a pathway to atmospheric carbon removal that is genuinely independent of fossil fuel infrastructure. To realize the full potential of this approach, investments should focus on several key areas. These include driving DAC costs below **$100 per tonne CO_2**, as outlined in recent Department of Energy (DOE) and International Energy Agency (IEA) roadmaps (Küng et al., 2023). Expanding access to mineralization pilot sites in suitable geological regions is another priority. Finally, integrating DAC systems with renewable energy is essential to avoid indirect emissions that could undermine the climate benefits of captured carbon (Rasool and Ahmad, 2023).

In summary, while DAC combined with mineralization is not a silver bullet, it provides a quantitatively and scientifically superior pathway compared to pouring further resources into failing CCS retrofits attached to fossil assets. Redirecting investments toward scaling these technologies could offer one of the most robust and credible routes to achieving durable negative emissions by the middle of this century.

6.2. Rapid renewable energy expansion: eliminating carbon at the source

The most effective way to reduce carbon emissions is to prevent them from being generated in the first place. Accelerating the deployment of renewable energy technologies, including solar photovoltaics, wind power, hydropower, and next-generation geothermal systems, offers a proven and scalable strategy for replacing fossil fuel-based electricity generation (Fig. 17). Unlike carbon capture technologies, which attempt to mitigate emissions after combustion, renewable energy eliminates the need to emit carbon altogether. Moreover, recent market data strongly supports this transition. The cost of utility-scale solar photovoltaic power has dropped to between $24 and $96 per megawatt-hour (MWh), while onshore wind ranges from $24 to $75 per MWh. By comparison, new natural gas plants average $39 to $101 per MWh, and coal plants range from $68 to $166 per MWh, even before adding the additional costs of carbon capture retrofits, this shows that renewables are not only environmentally superior but also economically competitive or outright cheaper in many global markets (Kabeyi and Olanrewaju, 2023; Timmons and Weil, 2022).

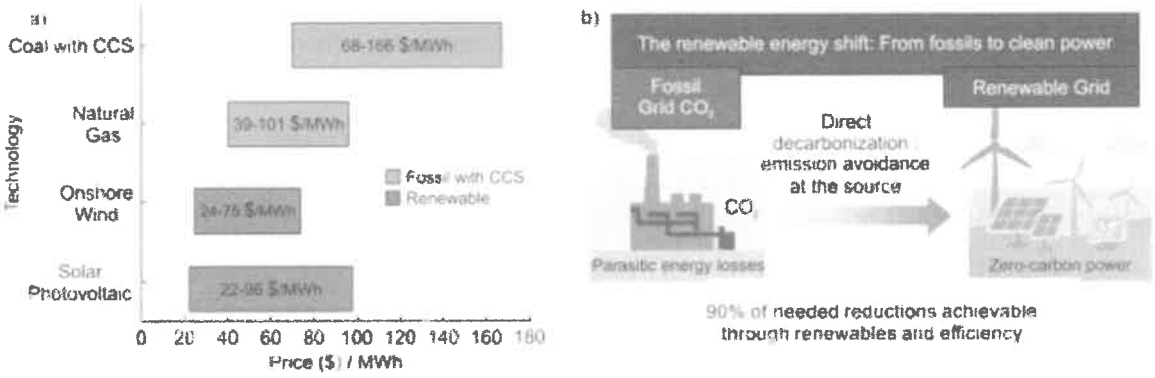

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Fig. 17. Renewable energy reliance as an alternative to CCS for combatting climate change.

Renewable technologies deliver immediate, measurable emissions reductions without the energy penalties or long-term liabilities associated with carbon capture systems. For example, carbon capture technologies typically consume 20 to 30 percent of a power plant's output to operate the capture equipment, creating what is known as a "parasitic load." Renewable energy systems avoid this entirely, providing carbon-free electricity from the point of generation. While concerns remain regarding the intermittency of wind and solar, these challenges are increasingly manageable through practical solutions. These include grid modernization and digital optimization, diversified energy portfolios combining multiple renewable sources, demand-side management, and the rapid

scaling of energy storage systems. Storage technologies such as lithium-ion batteries, flow batteries, and pumped hydro play a growing role. Global investment in energy storage is projected to exceed $620 billion by 2040, improving grid reliability and reducing the need for fossil-based peaker plants (Chatzipanagi et al., 2022).

The climate benefits of renewable deployment are immediate and reliable. The International Renewable Energy Agency (IRENA) estimates that scaling renewables and improving energy efficiency together could deliver up to 90 percent of the emissions reductions required to meet the 1.5 °C climate target by mid-century. In contrast, carbon capture and storage technologies remain costly, underperforming, and largely unproven at global scale (Simonyan and Solntsev, 2010). Every dollar invested in wind farms, solar arrays, or grid-scale batteries produces clear, near-term climate gains. These investments prevent emissions from occurring, rather than trying to manage them after they happen. With strong political momentum aligned with technological readiness, the global power sector could achieve near total decarbonization within the next **20 to 30 years**, removing the need for complex and expensive downstream carbon capture systems.

6.3. Nature-based solutions: carbon sinks with Co-benefits

Restoring and enhancing natural ecosystems remains one of the most powerful and underused strategies for large-scale carbon sequestration. Forests, wetlands, peatlands, grasslands, and mangrove systems function as living carbon sinks, pulling carbon dioxide from the atmosphere through photosynthesis and long-term biomass storage (Fig. 18). Estimates from the Intergovernmental Panel on Climate Change (IPCC) suggest that nature-based solutions could deliver up to 11.3 gigatonnes of CO_2 reductions per year by 2030 if implemented at global scale, representing nearly 30 percent of the mitigation needed to stay below the 2 °C climate target. Unlike mechanical carbon capture and storage systems, nature-based solutions offer critical ecological co-benefits. These include preserving biodiversity, improving water filtration and regulation, maintaining soil fertility, and increasing landscape resilience to climate extremes such as floods, droughts, and heatwaves. For example, mangrove forests not only sequester up to 10 times more carbon per hectare than terrestrial forests but also provide coastal protection for over 300 million people living in low-lying regions (Song et al., 2023a).

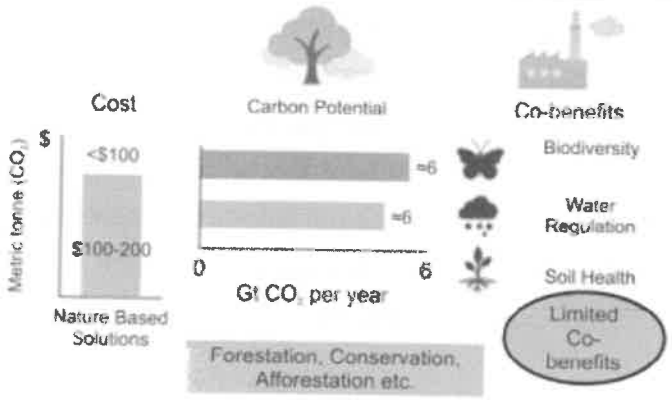

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Fig. 18. Nature based solution as a CCS alternative.

Reforestation and afforestation projects, when designed with ecological integrity, can offer some of the lowest-cost mitigation options, typically ranging between $10 and $50 per tonne of CO_2 sequestered (Busch et al., 2019; Nave et al., 2019). However, responsible design is essential to avoid pitfalls such as planting monocultures, displacing local communities, or undermining indigenous land rights. Similarly, protecting old-growth forests and restoring degraded peatlands can prevent massive carbon releases, given that peatlands store approximately 550 gigatonnes of carbon globally, equivalent to twice the carbon held in all the world's forests. It is important to recognize that nature-based solutions are not without risks. Climate-driven disturbances such as wildfires, pest outbreaks, and prolonged drought can compromise their long-term stability and carbon permanence (McDowell et al., 2018). Therefore, these strategies must be supported by robust monitoring, transparent reporting, and independent verification to prevent greenwashing and ensure that they deliver real, durable climate benefits.

Properly governed, nature-based solutions provide a high-value, low-regret climate pathway. They offer not only carbon sequestration but also multiple ecological, social, and economic benefits. Compared to mechanical CCS, nature-based approaches stand out for their scalability, cost-effectiveness, and alignment with ethical and conservation goals, making them an essential pillar in any comprehensive climate strategy (Heinrich et al., 2021; Huang et al., 2020; Nzabarinda et al., 2025).

6.4. Energy demand reduction: the neglected pathway

The cleanest and most climate-friendly unit of energy is the one that is never consumed. Despite this, energy efficiency and demand reduction strategies continue to be underused in global climate policy, often overshadowed by more high-profile technological solutions. Reducing energy demand through building retrofits, industrial process improvements, urban design innovations, and behavioral changes can deliver major emissions reductions at a fraction of the cost of supply-side interventions (Fig. 19). Moreover, according to the International Energy Agency (IEA, 2021c), energy efficiency improvements could contribute more than 40 percent of the total emissions reductions required to meet global net zero targets by 2050. In practical terms, this translates into approximately 6–7 gigatonnes of CO_2 per year by mid-century. For example, passive building design alone can reduce heating and cooling energy demand by up to 80 percent compared to conventional buildings. Similarly, electric vehicle adoption reduces energy consumption per kilometer traveled by about 60 percent compared to gasoline vehicles, while smart grid technologies can reduce overall electricity demand by 10–15 percent through better load management (Li et al., 2019).

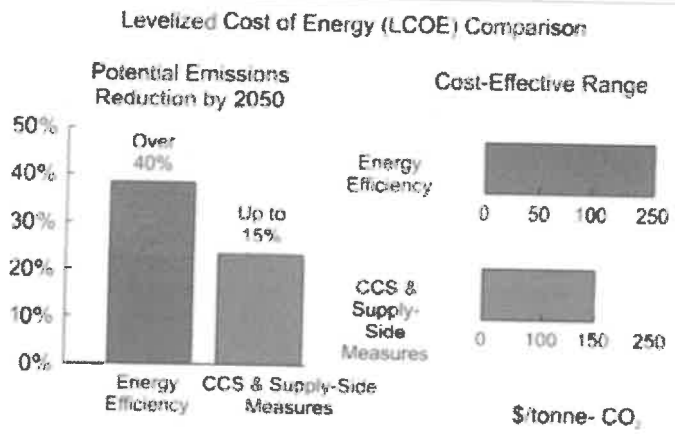

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Fig. 19. Reduction in energy demand as a CCS alternative.

Demand-side measures have also proven effective at decoupling economic growth from emissions. Countries such as Denmark, Japan, and Germany have shown that energy use can be stabilized or even reduced while maintaining or increasing GDP, largely through aggressive efficiency standards and public investment in low-energy infrastructure (Sovacool, 2013). Despite these successes, many governments continue to underinvest in efficiency measures, often channeling larger funding streams toward politically safer but less cost-effective options like carbon capture and storage (CCS) or marginal renewable energy expansions. Beyond emissions reductions, demand-side strategies offer significant resilience advantages. Societies that consume less energy are less vulnerable to fossil fuel price shocks, more insulated from infrastructure failures, and better able to maintain essential services during climate-driven disruptions. Efficiency measures also tend to deliver immediate and reliable carbon reductions, whereas CCS projects typically require large upfront capital investments and offer uncertain or delayed benefits.

In summary, prioritizing energy demand reduction represents one of the most cost-effective and reliable pathways for achieving climate goals. Scaling up investments in efficiency and behavioral change not only cuts emissions but also strengthens economic and social resilience, providing a robust foundation for a sustainable energy future (Cullen et al., 2011; Royston et al., 2018; Sorrell, 2014).

6.5. Enhanced weathering: unlocking Earth's natural thermostat

Enhanced weathering is an emerging but highly promising negative emissions technology that accelerates natural rock weathering processes to remove atmospheric carbon dioxide. By spreading finely ground silicate or basaltic rocks over agricultural lands or coastal regions, it is possible to significantly increase the rate at which CO_2 reacts with minerals, ultimately locking the carbon into stable carbonate forms (Fig. 20). Moreover, according to recent field trials in Europe and Australia, enhanced weathering has the potential to sequester between 2 and 4 gigatonnes of CO_2 per year at

the global scale. This capacity could account for nearly 5 to 10 percent of the total annual emissions reductions needed by mid-century to limit warming to below 2 °C, based on IPCC carbon budget estimates. In addition to its climate benefits, enhanced weathering can improve soil pH, increase nutrient availability, and potentially boost crop yields, providing important agricultural co-benefits (Taylor et al., 2016).

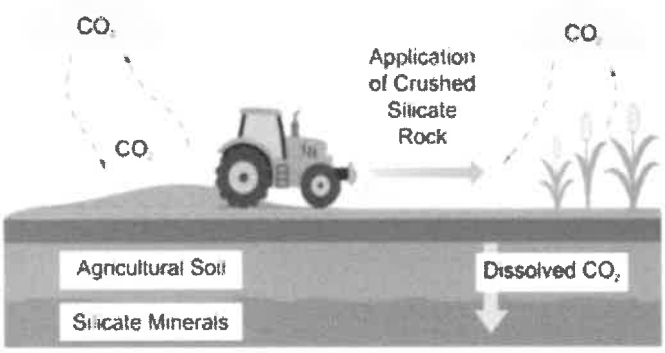

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Fig. 20. Enhanced weathering as a conventional CCS alternative.

One key advantage of enhanced weathering over conventional carbon capture and storage is the permanence of the captured carbon. Rather than injecting compressed CO_2 into underground reservoirs, where long-term leakage and monitoring remain persistent risks, enhanced weathering converts CO_2 into chemically stable mineral forms that are effectively immune to re-release. However, despite its promise, enhanced weathering still faces technical and logistical challenges. Chief among these are the energy demands associated with mining, grinding, and transporting copious quantities of rock. Estimates suggest that grinding rock to optimal particle sizes consumes between 50 and 150 kW-hours per ton of CO_2 sequestered, depending on the material type and grain size. However, coupling these operations with renewable energy sources can significantly reduce indirect emissions, ensuring that the process delivers net climate benefits (Strefler et al., 2018).

Deployment logistics also require careful planning. Global modeling studies indicate that enhanced weathering would need to apply between 1 and 5 gigatonnes of crushed rock per year to meet sequestration targets. This scale is substantial but feasible, particularly if aligned with existing agricultural and land management systems. Unlike CCS, which relies on complex, high-risk underground storage systems, enhanced weathering leverages Earth's natural carbon cycle mechanisms. This approach offers a safer, more permanent, and nature-integrated solution for removing atmospheric CO_2, positioning it as a promising component of a diversified global climate strategy (Andrews and Taylor, 2019; Kantola et al., 2017; Schuiling and Krijgsman, 2006).

6.6. Gold hydrogen production

Gold hydrogen, also known as naturally occurring subsurface hydrogen, represents an exciting and largely untapped frontier in clean energy sourcing. Unlike green hydrogen, which is produced using renewable-powered water electrolysis, or blue hydrogen, which is derived from natural gas combined with carbon capture and storage (CCS), gold hydrogen comes directly from geological formations where natural chemical reactions generate hydrogen (Fig. 21). These reactions, including serpentinization (the interaction between water and iron-rich rocks), can produce hydrogen in significant quantities beneath the Earth's surface. Early-stage exploration projects in regions such as Mali, France, and parts of the United States have identified natural hydrogen accumulations with concentrations as high as 98 percent purity, according to field surveys. Global estimates suggest that accessible subsurface hydrogen resources could total up to 150 million tonnes, potentially providing a meaningful new low-carbon energy source (Coveney et al., 1987).

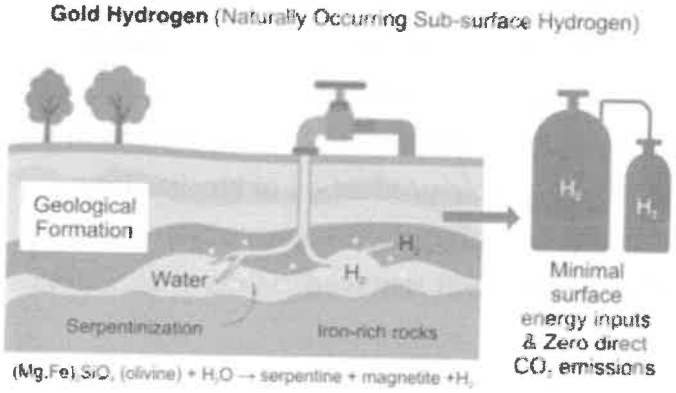

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Fig. 21. Gold hydrogen as a viable CCS alternative for combatting climate change.

One of the key advantages of gold hydrogen lies in its inherently low carbon footprint. Unlike conventional hydrogen production, which typically requires 40 to 60 kW-hours of electricity per kilogram of hydrogen (for electrolysis) or emits 8–12 kg of CO_2 per kilogram of hydrogen (for steam methane reforming), gold hydrogen requires minimal surface energy inputs and releases no direct CO_2 during extraction. Provided operations are carefully managed to prevent methane leakage and other unintended emissions, the extraction process offers a near-zero carbon alternative (Patonia et al., 2024).

Commercial-scale development remains in the initial stages, and key technical challenges include reservoir identification, safe extraction methods, and effective environmental monitoring. However, the potential of scalability is significant. Even modest exploitation of natural hydrogen reserves could help meet the projected global hydrogen demand of 500–700 million tonnes per year by 2050, as estimated by the International Energy Agency (IEA). To fully realize this potential, research and investment should shift away from carbon capture schemes attached to fossil-based hydrogen (blue hydrogen) and instead focus on developing technologies and regulatory frameworks that can safely and efficiently harness gold hydrogen resources. This approach offers a fundamentally

cleaner pathway, bypassing the energy penalties and carbon liabilities associated with fossil-derived hydrogen.

With appropriate exploration, governance, and scaling strategies, gold hydrogen has the potential to become a transformative component of the global energy transition, contributing to a secure, low-carbon energy future (Aftab et al., 2022; Du et al., 2024; Yedinak, 2022).

6.7. Biochar production for soil carbon sequestration

Biochar, a stable and carbon-rich material produced by pyrolyzing biomass under low-oxygen conditions, offers a scientifically supported and scalable pathway for permanent carbon sequestration. Once applied to soils, biochar can lock away carbon for hundreds to thousands of years, with studies estimating mean residence times ranging from 500 to over 1000 years depending on the feedstock and soil conditions (Fig. 22). In addition to carbon storage, biochar improves soil fertility, enhances water retention by up to 15 percent, and boosts microbial activity, creating multiple co-benefits for agricultural systems. Field trials and commercial operations in the United States, Europe, and Australia have demonstrated sustainable production of biochar from agricultural residues, forestry waste, and organic by-products, with carbon sequestration costs typically ranging between $30 and $120 per tonne of CO_2 equivalent removed (Salma et al., 2024; Woolf et al., 2010).

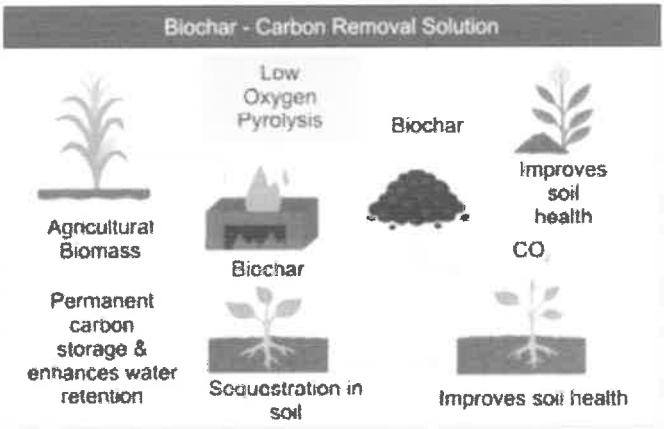

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Fig. 22. Biochar for carbon removal as a CCS alternative.

Unlike mechanical carbon capture and storage technologies, which require continuous energy input, active maintenance, and long-term monitoring, biochar sequesters carbon passively once it is incorporated into soil. It avoids many of the environmental and social challenges linked to industrial-scale CCS by embedding carbon management directly into agricultural landscapes, where it also enhances ecosystem resilience and improves food system sustainability. With an expanding body of peer-reviewed research confirming its efficacy and co-benefits, biochar presents a cost-effective and nature-integrated climate mitigation strategy. If deployed globally, biochar has the

potential to sequester between 0.5 and 2 gigatonnes of CO_2 equivalent per year, positioning it as a meaningful component of a diversified carbon removal portfolio (Lehmann et al., 2021).

6.8. Massive electrification of end-use sectors

Decarbonization is not solely a matter of capturing carbon emissions after they are produced; it requires the fundamental redesign of energy systems to eliminate combustion emissions at the source. The widespread electrification of transportation, heating, and industrial processes presents one of the most immediate and scalable strategies for achieving deep emission reductions. According to the International Energy Agency (IEA), electrification could contribute up to 45 percent of the cumulative CO_2 reductions needed by 2050 to meet global net-zero targets. Moreover, electric vehicles already deliver lifecycle emissions reductions of 50–70 percent compared to internal combustion engine vehicles when powered by a moderately decarbonized grid. Heat pumps provide two to four times greater energy efficiency than conventional fossil-fuel-based heating systems, offering significant emissions and cost savings. In the industrial sector, electric arc furnaces can reduce the carbon intensity of steel production by 80 percent relative to traditional blast furnace routes, provided they are powered by low-carbon electricity.

Unlike carbon capture and storage (CCS), which requires continuous energy input, monitoring, and long-term liability management, electrification strategies deliver immediate and direct emission cuts. Furthermore, electrification integrates synergistically with renewable energy expansion, allowing decarbonization efforts to progress simultaneously on both the supply and demand sides of the energy system. To fully realize this potential, policy frameworks must prioritize investments in grid modernization, large-scale storage solutions, and financial incentives that accelerate the deployment of electric technologies. Continuing to direct public resources toward capturing emissions from aging fossil infrastructure risks diverting attention and funding away from more durable, system-level solutions (Dennis et al., 2016; Sugiyama, 2012; Tsao et al., 2018).

6.9. Comparative risk and feasibility assessment of emerging climate mitigation technologies

While CCS faces criticism for its cost, permanence concerns, and limited scalability, it is important to subject alternative mitigation technologies to the same level of critical scrutiny. Overly optimistic portrayals of emerging solutions risk underestimating technical, economic, and environmental constraints. A systematic comparison of these technologies such as DAC, renewable energy expansion, enhanced weathering, gold hydrogen, and biochar reveals significant feasibility and deployment challenges. Furthermore, each of these technologies carries important caveats that must be considered before large-scale adoption (Küng et al., 2023; Schuiling and Krijgsman, 2006; Stalker et al., 2022).

DAC although technologically compelling, remains economically prohibitive at current costs exceeding USD 500/ton CO_2 for many configurations. The energy demand for large-scale DAC may

create a feedback loop that counteracts emissions reductions unless paired with low-carbon electricity.

Renewable energy, while central to a low-carbon future, faces risks of grid instability due to intermittency, and accelerated transitions may lead to premature asset stranding, particularly in developing economies with aging infrastructure.

Enhanced weathering involves large-scale mineral mining, grinding, and land application, which introduces high energy costs, logistical challenges, and environmental uncertainties such as heavy metal runoff and soil chemistry disruption.

Gold hydrogen, an emerging interest in natural subsurface hydrogen reservoirs, is limited by unclear reserve volumes, lack of detection and extraction infrastructure, and uneven global distribution making it a high-risk early-stage technology.

Biochar offers carbon sequestration through soil amendment, yet its adsorption capacity has a practical upper limit, and questions remain about its permanence, land-use implications, and energy intensity of pyrolysis at industrial scale.

To support a balanced view, we present a structured, data-backed comparative table that evaluates each mitigation pathway across four critical dimensions: (1) Technological Maturity, (2) Economic Feasibility, (3) Policy and Regulatory Support, and (4) Key Risks and Implementation Constraints. Each assessment includes deployment, cost ranges, and high-impact limitations relevant to large-scale adoption as shown in Table 4.

Table 4. Deployment and feasibility comparison of alternative technologies (Abdalqadir et al., 2023; Caballero et al., 2023; Knittel and Oh, 2025; Zolfaghari et al., 2022).

Technology	Tech. Maturity (TRL & Deployment) (Approx. values)	Economic Feasibility (Approx. ranges)	Policy & Regulatory Support	Key Risks & Critical Constraints
CCS (Retrofit)		\$60–120/ton CO_2 for power plant retrofit (lower in industrial sectors); Capex heavy	Strong in US, UK, China (IRA in US); limited in Global South	CO_2 leakage liability; site-specific geology; high energy penalty; public resistance; pipeline infrastructure bottlenecks

Technology	Tech. Maturity (TRL & Deployment) (Approx. values)	Economic Feasibility (Approx. ranges)	Policy & Regulatory Support	Key Risks & Critical Constraints
Direct Air Capture (DAC)	TRL 4–6; <20 plants operating globally; captures ~10,000 tCO_2/year per facility	\$500–1000/ton CO_2 (Climeworks, 2023); 7–10 GJ energy per ton captured	Early-stage support (US DAC Hubs); minimal deployment incentives globally	Net positive emissions unless powered by renewables; land/water footprint; scale-up pace too slow for 2050 targets
Renewable Energy Expansion	TRL 9; ~30% global electricity (IEA, 2021b); Solar/Wind LCOE: \$30–50/MWh	Competitive cost; grid parity or cheaper than fossil fuels in most regions	High global support; central to NDCs and net-zero strategies	Grid reliability; storage integration; raw material demand (lithium, rare earths); risk of fossil asset stranding; NIMBYism in large projects
Enhanced Weathering	TRL 5–6; pilot scale (<1 $MtCO_2$/year globally)	\$200–600/ton CO_2 (including mining, grinding, transport); high uncertainty	Virtually no regulatory framework; limited R&D funding	Energy-intensive mineral preparation; limited reactive surface area in natural settings; soil metal leaching; land use scalability; social license
Gold Hydrogen (Natural H_2)	TRL 2–4; <10 pilot sites globally; no commercial production yet	Unknown; exploratory stage with no cost benchmarking. Very limited pilot scale projects.	No enabling regulation or exploration incentives	Geological uncertainty in reserves; hydrogen migration/loss in subsurface; unproven detection & extraction methods; may not be scalable globally
Biochar Carbon Removal	TRL 6–7; ~0.04 $GtCO_2$/year sequestration potential (vs. 10 Gt needed by 2050)	\$100–300/ton CO_2 (region- and feedstock-dependent); co-benefits for soil fertility	Moderate support in EU, US (carbon farming, voluntary credits)	Limited sorption capacity (~0.3–0.5 tCO_2/ton biochar); permanence not guaranteed; risk of biomass competition with food/agriculture; variable efficacy in different soils

7. Predictive framework: matching CCS alternative technologies to emission sources

7.1. Introduction to the framework

To guide the strategic deployment of carbon capture technologies across diverse industrial and environmental contexts, this section proposes a predictive framework designed to systematically match advanced and innovative capture systems to specific CO_2 emission sources. Given the wide variation in industrial processes, energy conditions, and geographic settings, no single carbon capture approach can serve as a universal solution. This framework offers a structured method for aligning the performance characteristics of each technology with the operational, chemical, and economic realities of particular emission sources, ensuring that carbon capture investments deliver the greatest possible climate impact with technical feasibility and cost-effectiveness.

7.2. Characterization of the emission source

The predictive process begins with a careful characterization of the CO_2 source. Key factors include the CO_2 concentration of the gas stream, which can range from 10 to 15 percent in coal plant flue gas, 15 to 25 percent in cement kilns, and up to 30 to 60 percent in natural gas processing, compared to just 0.04 percent in ambient air. It also considers the scale of emissions, from distributed kilotonne-scale sources to major industrial hubs emitting megatonnes annually, as well as the temperature and pressure conditions of the process. For example, high-temperature, high-pressure streams may favour membrane or cryogenic separation technologies, while ambient-pressure systems may be better suited to solvent or solid sorbent capture. In addition, the level of impurities such as sulphur oxides, nitrogen oxides, particulates, or water vapor must be considered, as these can significantly affect material performance. The geographic and infrastructure context is equally important, including proximity to storage reservoirs or utilization pathways, access to low-carbon energy, and the existing industrial layout.

7.3. Technology matching criteria

To predict which technology best fits a particular source, the framework evaluates several performance dimensions for each capture system. These include capture efficiency, expressed as the percentage of CO_2 removed per unit of gas processed; energy requirement, typically measured in megajoules or kilowatt-hours per tonne of CO_2 captured; and both capital and operational costs, often quantified as dollars per tonne of CO_2 removed. It also considers scalability and modularity, evaluating whether a technology is suitable for small distributed systems or requires large-scale installations. Another critical factor is the permanence of the storage or utilization pathway, as well as the technology readiness level (TRL), which indicates the maturity of the system (See Section S1 in Supporting Information).

7.4. Predictive decision matrix

Using this information, a predictive decision matrix can be constructed to match technologies to sector-specific applications. For instance, membrane systems are predicted to perform best in high-concentration, high-pressure streams such as natural gas processing, where their selectivity and

pressure-driven operation offer advantages. Direct air capture systems are predicted to be the most suitable for diffuse, low-concentration sources like aviation or historical atmospheric CO_2, where point-source capture is not possible. Cryogenic separation technologies are matched to processes with already cold or high-purity CO_2 streams, such as industrial gas separation, while enhanced weathering approaches are best aligned with agricultural or land-based sectors where crushed silicate rock can interact directly with CO_2 at the surface.

To operationalize the framework, a predictive decision matrix is constructed to evaluate carbon capture technologies across key performance parameters. These include capture efficiency, energy requirements, cost per tonne of CO_2 captured, scalability, and permanence of storage (Please see Table S1 in supplementary information).

To enhance the interpretability of these results, a heatmap-based scoring system was developed as a visual extension of the predictive decision matrix (Fig. 23). This heatmap summarizes the predicted strength of alignment between advanced carbon capture technologies and key emission sectors using a simplified scoring scale. Each cell in the heatmap presents a match score from 1 to 4, derived from the matrix criteria, where 1 indicates a very weak match and 4 indicates a strong or optimal match. The scoring system was developed based on published techno-economic assessments, peer-reviewed case studies, and international energy reports, including analyses by the International Energy Agency (IEA), the Intergovernmental Panel on Climate Change (IPCC), and leading academic reviews. Together, these sources provide quantitative benchmarks on capture efficiency, energy demand, cost ranges, scalability, and permanence, ensuring that the framework reflects current scientific understanding and consensus (International Energy Agency, 2021c; Ozkan, 2024; Pathak et al., 2022; National Academies of Sciences, Engineering, and Medicine, 2019; Zhuo-Ni et al., 2022). The x-axis represents different CO_2-emitting sectors such as natural gas processing, coal-fired power plants, cement kilns, aviation, and agriculture, while the y-axis lists of conventional carbon capture and alternative mitigation technologies. This includes conventional capture technologies (DAC, membrane systems and solvent-based) and nature-based removal, gold hydrogen and enhanced weathering as an alternative to CCS.

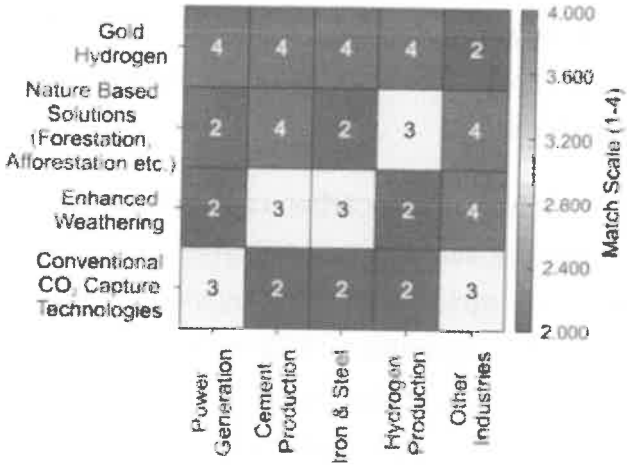

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Fig. 23. Heatmap of alignment scores (1–4) between sectoral CO_2 sources and mitigation options, spanning capture and capture-avoidance/removal pathways (higher = stronger fit). "Other Industries" groups heterogeneous emitters (e.g., chemicals, aluminium/glass, textiles, food & beverage). Gold (natural) hydrogen is treated as a capture-avoidance option: a score of 4 denotes near-full fuel substitution that prevents CO_2 formation at the source; NbS and enhanced weathering represent system-level removals that complement, not replace, point-source capture.

To improve clarity, the category "Other Industries" on the horizontal axis of the heatmap refers to industrial sectors not covered by more specific labels like power generation, cement, or oil and gas. This includes emission sources such as chemical manufacturing (e.g., ammonia or methanol production), aluminium and glass production, textile processing, and food and beverage industries. These sectors vary in CO_2 intensity, scale, and concentration, and therefore exhibit a wide range of suitability across different capture technologies. Their grouping under a single category reflects the need to evaluate smaller or more heterogeneous emitters in the industrial landscape while maintaining a practical structure in the heatmap.

Nature-Based Solutions (NbS) refer to land-use and ecosystem-based approaches that sequester carbon naturally. These include afforestation, reforestation, wetland restoration, soil carbon enhancement, and agroforestry. Though not engineered capture systems, their long-term carbon storage potential and additional biodiversity and ecosystem benefits make them essential components of a comprehensive decarbonization strategy. Their inclusion in the heatmap reflects the need to consider both removal and avoidance pathways. Additionally, the heatmap reveals that technologies are not universally applicable; instead, their effectiveness varies widely depending on the emission context. For instance, membrane systems score highly (score 4) in natural gas processing, where CO_2 is released in high-pressure, high-concentration streams conditions under which membranes operate most efficiently. Their score is reduced (score 1–2) in sectors such as cement or coal-fired power generation due to limitations in handling low-pressure, low-concentration emissions. Similarly, solvent-based CCS systems receive high scores (score 4) for coal and gas power plants and cement kilns, where they are already commercially deployed and exhibit high capture efficiency. However, they score lower (1–2) in sectors like aviation or agriculture due to poor suitability for small-scale or distributed emission sources.

Importantly, the heatmap also includes technologies that are not strictly carbon capture systems but offer significant decarbonization potential through emission avoidance or negative emissions. While Gold Hydrogen is not a carbon capture technology in the strict sense, its relevance to this framework lies in its function as a capture-avoidance pathway. Conventional CCS targets CO_2 after it has already been released, whereas Gold Hydrogen prevents CO_2 formation at the source by substituting fossil fuels in high-emission sectors. This distinction is important because, in several industries such as power generation, steelmaking, and hydrogen production, the option to replace carbon-intensive feedstocks with naturally occurring hydrogen can directly eliminate the need for

post-combustion capture infrastructure. Including Gold Hydrogen in the comparison therefore widens the framework beyond "end-of-pipe" abatement to encompass preventive solutions that can deliver equivalent or greater climate benefits.

The high alignment scores assigned to Gold Hydrogen across most sectors reflect this preventive potential. In power generation, it could displace coal or natural gas in turbines; in steel, it underpins hydrogen-based direct reduction; and in hydrogen production itself, it eliminates the dependence on grey or blue H_2 derived from hydrocarbons. For cement, Gold Hydrogen can substantially reduce fuel-related emissions from kilns, although process CO_2 from calcination would still require complementary CCS. In contrast, "Other Industries" receive lower scores since many rely on carbon feedstocks where hydrogen substitution is limited. By positioning Gold Hydrogen as a capture-avoidance complement rather than a direct substitute for CCS, the framework highlights that emission reduction strategies must consider both post-emission abatement and upstream prevention (see supplement section S1).

7.4.1. Sensitivity and uncertainty analysis

To ensure robust predictions, the framework includes sensitivity and uncertainty analyses. This is critical because key parameters such as the cost of renewable energy, the energy demand of capture systems, or the market price of CO_2 can shift over time, altering the relative performance and cost-competitiveness of various technologies. For example, increasing the share of renewable energy on the grid reduces the energy penalty disadvantage of direct air capture, while rising carbon prices make lower-cost technologies more attractive even if their capture efficiencies are slightly lower.

To test the framework's robustness under such variations, we conducted a formal sensitivity analysis by adjusting key input parameters by ±20 percent across capture efficiency, energy requirement, and cost metrics. The results, summarized in Fig. 24, shows that while absolute match scores fluctuated modestly under these shifts, the relative rankings of best-fit technologies by sector remained stable. For example, direct air capture maintained its relative sectoral position across all scenarios, reinforcing the predictive reliability of the framework even under conditions of input uncertainty. Additional detailed sensitivity analysis results, including all technologies and numeric tables, are provided in the supporting information (see section 2.1 in supporting information).

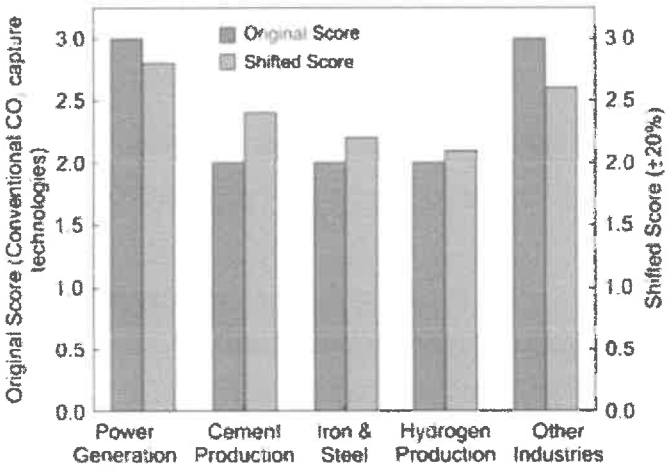

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Fig. 24. Sensitivity analysis of conventional CO_2 capture technologies (as an example) match scores across sectors under ±20% parameter shifts. Bars show original predictive scores (teal) and shifted scores (orange), demonstrating that while absolute values fluctuate slightly, relative rankings remain stable, indicating the framework's robustness.

7.4.2. Policy and investment implications

Ultimately, this predictive framework provides policymakers, investors, and industrial stakeholders with a powerful tool to align technology deployment with the specific decarbonization needs of each sector. Rather than applying blanket funding or speculative investments, decision-makers can direct resources toward applications with the highest technical fit, scalability, and climate benefit. By integrating technology capabilities with real-world source characteristics, this approach helps accelerate the transition toward net-zero emissions in a targeted, cost-effective, and scientifically grounded manner.

8. Conclusions

The evidence reviewed in this paper reveals a consistent and troubling pattern: Carbon Capture and Storage (CCS), despite decades of promotion and investment, remains technologically constrained, economically inefficient, and strategically misapplied. Projects often labelled as "successful" do not meet the rigorous standards required for durable climate mitigation when examined against metrics such as capture efficiency, long-term storage integrity, scalability, and cost-effectiveness. Meanwhile, many headline projects: Petra Nova, In Salah, Gorgon, have either underperformed or failed entirely due to unresolved engineering barriers and systemic oversights in planning and regulation. These outcomes suggest that CCS is not just lagging behind expectations but may be fundamentally ill-suited to serve as a cornerstone of climate policy under current timelines and global carbon budgets.

This review reinforces that mitigation strategies must prioritize solutions that are already scalable, economically viable, and socially accountable. By introducing a predictive technology-emission matching framework, this paper provides a diagnostic tool to guide where, if at all, carbon capture may have niche applicability. However, the broader conclusion is clear: continued reliance on CCS risks diverting political will and financial resources away from more effective interventions such as renewable electrification, mineralization, and ecological restoration. If climate action is to be credible and timely, CCS must be critically reevaluated not as a default pathway, but as a limited tool with sharply defined boundaries and diminishing justification for large-scale deployment. Nevertheless, it is imperative to point out that the next five years (2026–2030) are the hinge of fate for CCS either a theory that lingers, or a scale that rises.

Authors' contribution

Muhammad Hammad Rasool: Conceptualization, writing-original draft, visualization. investigation; *Syed Abdul Moiz Hashmi*: Writing-original draft, methodology, visualization and validation.

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.

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Appendix A. Supplementary data

The following is the Supplementary data to this article:

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Multimedia component 1.

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RELX™

CCS In Indiana

CAC Campaigns

Carbon Capture and Sequestration (CCS) is exploding across Indiana and the Midwest under the guise of reducing carbon dioxide (CO_2) emissions to mitigate climate change.

(https://www.bloomberg.com/news/features/2023-08-16/biden-climate-plan-for-carbon-capture-tech-faces-local-protests?accessToken=eyJhbGciOiJIUzI1NiIsInR5cCI6IkpXVCJ9.eyJzb3VyY2UiOiJTdWJzY3JpYmVyR2ImdGVkQXJ0aWNsZSIsImlhdCI6I8zdBUJxWeeaRbyBCiz3xogIGJdhuWlCOtNv2N6w4&leadSource=uverify%20wall)**However, the reality is that CCS:**

- is a **false climate solution** (https://biologicaldiversity.org/campaigns/carbon-capture-and-storage/pdfs/CCS-explainer.pdf).
- is **way too expensive** (https://ieefa.org/articles/carbon-capture-and-storage-power-sector-will-worsen-energy-inflation).
- will actually **increase emissions** (https://www.foodandwaterwatch.org/2021/07/20/top-5-reasons-carbon-capture-and-storage-ccs-is-bogus/).

CAMPAIGN TOOLS

The Rush for Hydrogen and CCS in Indiana

Check out our webinar discussion of the risks of hydrogen and carbon capture & storage (CCS), what's happening in Indiana, and what you can do to take action in your community!

Risky Business: The Need for 3D Seismic Imaging at the Wabash Valley CCS Project

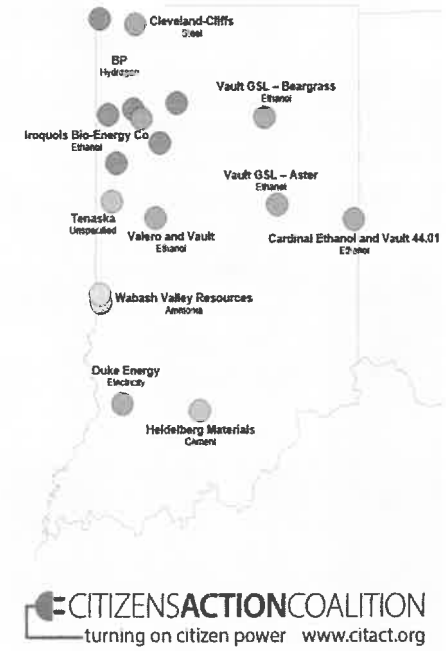
Check out our webinar discussion in which **3D Seismic Solutions (https://3dseismicsolutions.com/)** offers a critical analysis of the geological and seismic risks of the Wabash Valley Resources proposed CCS project.

disaster.

CCS poses **huge risks to our health, our environment, and our safety.** It will **further enrich the fossil fuel industry** and Wall Street investors while **diverting resources away from real, cost-effective solutions like energy efficiency and renewable energy**.

Proposed CCS projects in Indiana:

At least 9 CCS projects are being developed in Indiana in these industries: hydrogen, steel, ethanol, ammonia, cement, diesel, and electricity. They are:



- **Wabash Valley Resources (https://www.citact.org/wvr)** in Vigo and Vermillion Counties
- **BP Project Crossroads** (https://www.energy.gov/fecm/project-selections-foa-2711-carbon-storage-validation-and-testing-round-2) in Lake, White, Jasper, Newton, Pulaski, and Benton Counties
- **Tenaska Hickory CCS Hub** (https://www.tenaska.com/our-business/development/carbon-capture-and-sequestration/) in Warren County
- **Cardinal Ethanol and Vault 44.01 One Carbon Partnership** (https://www.businesswire.com/news/home/20230130005121/en/Cardinal-Ethanol-and-Vault-44.01-Form-Joint-Venture-to-Implement-a-Carbon-Capture-and-Sequestration-Project-in-Indiana) in Randolph County

We are paying for CCS with our tax dollars!

Companies are motivated to profit from carbon pollution because we're paying huges subsidies to them through our federal tax dollars.

The robust interest in CCS has been motivated by the **enormous federal CCS tax credit, called IRA Section 45Q** (https://www.elliottdavis.com/tax-credit-for-carbon-oxide-sequestration-ira-section-45q/#:~:text=In%20general%2C%20Section%2045Q%20is,power%20plants%20c This tax credit was initially **put in place** as part of the Energy Improvement and Extension Act of **2008, under the watch of President Bush**. Both the **Trump and Biden administrations significantly expanded** the use of the tax credit, first under the Bipartisan Budget Act of 2018, then under the Inflation Reduction Act (IRA) of 2022.

The Section 45Q tax credit now **gives polluters $85 per ton of CO2** sequestered for up to 12 years. The IRA allows owners of these tax credits to get **cash** for them **by direct pay for 5 years**, or to sell them to

Plant in Montgomery County

- **Heidelberg Materials** (https://www.heidelbergmaterials.com/en/carbon-capture-and-storage-ccs) in Lawrence County
- **Duke Energy Indiana's Edwardsport IGCC** (https://www.duke-energy.com/our-company/about-us/power-plants/edwardsport) coal gasification power plant in Knox County
- Cleveland-Cliffs in Lake and Porter Counties
- Iroquois Bio-Energy Company in Rensselaer County
- POET and Vault at Vault GSL - Aster in Madison County
- POET and Vault at Vault GSL – Beargrass in Wabash County

Scale of known carbon sequestration projects under consideration thus far:

- BP: 23 million tons per year
- Duke Energy Indiana: 3.6 million tons per year
- Cleveland-Cliffs: 2.8 million tons per year
- Heidelberg Materials: 2 million tons per year
- Wabash Valley Resources: 1.67 million tons per year
- One Carbon Partnership: 450,000 tons per year

A **Class VI permit from the U.S. EPA** (https://www.citact.org/ccs-indiana#epa-class-vi) is required to permanently sequester CO2 underground, which takes an **approval period of about two years**.

- Wabash Valley Resources has obtained a permit. (The U.S. EPA issued a Draft Class VI injection permit in 2023, and they issued the final permit in January 2024, although that permit is under appeal before the Environmental Appeals Board.)
- Two ethanol CCS projects (One Carbon Partnership and Valero and Vault-Linden) have submitted Class VI permit applications
- No other CCS projects in Indiana have submitted EPA Class VI permit applications as of December 22, 2023.

For BP, CCS is directly tied to their "Hydrogen Hub" (https://www.energy.gov/oced/regional-clean-hydrogen-hubs-0) plans, which are being highly subsidized by our federal tax dollars. BP is leading the **MachH2 Hydrogen Hub**

credits" for all 12 years. For the **Wabash Valley Resources proposed CCS project in West Terre Haute** (https://www.citact.org/wvr), the math adds up to **$142 million per year and over $1.7 billion from taxpayers** for the first 12 years of the project.

EPA Class VI Permits

In 2010, the EPA created Class VI permits for injection wells used to dump CO2 deep underground. (https://www.epa.gov/uic/table-epas-draft-and-final-class-vi-well-permits) Since that time, there have been **only 6 Class VI permits issued by the EPA, with 4 of them being voided** since those proposed CCS operations were **cancelled prior to construction.** Currently, **only 1 Class VI permit is active in the United States.**

Proponents of CCS like to point to the fact that there have been 145,000 permits issued for either active or idled CO2 injection operations. However, **those permits were Class II permits**

network and storage wells across six Northwest Indiana counties (**listed above (https://www.citact.org/ccs-indiana#BP-ccs-counties)**), and potentially extending into Illinois and Michigan, to **store the CO2 made in the process of making hydrogen**. They could **also transport and store CO2 from other heavy industries** in Northwest Indiana, such as steel.

To understand the impact of the 45Q federal tax credit (https://www.citact.org/ccs-indiana#45Q), consider BP's planned CCS project in Northwest Indiana:

- 23 million tons per year CO2 sequestered
- 12 years of operation
- $85 per ton tax credit
- **= $23.46 billion in federal government tax credits**

Duke Energy and Heidelberg Materials have been awarded money from the U.S. DOE for Front-End Engineering Design (FEED) studies to evaluate the technical and economic feasibility of CCS at their facilities.

- Duke plans to evaluate the feasibility of capturing and storing CO2 from flue gases at the Edwardsport power plant in Knox County, Indiana.
- Heidelberg plans to evaluate the cost and performance of retrofitting a cement plant with carbon capture technology.

More than 25% of the nation's primary steel is made in Northwest Indiana at three large integrated steel mills. Cleveland-Cliffs owns two of these facilities, and is the largest flat-rolled steel producer in North America.

- Indiana Harbor facility: located near the BP Whiting facility, which is part of the MachH2 Hydrogen Hub that BP is planning. **Cleveland-Cliffs is currently building a hydrogen pipeline from their Blast Furnace No. 7 in the direction of the BP Whiting facility.**
  - Blast Furnace No. 7 is the largest in the Western Hemisphere.
  - Presumably connecting to BP Whiting Refinery
  - Major purchaser of hydrogen from the MachH2 Hydrogen Hub (uses CCS).
- Burns Harbor facility: Applied for U.S. DOE

operations (https://www.epa.gov/uic/class-ii-oil-and-gas-related-injection-wells) for what is known as enhanced oil recovery. **That CO2 was not injected for purposes of long-term or permanent storage, but rather to recover additional oil or gas from depleted or low-producing wells.**

CCS is something entirely different, which is why the EPA created a new permit. The fact is that we have **virtually no experience** injecting CO2 for purposes of "permanent" sequestration and therefore, **every project at this point is an experiment** which **forces unwilling communities and property owners to be the guinea pigs and assume all the risks.**

Indiana Law

Despite potentially significant environmental and public health threats posed by CO2 pipelines and sequestration, Indiana state government is promoting it anyway. **Since 2011, the Indiana General Assembly has passed four major pieces of legislation enabling CCS.** The first law was signed by Governor Mitch Daniels and the other three signed by current Indiana Governor Eric Holcomb.

The pursuit of CCS at these facilities is distracting Cleveland-Cliffs from making the investments they need to make to pursue steel manufacturing that would actually be sustainable. What that means is discussed in detail in the report that the ACEEE published on our behalf in August 2023: **Sustainable Metals Manufacturing Opportunities in Indiana** (https://www.aceee.org/sites/default/files/pdfs/sustainable_metals_manufacturing_opportunities_in_indiana-encrypt.pdf).

What is CCS?

CCS is **carbon capture and sequestration**, also sometimes referred to as **carbon capture and storage**. CO2 emissions are captured from industrial processes before they are released into the atmosphere. The carbon is then transported via pipeline to the injection well, where it will be injected into deep, underground geologic formations for "permanent" storage.

Industrial processes slated for CCS could include coal or gas power plants, steel mills, concrete plants, oil refineries, ethanol plants, and other **fossil-fuel intensive heavy industries**.

CCS includes three distinct stages:

- **Capture** - CO2 is **removed from emissions (https://www.lse.ac.uk/granthaminstitute/explainers/what-is-carbon-capture-and-storage-and-what-role-can-it-play-in-tackling-climate-change/#:~:text=The%20main%20methods%20for%20capturing,after%20the%20fuel%20is%20burnt.)** either:
  - Pre-combustion by converting the fuel to a gas mixture consisting of CO2 and hydrogen before it is burned.
  - Post-combustion by separating the CO2 from the flue gas (the exhaust gas that is expelled from the smokestack) using a mixture of chemical solvents.
  - Oxy-fuel combustion, which uses pure oxygen instead of air to combust fuel, resulting in a flue gas composed of CO2 and water vapor.

2011 (https://archive.iga.in.gov/2011/bills/billinfoca5f.html?year=2011&session=1&request=getBill&doctype=SB&docno=0251)

Among many other things (https://www.citact.org/news/sb251-indiana-legislature-votes-raise-taxes-through-utility-bills-house-adds-eminent-domain), this legislation created a **permitting process for CO2 pipelines** and granted **eminent domain to operators of CO2 pipelines**. Developers of the **failed Leucadia Indiana Gasification plant** (https://www.citact.org/utility-rates-regulation/campaign/leucadia-rockport-plant) proposed for Rockport, Indiana pushed for SEA251. They intended to make substitute natural gas using Indiana coal, capture the CO2 emissions from the plant, and transport the CO2 waste to be used in oilfields in Louisiana and Texas.

Senate Enrolled Act 442, 2019 (https://iga.in.gov/legislative/2019/bills/senate/442/details)

This bill is exclusive to the proposed Wabash Valley Resources (WVR) project in West Terre Haute. (https://www.citact.org/news/2019-consumer-energy-and-utility-bill-watch-list#sb442) The bill **established WVR as a "carbon sequestration pilot project."** It granted WVR **eminent domain** for the sequestration sites if they acquired 60% of the needed property by means other than condemnation. WVR didn't get everything they wanted with this bill - see **SEA451 (2023)** below.

Transport - Once CO2 is captured, it is **compressed into a supercritical state** (https://www.scimed.co.uk/education/what-is-a-supercritical-fluid/) (combining the properties of gasses and liquids), **pressurized to approximately 2000 PSI**, and transported by hazardous pipelines to the injection sites.

- **Sequestration** - The supercritical CO2 is **injected into deep geologic formations**, usually at least ¾ of a mile deep, to be "permanently" stored in areas where the geology is deemed "suitable," like depleted oil and gas reservoirs, coal beds, or deep saline aquifers.

Risks and Hazards of CCS

Each of the three stages of the CCS process create economic, environmental, and public health risks.

Over 300 residents were evacuated and 45 people sent to area hospitals after a pipeline ruptured in Yazoo County, Mississippi on 2/22/20. First responders were among those taken to the hospital. *Mississippi Emergency Management Agency*

(https://www.clarionledger.com/story/news/local/2020/02/27/yazoo-county-pipe-rupture-co-2-gas-leak-first-responders-rescues/4871726002/)**Capturing CO2 requires significant amounts of energy.** This can **drive up the cost of energy** for everyone and **increase CO2 and other toxic emissions**. Capturing CO2 is also **extremely expensive**, often requiring **putting the public on the hook** with financial support from local, state,

SEA442 also included a request for a study committee on geologic CO2 sequestration. Unfortunately, the study committee never happened. In other words, **the Indiana General Assembly never bothered to take the time to study geologic CO2 sequestration before passing legislation that enables it.** This is shocking, considering that SEA442 declared "the underground storage of carbon dioxide to be a public use and service, in the public interest, and a benefit to the welfare and people of Indiana."

House Enrolled Act 1209, 2022
(https://iga.in.gov/legislative/2022/bills/house/1209/details)

This bill was primarily **pushed by BP to enable their scheme to store a fraction of the enormous amount of CO2 bellowing from their refinery in Whiting.** (https://www.citact.org/news/2022-consumer-energy-utility-bill-watch-list#hb1209) HEA1209 created a statewide framework for the siting and permitting of CO2 injection wells. The legislation **makes Indiana taxpayers liable**, instead of BP or other corporations, for any problems that occur after the site is "closed" - in other words, **forever**.

This legislation also authorizes the Department of Natural Resources to issue a permit approving an operator to inject CO2, but only if amongst other items, the operator "has

quality/) and the leaching of other contaminants, such as **lead and mercury**. The release of CO2 could cause damage to aquifers and the **acidification of water**, as well as **damage to soil and crops**.

Current Campaigns

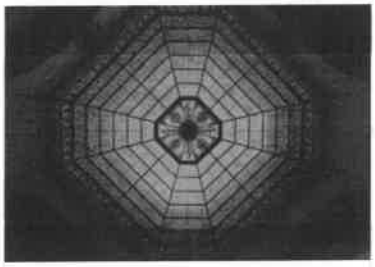
These are the issues of immediate importance we are working on right now.

(/ai-data-centers)

AI Data Center Build-Out Creates Unprecedented Risk to Hoosiers (/ai-data-centers)

(/campaign/2025-indiana-general-assembly-voting-records)

2025 Indiana General Assembly Voting Records (/campaign/2025-indiana-



(/26iga)

2026 Indiana General Assembly (/26iga)

(/aes-rate-hike-2025)

AES wants to hike your electric bill by another $30/month (/aes-rate-hike-2025)

ACTION

(/)

The CAC Mission: To initiate, facilitate and coordinate citizen action directed to improving the quality of life of all inhabitants of the State of Indiana through principled advocacy of public policies to preserve democracy, conserve natural resources, protect the environment, and provide affordable access to essential human services.

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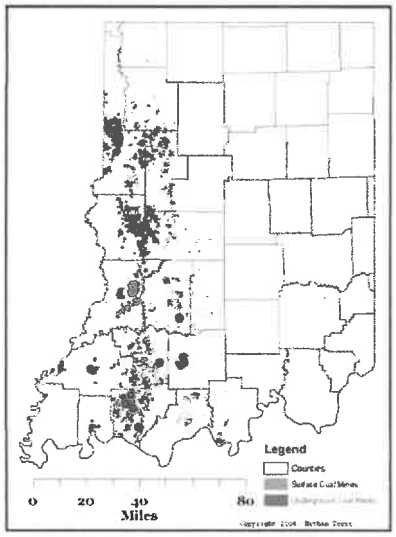
(https://www.facebook.com/cacindiana) (https://instagram.com/cacindiana) (https://twitter.com/cacindiana) (https://www.youtube.com/channel/UC8NdCkO5H_na1pgYD49YXPA)

Sign up for email Action Alerts (/cac-email-sign-up)

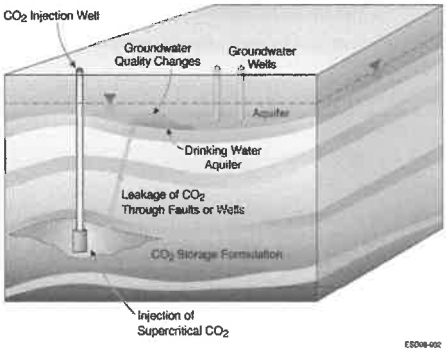


Southwest Indiana's Mined Lands

- (https://www.in.gov/dnr/reclamation/files/ISMR/2009/Robinson/Tues_1030_Robinson.pdf)**CO2 migrating to the surface**

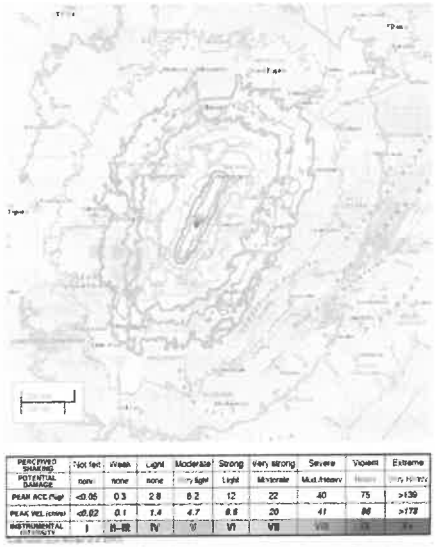
  There are numerous **abandoned mine shafts** in the part of Indiana where multiple industries are attempting to dump their CO2 waste. These old mine shafts **provide the CO2 easy access to the surface**.

  In 2009, the Indiana DNR and the U.S. Geological Survey released a report entitled **"The Occurrence and Mitigation of Carbon Dioxide in Homes Built on Reclaimed Coal Mines** (https://www.in.gov/dnr/reclamation/files/ISMR/2009/Robinson/Tues_1030_Robinson.pdf)." Their findings indicate that **CO2 is already entering the basements of new construction homes on mined lands** in Indiana. CCS is likely to exacerbate that problem, which could have deadly consequences.



- **(https://eesa.lbl.gov/projects/potential-impacts-of-co2-leakage-on-groundwater-quality/)Water and soil contamination**

  The release of CO2 into underground water or other waterways would result in **contamination of our drinking water** (https://eesa.lbl.gov/projects/potential-



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Shake map from a hypothetical M 7.5 earthquake striking in the Wabash Valley Seismic Zone.

that the **conditions in Indiana are similar to those in Oklahoma** that led to **hundreds of earthquakes after tens of millions of gallons of toxic wastewater from fracking were dumped underground.**

The **strength of those earthquakes is expected to increase**, as the underground dumping of fracking wastewater continues. Earthquakes have also occurred miles from the injection zones, indicating that **the liquid toxic waste travels long distances underground.**

Check out this 2019 article by Tyler Sebree of ABC 57 in South Bend: ***The chance of a major earthquake in or near Indiana may surprise you*** *(https://www.abc57.com/news/the-chance-of-a-major-earthquake-in-or-near-indiana-may-surprise-you).*

- **Asphyxiation and Stalled Vehicles**

  CO2 is heavier than air. If released, it will pool in one area and displace oxygen, resulting in **asphyxiation and/or death of animals and humans in the area**.

Symptoms could also include:

- comas
- seizures
- elevated blood pressure
- dizziness
- arrhythmias
- brain and/or lung damage

Since vehicles require oxygen for combustion, this would also result in vehicles stalling, which would make it **impossible to use vehicles to**

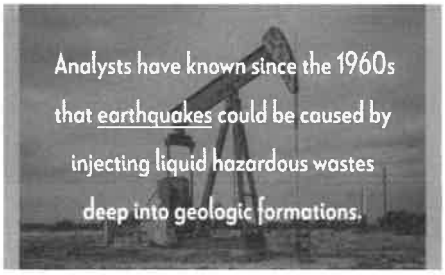
tax credits, taxpayer funded grants, and loan guarantees.

Transporting supercritical CO2 from where it is captured to where it will be stored also creates **risks for local communities**. A **CO2 pipeline rupture in Mississippi** (https://www.clarionledger.com/story/news/local/2020/02/27/yazoo-county-pipe-rupture-co-2-gas-leak-first-responders-rescues/4871726002/) led to hundreds of people being evacuated and dozens sent to hospitals. **First responders said that some of the victims exposed to CO2 looked like wandering zombies.** Others were found unconscious.

The Pipeline Safety Trust has an excellent resource, **Carbon Dioxide Pipelines: Dangerous and Under-Regulated** (https://pstrust.org/carbon-dioxide-pipelines-dangerous-and-under-regulated/), that discusses the Mississippi incident and all of the risks associated with CO2 pipelines.

Storing supercritical CO2 "indefinitely" poses numerous risks:

- **Earthquakes**



(https://www.cpr.org/2015/05/04/as-worries-grow-over-man-made-quakes-50-year-old-colorado-temblors-reverberate/#:~:text=two%20to%20Belize!-,As%20worries%20grow%20over%20man%2Dmade%20quakes%2C%2050%2D,year (Courtesy%20Library%20of%20Congress)%20This,caused%20earthquakes%20on%20the%20site.)The area in Indiana where multiple industries are attempting to dump their CO2 waste sits in the Wabash Valley Seismic Zone. **The U.S. Geological Survey, or USGS, is still attempting to determine whether carbon sequestration is safe** (https://www.usgs.gov/centers/geology-energy-and-minerals-science-center/science/induced-seismicity-associated-carbon), geologically speaking.

(https://www.abc57.com/news/the-chance-of-a-major-earthquake-in-or-near-indiana-may-surprise-you) Their preliminary findings show

the owners of the pore space underlying at least seventy percent (70%) of the surface area above the proposed facility." **Wabash Valley Resources is exempt from this legislation, including the requirement that they obtain the consent of property owners.**

Senate Enrolled Act 451, 2023 (https://iga.in.gov/legislative/2023/bills/senate/451/details)

This was the **second piece of special legislation passed exclusively for Wabash Valley Resources** (https://www.citact.org/2023-iga#sb451), and **only impacts Vigo and Vermillion counties**. After failing in 2020, 2021, and 2022, WVR finally got what they wanted with SEA451. This legislation effectively **authorizes WVR - and only WVR - to inject CO2 in Vigo and Vermillion counties, without having to compensate, notify, or negotiate with property owners** before injecting, but rather only "before the anticipated migration of carbon dioxide as predicted by testing and monitoring." The legislation also **shifts the burden of proving damage, harm, or injury resulting from the project onto the backs of the public**, effectively **immunizing investors from risk**. What a deal for communities in Vigo and Vermillion Counties: all risk, no reward.

One year, four accidents at Archer Daniels Midland's Decatur, Ill. headquarters; company fined over $400,000 in past 10 years

Archer Daniels Midland regional headquarters in Decatur, Illinois. Photo from ADM's website.

An explosion in September at the Archer Daniels Midland (ADM) plant in Decatur, Illinois injured eight workers, but federal work safety data shows it was only the latest in series of safety incidents and issues over the past 10 years.

The September explosion is the fourth incident this year at the plant. An August three-alarm fire, an April dust explosion and an April rail accident also left people hospitalized, and one person died.

Since 2013, the Occupational Safety and Health Administration (OSHA) has investigated the company 32 times, resulting in $405,418 in fines. The issues are categorized as either health or safety violations, but all have been identified as safety violations.

The majority of the fines came as a result of the April explosion this year — totaling $324,796.

OSHA's database provides inspection records and details health and safety violations of various companies such as ADM. Inspections are either planned, or they can be as a result of a complaint or referral. When an inspection is issued, the details are recorded and filed on OSHA's website.
Decatur is home to ADM's North American headquarters, making it the "single largest location and employee base across ADM's global footprint," according to its website. The facility is home to nearly 4,000 employees and is one of the largest corn wet mills in the world.

The Decatur facility has been inspected by OSHA five times this year. Only one was planned.

Details of serious safety violations from ADM's Decatur facility date back years. In 2018, an employee suffered serious injuries after falling six feet. In 2016, an employee died after disassembling equipment.

David Horn, Decatur city council member, said he believes ADM's repeated explosions and fires should sprout its own private investigations.

"I'm very thankful that the federal government is going to provide an investigation into a couple of those incidents," Horn said in an interview. "I hope that [the] ADM company will also do its own investigations. I think that all parties want to make sure that these types of incidents don't take place so that the employees stay safe at their workplace, but also that the city's residents feel safe near manufacturing facilities as well."

ADM Media Relations Director Jackie Anderson said in a statement safety of workers is a core value for the company.

"The safety of our employees is always our top priority," Anderson said. "We take incidents like these very seriously and are fully cooperating with OSHA's investigation."

OSHA categorizes the scope of the investigation as partial or complete. Of the 32 listed, there have been five complete investigations, and 26 were partial investigations. One case was marked as "No Inspection". Six citations were deleted, removing the associated fine, due to settlement or a change in the investigation.

#	Activity	Date Opened	RID	ST	Type	Scope	SIC	NAICS	Violations	Establishment Name
1	[illegible]	06/28/2018	0524500	IL	Complaint	Partial		311999		Archer Daniels Midland Co.
2	[illegible]	05/31/2018	0524500	IL	Referral	Partial		311119	1	Archer-Daniels-Midland Company
3	1311842.015	04/27/2018	0524530	IL	Planned	Complete		424510		Archer-Daniels-Midland Company
4	1215170.015	03/06/2017	0524200	IL	Referral	Partial		311211		Archer Daniels Midland Company
5	[illegible]	05/05/2016	0524500	IL	Fat/Cat	Partial		311221		Archer-Daniels-Midland Company
6	[illegible]	03/09/2016	0524500	IL	Unprog Rel	Partial		311224	1	Archer Daniels Midland Company
7	1116091.015	01/06/2016	0524500	IL	Unprog Rel	Partial		311221		Archer Daniels Midland Company
8	1113086.015	12/15/2015	0524500	IL	Complaint	Partial		311221		Archer Daniels Midland Co.
9	1078574.015	07/10/2015	0524530	IL	Referral	Partial		424510		Archer Daniels Midland Company Dba Adm Shobonier
10	[illegible]	03/10/2015	0521400	IL	Referral	Partial		424510	1	Archer Daniels Midland Company
11	998120.015	10/02/2014	0524500	IL	Complaint	Complete		424510		Archer Daniels Midland Company
12	973989.015	04/23/2014	0524500	IL	Complaint	Partial		311222		Archer Daniels Midland Company
13	961218.015	03/05/2014	0524530	IL	Planned	Partial		311221	1	Archer Daniels Midland Company
14	957808.015	02/06/2014	0524500	IL	Referral	Complete		424510		Archer-Daniels-Midland Company
15	[illegible]	01/29/2014	0524500	IL	Complaint	Partial		424510	3	Archer-Daniels-Midland Company
16	956085.015	01/23/2014	0521400	IL	Planned	Complete		424510	1	Archer Daniels Midland Company

A screenshot of OSHA's database showing Archer Daniels Midland's inspection activity and safety violation details. Source: OSHA Establishment Search

Any violations or penalties given are classified as serious, willful, repeat, other or unclassified. Their 2018 citation was classified as serious after an employee fell 6 feet after being hit in the head with an agitator motor inlet filter.

They were transported to the hospital but suffered multiple fractures to their skull, both eye sockets, nose, cheekbones, ribs and wrist, and trauma on their right elbow and knee. The company initially incurred $10,163 in violation fees.

In April 2016, OSHA reported how an employee suffered fatal injuries while disassembling a piece of equipment within one of the plants. A chain fell off a trolley system and swung into another piece of equipment, then into the employee's face. The individual had a fractured cheekbone and sternum and later died from those injuries.

Four accidents, one death at ADM's Headquarters in 2023

ADM's third explosion this year occurred at 7 p.m. on September 10. The explosion was so intense that neighboring residents reported to local news that they felt their houses shake from the eruption. Large plumes of dark smoke rose high above the ten-story facility.

The blast brought over 30 firefighters to the food manufacturing plant that Sunday evening, where it then took them nearly seven hours to get under control as noted by the police report. Facilities adjacent to the fire, including a corn processing plant, also received significant damage.

The explosion left eight employees seriously injured, and six were taken by helicopter and ambulance to the local hospital to receive care for their wounds. However, this is the company's third accident in a single year – all of which involved serious injuries. This prompted OSHA to investigate the scene for a third time this year.

A few weeks prior to the explosion, a third-alarm fire erupted at ADM's east plant within their processing tank, requiring triple the number of firefighters, trucks and equipment. Third-alarm fires are considered to be very large fires in nature and typically take a prolonged time to extinguish. 46 firefighters were called to extinguish the fire, leaving two in the hospital. First responders were at the facility until 5 a.m. the next morning working on getting the fire under control.

In April of this year, a dust explosion in ADM's West plant within their grain elevators left three employees hospitalized. Ten days prior, a rail accident resulted in the death of a locomotive operator.

The September explosion received a considerable amount of attention from the press and even made national news. The incident prompted Illinois Governor JB Pritzker to share his sentiments in a post on Facebook for those injured by the explosion. He offers employees and the company "state support" in any way possible and wishes "a speedy recovery for the workers."

OSHA's third investigation into ADM's working conditions for its employees in a single year raised the attention of many. Illinois Congresswoman Nikki Budzinski said she believes the company's third explosion this year warrants a thorough investigation.

"I'm glad to see that OSHA is doing this investigation... I think this situation calls for an investigation, that investigation is underway. And like I said, I'm very much looking forward to see the answers, to what turns up," Budzinski told local news WCIA.

OSHA explained in a statement how they have "six months to complete its investigation, issue citations and propose penalties if violations of workplace safety and health regulations are found."

The Carbon Capture Boom Is Starting to Crack

By Felicity Bradstock-July 25, 2026, 2:00 PM CDT

- Governments and major energy companies have committed billions of dollars to carbon capture projects as a way to reduce emissions from hard-to-abate industries.
- Many CCS projects have failed to achieve their expected capture rates, while costs remain significantly higher than initially forecast.
- Growing evidence suggests CCS may play only a limited role in decarbonization, with critics arguing that greater investment should go toward permanent low-carbon alternative.

Carbon capture and storage (CCS) technology grew in popularity during the Covid-19 pandemic as several governments and private companies pledged to support a green transition. The use of CCS was expected to help decarbonize hard-to-abate industries until a long-term transition tp clean energy could be achieved. However, in recent years, many have become more skeptical about the effectiveness of CCS technologies, as several projects have failed to perform.

CCS technology is sued to capture carbon dioxide at emission sources, so it can be transported and stored or buried in a suitable underground location. Several CCS technologies have been launched in recent years, including convention CCS installations and direct air capture (DAC)- which removes CO2 directly from the atmosphere-as they have grown in popularity, particularly across hard-to-abate industries.

As governments have put increasing pressure on industries to decarbonize their operations, companies that cannot simply switch to renewable alternatives have invested heavily in CCS activities to reduce emissions. While many have criticized companies for relying on carbon capture rather than cutting emissions at the source, CCS tech has been expected to help companies support a green transition as they assess possible long-term solutions.

In 2025, the World Economic Forum predicted that the CCS industry would grow fourfold by the end of the decade. This prediction is supported by a massive pipeline of CCS activities, as several invest heavily in the technology. In the oil and gas industry, ExxonMobil, Shell, Chevron, TotalEnergies, Equinor, and Occidental have all pledged major investments in CCS technologies.

Some governments are also backing CCS in a big way. In May, Germany launched a 5.7 billion Carbon Contracts for Difference scheme that aims to promote and support CCS and carbon capture and utilization (CCU) projects. In 2024, in the United Kingdom, the government announced up to $29 billion of funding over 25 years to make the country and early leader in two growing global sectors, CCUS and hydrogen, to be allocated between these two clusters.

Meanwhile, in Denmark, the cement maker Aalborg Portland signed a $2.55 billion CCS contract with the country's energy agency. Aalborg Portland's CEO Soren Holm Christensen stated, "We can now take the decisive step toward realizing a project that is not only significant in a Danish context, but is also among the larges industrial CO2 capture projects in Europe."

Despite the clear optimism around CCS technology, the cracks are starting to show as several companies fail to see the results expected from CCS operations. An Institute for Energy Economics and Financial Analysis (IEEFA) review of 13 operating CCS projects around the world found that most captured below design levels of 90 percent, while some failed outright, highlighting the ongoing technical challenges of CCS as a solution and the potential for further cost escalation per ton. According to the Global CCS Institute, only 50 facilities were operating worldwide in2024, with the capacity to capture around one thousandth of global emissions.

Meanwhile, environmentalists argue that CCS is simply another form of greenwashing, and that funding for the technology could be better spent exploring alternative, clean energy options to decarbonize hard-to-abate industries. Many

argue that using CCS technologies will give companies an excuse to use the "transition fuel" of natural gas for longer than necessary. In addition, CCS is being used by the oil industry to allow them to claim that they are producing "low-carbon oil", even though burning fossil fuels continues to contribute heavily to climate change.

CCS technology is extremely expensive to incorporate into operations, with many projects relying on taxpayer support. For this purpose, key industry players suggest that CCS should only be pursued after other green solutions during a 2025 conference in London.

In the United States gas industry, the cost of adding CCS to U.S. plants is estimated a $2(MWh), which could potentially double the cost of power production. Meanwhile, in Europe, the think tanks Agora Industry and OekoInstitut, estimate the cost of carbon capture, transport, and storage at between $170 and $340 a ton. "According to these calculations, the costs of existing or planned CO2 storage projects are at least 50 percent higher than previous forecasts, " the think tanks stated in a press release.

Several fossil-fuel dependent industries and companies have long promoted CCS technology as key to decarbonizing operations. This has helped improve the image of CCS and allowed major oil companies and heavy industry to get government backing. However, the high cost of CCS technology use, as well as the barriers to commercial rollout, suggest that CCS promotion may have been one big (and fairly successful) PR stunt. While it may still be used in a limited capacity, governments should be encouraging companies to invest in long-term decarbonization solutions if they hope to achieve a green transition.

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December 19, 2025

Ms. Jennifer O'Keefe
Vault4401, Ltd
Jennifer@vault4401.com
VIA ELECTRONIC MAIL

Dear Ms. O'Keefe:

As you know, this firm represents the Madison County Plan Commission. I have been requested by the county's executive director, Larry Strange, to provide a legal opinion on whether your company's proposed carbon sequestration capture facility implicates Madison County's zoning authority. Please find below the county's rationale for its position that local municipalities, such as Madison County, retain zoning authority over the proposed project.

Background: Local Context

The Madison County Planning Commission is addressing updates concerning energy-related projects, including those by POET and VAULT 44.01. POET is planning a carbon sequestration capture facility north of Alexandria. The project involves drilling to approximately 3,000 feet and injecting carbon from industrial operations to disperse at that depth under surrounding properties. POET and its consultant are executing leases with adjacent property owners. County staff have taken the position that, because the affected properties are in the county, their use is subject to county zoning. The County previously adopted a BESS ordinance designed to respond to new energy-related developments, including carbon sequestration, through existing approval processes. Applicants understand that County approvals involve the Plan Commission, Board of Commissioners, and Board of Zoning Appeals, as applicable.

Legal Authority: State Enabling Statutes and County Jurisdiction

Indiana Code § 36-7-4-601 grants the legislative body having jurisdiction exclusive authority to adopt a zoning ordinance after a comprehensive plan is approved. Zoning ordinances may include requirements concerning utilities and infrastructure, including site conditions and other nonstructural improvements. When adopting zoning, the legislative body acts to secure safety from dangers and to promote public health, safety, comfort, morals, convenience, and general welfare. Plan commissions prepare zone maps indicating the districts for incorporated and unincorporated areas. In the area planning context, once

established and upon adoption of a zoning ordinance, the planning department exclusively exercises the planning and zoning functions for the county and participating municipalities. Madison County's Zoning Ordinance is adopted pursuant to IC 36-7-4 et seq. It applies throughout unincorporated Madison County and areas not owned by the state or federal government. The ordinance applies to all county land outside incorporated jurisdictions and state/federal ownership. The Madison County Plan Commission is an advisory plan commission under Indiana Code. The County's comprehensive plan authority is exercised under the IC 36-7-4-500 series.

Carbon Sequestration Statutes Confirm Local Law Compliance

Indiana Code § 14-39-2-5 authorizes carbon sequestration projects to inject CO2 via UIC Class VI permits and to employ underground storage. A storage operator may not operate a carbon sequestration project without a UIC Class VI permit and a valid state-issued permit. IC 14-39-2-5(b) expressly prohibits operation without both permits. The statute defines carbon dioxide injection wells, carbon sequestration, carbon sequestration projects, and UIC Class VI permits by reference to the federal Safe Drinking Water Act program. Importantly, the state permitting application must include a statement describing how the applicant will construct, operate, and maintain the project in accordance with applicable local, state, and federal law to ensure safety. For CO2 pipelines, IC 14-39-1-4(a)(4)(E) similarly requires construction, operation, and maintenance in accordance with applicable local, state, and federal law. State law references federal UIC Class VI permitting, reflecting the interaction of federal and state programs governing underground injection.

These provisions explicitly recognize applicability of local law and standards, thereby supporting Madison County's zoning oversight for siting, development standards, and approvals.

Local Zoning Framework Applied to Carbon Sequestration Uses

Under the County ordinance, specific land uses are categorized as permitted, special, or non-permitted by district. Any use not listed is non-permitted unless the Planning Director determines otherwise. Industrial zoning districts include LI (Limited Industrial) and GI (General Industrial). General industrial uses involve processing of goods/materials with greater-than-minimal environmental impacts, including those made from raw materials. The GI district provides for development of manufacturing and waste disposal facilities. Utility-type facilities, including sewage treatment plants and water towers, are addressed as permitted or special uses within industrial districts, indicating County regulation of utility facilities through zoning. The GI district also includes mineral extraction and processing, with use-specific siting standards. GI permits high-impact industrial uses with larger setbacks and standards.

Development, Performance, and Environmental Standards

County performance standards apply to industrial districts and are designed to protect public health, safety, and general welfare by limiting air pollution, noise, odor, vibration, heat/glare, waste, and water pollution. These standards expressly serve public health and welfare objectives. Environmental standards require land suitability, drainage, and compliance with hazardous waste and environmental codes, referencing state regulations for awareness alongside

local law. References to state regulations do not imply County enforcement of state rules; they are noted in addition to local law. All structures and land uses commenced after the ordinance's effective date are subject to applicable development standards. Major expansions trigger full-site compliance with Article Six standards.

Procedural Tools and Permitting

No structure or major infrastructure may be erected, moved, or added without an Improvement Location Permit (ILP), and no ILP issues unless the project conforms to the Zoning and Subdivision Ordinances and other applicable County regulations. Site Development Plans for ILP-required projects must include detailed site, utility, drainage, and operational information and are reviewed by the Technical Review Committee, with Plan Commission review and public notice where applicable. Site Development Plans are required for developments needing an ILP; neither the TRC nor the Plan Commission may waive ordinance requirements in such reviews. The TRC acts under adopted county, state, and federal standards; decisions are appealable to the Plan Commission. The BZA has jurisdiction over Special Uses and Variances and may impose reasonable conditions and require written commitments under IC 36-7-4-921 to protect public health, safety, morals, and general welfare. Variance and Special Use processes require applications, public notice, hearings, findings, and allow conditions/commitments with rehearing limits. Rezoning follows TRC review, Plan Commission hearing/recommendation, and Board of County Commissioners action, guided by decision criteria and recording of commitments. The County may enforce compliance through investigations, stop-work, injunctions, and fines up to $2,000 per day under IC 36-7-4-1000 et seq.

Public Health, Safety, and Welfare Rationale

Indiana's enabling act directs zoning to promote public health, safety, comfort, morals, convenience, and general welfare. Madison County's ordinance mirrors this purpose, emphasizing protection of public health, safety, comfort, convenience, morals, and general welfare. It further aims to secure adequate light, air, access, and safety from fire, flood, and other dangers while planning for industry and business needs. Performance standards operationalize these purposes by limiting potential off-site impacts.

Interaction with State/Federal Programs

No Preemption of Local Zoning Indiana Code § 14-39-2-5 authorizes carbon sequestration projects and requires both UIC Class VI and state permits. The Class VI permitting requirement reflects interaction with the federal UIC program. State law requires applicants to explain how they will comply with applicable local law, confirming coexistence with local zoning and safety standards. The County ordinance's conflict clause provides that the greater restriction controls and does not alter or negate other applicable regulations, harmonizing local requirements with state/federal rules. County references to state standards are for awareness and do not imply state rule enforcement by the County.

Utility/Political Subdivision Case Law and Statutes

Indiana Code § 8-1-2-89(b) states sewage disposal companies are under IURC oversight but are subject to local comprehensive plan, zoning, and subdivision requirements of the governmental units having jurisdiction. Courts have upheld BZA jurisdiction where the statute expressly subjects the utility to local zoning (Wastewater One v. Floyd County BZA). By contrast, in Howell v. Indiana-American Water Co., a water utility was held not subject to local zoning for siting a water storage tank. Zoning authorities cannot enforce their regulations on other political subdivisions without explicit statutory authorization; courts balance interests in disputes. Land use control is local and implemented through zoning, but the power does not include requiring other political subdivisions to comply absent explicit authority.

These authorities do not displace County zoning of private carbon sequestration operators. Rather, they illustrate that where statutes speak, local regulation applies (as with sewage disposal companies), and where they are silent, local zoning remains the default for private actors within jurisdictional bounds. Here, the carbon sequestration statutes explicitly contemplate compliance with applicable local law.

Application to POET Carbon Sequestration Activities

POET proposes a carbon sequestration capture facility in unincorporated Madison County. The project entails drilling and injection at approximately 3,000 feet with lateral dispersion under surrounding properties. The operator is securing subsurface leases from adjacent owners. These lands are within the County's zoning jurisdiction unless within a municipality's extended jurisdiction or state/federal ownership. County zoning does not apply only where a municipality has established extended jurisdiction per Indiana law. Separate from local approvals, the operator must obtain a UIC Class VI permit and a state permit to operate. The state application must demonstrate how the project will comply with applicable local laws to ensure safety.

Accordingly, the County may require: (1) appropriate zoning entitlements (e.g., determination of use classification, special use if applicable, or rezoning where necessary), (2) Site Development Plan review through the TRC and, where required, Plan Commission hearing, (3) issuance of an ILP upon conformity, (4) imposition of conditions and written commitments through BZA special use or variance processes where applicable, and (5) compliance with performance and environmental standards to mitigate offsite impacts.

County Procedures and Enforcement for Compliance

ILPs are required for structures and major infrastructure and must conform to zoning and subdivision regulations. Site Development Plan submissions must include utilities, drainage, setbacks, and operational characteristics, with TRC/Plan Commission review and public notice, as applicable. The BZA may impose reasonable conditions and require written commitments for special uses/variances to protect public health, safety, morals, and general welfare. Public hearing notice must comply with IC 5-3-1 and mailed notice requirements. Decisions must be supported by Findings of Fact and are reviewable by certiorari under IC 36-7-4-1003. Violations are subject to enforcement, including stop-work, injunctions, and per-day fines under IC 36-7-4-1000 et seq.

Conclusion

Indiana's zoning statute grants local exclusive zoning authority within jurisdiction upon comprehensive planning, including utility-related provisions. Carbon sequestration is authorized under state law but requires federal and state permits. State law expressly anticipates and requires compliance with applicable local law for carbon sequestration projects and associated pipelines. Madison County's ordinance applies to unincorporated areas within the Plan Commission's jurisdiction. County performance and environmental standards protect public health, safety, and welfare. County permits and procedures govern site development and major infrastructure. The Plan Commission is on solid statutory and ordinance footing to regulate the siting and development standards applicable to a carbon sequestration company operating within unincorporated Madison County, in coordination with—but not supplanted by—state and federal permitting programs.

Thank you for your patience,

/s/: Jeffery K. Graham

Jeffery K Graham

ECC: Larry Strange, Executive Director
Madison County Plan Commission
Madison Couty Board of Zoning Appeals
Madison County Board of Commissioners

Local

Illinois Bans Carbon Sequestration Near Mahomet Aquifer to Protect Drinking Water for Residents

Dani Tietz • December 7, 2025 2 minutes read

Illinois Governor JB Pritzker has signed into law a ban on carbon sequestration activities near the Mahomet Aquifer, the sole source of drinking water for nearly one million central Illinois residents. The legislation, which takes effect January 1, 2026, marks a significant victory for environmental advocates and local communities who have long fought to protect the region's water supply from potential contamination risks.

The Mahomet Aquifer serves as the primary drinking water source for residents across 15 counties in east-central Illinois, stretching from the Illinois River to the Indiana border. In March 2015, the U.S. Environmental Protection Agency designated a portion of the aquifer as a sole source aquifer under the Safe Drinking Water Act, recognizing that contamination could pose significant public health risks and that no reasonably available alternative drinking water sources exist in the region.

The aquifer currently provides an estimated 53 to 58 million gallons of drinking water daily to approximately 500,000 to one million people, including residents of Champaign, Urbana, Savoy, and more than 100 other communities.

The bill received bipartisan support during its passage through the Illinois General Assembly. The legislation passed in the Illinois Senate on April 10, 2025 and cleared the House on May 20, 2025.

Governor Pritzker signed the bill into law on August 1, 2025.

The legislation amends the Illinois Environmental Protection Act to prohibit any person from conducting carbon sequestration activity within a sequestration facility that overlies, underlies, or passes through a sole source aquifer. Specifically, the law bans the underground injection and long-term storage of carbon dioxide streams into geologic formations beneath the Mahomet Aquifer's designated sole source area.

The law also establishes the Mahomet Aquifer Advisory Study Commission to study and review the safety of carbon capture and storage in the region. The commission will consist of state agency directors, legislative appointees, and other stakeholders, and must hold public meetings within the Mahomet Aquifer area. The Prairie Research Institute at the University of Illinois at Urbana-Champaign will conduct a comprehensive study on the potential for carbon sequestration in the area, submitting annual status reports starting in December 2027 and a final report by December 31, 2030. The commission will then issue its own final report to the governor and General Assembly by December 31, 2031, before dissolving on January 1, 2032.

The push for aquifer protection intensified following reported leaks at Archer-Daniels-Midland's (ADM) carbon sequestration facility in Decatur, Illinois, just a few miles from the Mahomet Aquifer. In March 2024, ADM detected a leak at its Class VI carbon storage site, the only operating EPA-approved Class VI project in the country not used for enhanced oil recovery.

The U.S. EPA determined in August 2024 that ADM had violated Safe Drinking Water Act regulations when at least 8,000 metric tons of liquified carbon dioxide and other fluids leaked into "unauthorized zones" roughly 5,000 feet below the surface. ADM later revised its estimate of the carbon dioxide leak to between 2,670 and 3,940 metric tons. In September 2024, a second leak involving brine was discovered. The EPA issued a proposed enforcement order, and ADM voluntarily paused carbon injections in late September 2024.

In July 2024, Governor Pritzker signed the Safety and Aid for the Environment in Carbon Capture and Sequestration (SAFE CCS) Act, which established statewide regulations for carbon capture and storage projects, including a two-year moratorium on carbon dioxide pipelines. However, the SAFE CCS Act did not specifically ban carbon sequestration beneath the Mahomet Aquifer, prompting local legislators and environmental groups to push for additional protections.

CARBON pipelines

By **Alex Gray**
New Products Editor
alex.gray@agriculture.com

Dakota Access Pipeline being constructed through farmland near Sioux Falls, South Dakota.

History and Safety

In part five of our carbon pipeline series, we look at the history of pipelines and the regulations behind them.

As the ethanol industry seeks to decarbonize, to meet tax credit requirements, pipeline companies are planning to establish routes across the Midwest. Those pipelines are intended to transport and sequester carbon dioxide (CO_2) generated during ethanol production, allowing ethanol plants to take advantage of tax credits.

The Inflation Reduction Act (IRA) of 2022 expanded the 45Q tax credit. According to documentation from the Iowa Corn Growers Association, this credit incentivizes carbon capture and sequestration (CCS), with the federal government providing funding as follows:

- **$85 per metric ton (17¢ per gallon of ethanol)** for CO_2 permanently sequestered underground; and
- **$60 per metric ton (12¢ per gallon of ethanol)** for CO_2 used for enhanced oil recovery or other industrial uses.

The 45Z tax credit specifically incentivizes fuel producers to lower their carbon intensity (CI) scores to 50 or lower. For on-road vehicles, 45Z offers 2¢ per gallon, up to $1 per gallon for every CI point reduction below 50. For sustainable aviation fuel, 45Z offers 3½¢ per gallon, up to $1.75 per gallon for every CI point reduction below 50.

Growing a Pipeline

The first large-scale CO_2 pipeline in the U.S. was the Canyon Reef pipeline, established in the 1970s for use during the enhanced oil recovery process in the Permian Basin in Texas. Pipeline infrastructure grew to around 3,000 miles during the early 2000s. Now, there are over 5,300 miles of carbon pipelines in the country, according to the U.S. Department of Transportation.

The U.S. Department of Energy estimates the country will need an increase of up to 20 times the existing carbon pipeline mileage by 2050. Several studies have attempted to optimize the required pipelines based on varying estimates of CO_2 that will need to be transported, with an estimated 30,000–96,000 miles of additional CCS pipelines required by 2050. In addition to the expansion in pipeline capacity, other modes of CO_2 transportation will also be required for facilitating offshore storage, shorter routes, and collection from facilities, including barge, ship, train, and truck, according to the Department of Energy.

Safety Responsibilities

While carbon pipelines haven't noted a fatality since reporting began in 1988, as with any project of this magnitude, landowners and advocacy groups have voiced concerns about safety.

Monte Shaw, executive director of the Iowa Renewable Fuels Association, a trade association for ethanol producers, said confusion and political agendas have clouded the discussion around carbon pipeline safety.

"We've been operating CO_2 pipelines in this country for 40 years, and they've been operating even longer in other countries," Shaw said. "There's never been a loss of life — you can't say that for almost anything else — so the track record is pretty good. I have to differentiate between the people who have safety questions and the people who use questions as a political instrument to oppose CO_2 pipelines because they don't like them."

Congress has the ultimate responsibility to set pipeline safety regulations. The federal Department of Transportation, through its Pipeline and Hazardous Materials Safety Administration (PHMSA), is ultimately responsible for issuing and enforcing safety regulations. States are allowed to accept the responsibility for regulations within their borders with an annual certification from PHMSA. State and local governments can regulate development near pipelines with their land use authority.

Inspections are performed by the pipeline company and →

Photography: Sinisa Kukic, Getty Images

pipeline regulators, according to the Pipeline Safety Trust, a nonprofit public watchdog organization; requirements for pipeline inspections vary on factors such as contents, location, and width. Some techniques include aerial flyovers, truck drive-bys, or on-foot inspections. Internal inspections are performed by a device called a "smart pig," which travels through the pipeline, using sensors to detect corrosion, dents, scratches, and other weaknesses.

PHMSA requires pipeline companies to produce dispersion models, as well as risk analyses to identify potential impacts to high-consequence areas. Factors include topography, weather, and leaked CO2 volume, as well as pipe diameter modeled at maximum, higher-than-normal operating volume.

A pipeline operator must have a written integrity management program that addresses the risk on each pipeline segment and identifies preventive and mitigative measures to protect each area. The plan must be continually evaluated throughout the pipeline's lifespan.

When a Burst Happens

Carbon dioxide is a colorless, odorless, heavier-than-air gas that can cause asphyxiation after prolonged exposure and is potentially lethal over wide distances. At normal temperatures, CO2 is a gas; CCS pipelines carry CO2 in highly pressurized liquid form. Natural gas pipelines are not suited for CO2 transportation. They have a maximum pressure rating of 1,480 pounds per square inch gauge (psig) — a Class 600 pipeline, according to the American National Standards Institute. A pipeline built for CO2 service is designed for 2,200 psig — a Class 900 pipeline.

Exposed to water, CO2 turns into carbonic acid, which can eat through a steel pipeline, potentially leading to a volatile rupture. When a pressurized pipeline bursts, the dramatic change of pressure at the release point can cause the CO2 to rapidly expand, dropping to subfreezing temperatures, according to the American Petroleum Institute.

Like dry ice, the cold CO2 presents a dermal hazard, causing frostbite to those coming into contact with the released gas or the nearby piping and equipment. It also can produce a thick water vapor cloud, which may be dispersed by the wind. Due to the density of CO2, during cool and humid conditions with little to no wind, the CO2 could accumulate in low-lying areas such as valleys and ditches. This cloud can also reduce visibility — especially at night — making driving or walking through the CO2 release hazardous. As the gas adjusts to ambient air temperatures, the opaque vapor cloud dissipates, but it may still be present.

The Denbury Inc. pipeline in Satartia, Mississippi, burst on Feb. 22, 2020, and leaked CO2 for about four hours.

Recent Pipeline Leaks

In February 2020, a pipeline operated by Denbury Inc. in Satartia, Mississippi, burst, spewing CO2 for about four hours before the rupture was repaired. Over 200 residents in the surrounding area were evacuated, and 45 were hospitalized, according to PHMSA's failure investigation report, which it released May 26, 2022. Many residents experienced seizure-like symptoms, knocking them to the ground, and causing tremors and difficulty breathing. Motor vehicles stopped working, impeding emergency response. In the subsequent years, some residents have reported ongoing respiratory issues, as well as headaches, difficulty concentrating, and muscle tremors, according to a report by NPR.

In response, PHMSA in 2022 announced steps to implement new safety measures in its oversight, created the failure investigation report, and began soliciting research to strengthen CO2 pipeline safety.

In its investigation, PHMSA attributed the pipeline burst to soil saturation from recent rainfall. Vertical erosion of the sloped hillside, exacerbated by the rainfall, had produced enough load to compress the pipeline and cause the welding to fail. PHMSA found that Denbury's operations and maintenance procedures →

Photography: Mississippi Emergency Management Agency

didn't address the potential for pipeline damage caused by soil instability and that the company's aerial inspection patrols failed to identify the potential geohazard before the incident.

According to PHMSA's report, Denbury failed to notify local responders, hindering the ability of emergency services to respond in a timely manner; local responders contacted Denbury about 40 minutes after the burst. The report also found that Denbury's CO2 dispersion model underestimated the potentially affected area that could be impacted by a release, and that the modeling did not identify Satartia.

In 2022, PHMSA issued a Notice of Probable Violation, Proposed Civil Penalty, and Proposed Compliance Order to Denbury Gulf Coast Pipeline, LLC for multiple violations of federal pipeline safety regulations, with proposed civil penalties amounting to $3,866,734. In 2025, another $2,366,900 of penalties was proposed. The final penalty assessed was $2,868,100.

In April 2024, Denbury, since acquired by ExxonMobil, was responsible for another pipeline burst in Sulphur, Louisiana. A 2-foot-diameter pipeline at a pump station ruptured and released around 107,000 gallons of CO2 over the course of nearly two and a half hours, according to the Ward Six Fire Protection District in Calcasieu Parish. Residents within a quarter mile of the pump were told to shelter in place, close doors and windows, and turn off air-conditioners. No injuries or serious illnesses were reported at the time.

Pipeline regulations are in further doubt following an executive order that targeted regulations deemed "unconstitutional" or that would "impose significant costs upon private parties that are not outweighed by public benefits."

Looking Forward

In the final days of President Biden's administration, PHMSA proposed new, comprehensive requirements for CO2 and other hazardous liquid pipelines.

"I have learned first-hand from affected communities in [Satartia,] Mississippi and across America why we need stronger CO2 pipeline safety standards," said Tristan Brown, PHMSA deputy administrator at the time of the announcement. "These new requirements will be the strongest, most comprehensive standards for carbon dioxide transportation in the world and will set our nation on a safer path as we continue to address climate challenges."

Those requirements were withdrawn days later when President Trump took office and froze all pending regulations by executive departments and agencies.

PHMSA's proposal would have strengthened standards for CO2 pipelines — including CO2 transported in a supercritical fluid state — and established new standards for transporting CO2 in a gaseous state via pipeline.

Regulations are in further doubt following Trump's executive order in February targeting regulations deemed "unconstitutional" or which would "impose significant costs upon private parties that are not outweighed by public benefits."

Despite changes to regulations, Shaw, of the Iowa Renewable Fuels Association, said he expects the Trump administration to continue supporting carbon pipeline projects.

"Trump is the godfather of the carbon pipelines — he's the one that signed 45Q in the law in such a way that it was actually economically viable to do these projects," Shaw said. "Biden further enhanced 45Q in the [Inflation Reduction Act]."

In March, South Dakota legislators banned the use of eminent domain for CCS projects; at press time, a similar bill awaited the Iowa governor's signature. Both significantly threaten the future of Summit Carbon Solutions' proposed pipeline, which has its storage location in North Dakota.

In April, the South Dakota Public Utilities Commission denied, for a second time, the permit for Summit's pipeline route. The company said it is planning to reapply with a reduced scope.

Shaw said banning eminent domain is a de facto ban on the pipeline that will hurt ethanol producers who can't take advantage of the 45Q and 45Z tax credits.

"This isn't part of some sort of political philosophy or political agenda: It's business," Shaw said. "We want to produce ultra-low carbon ethanol because we have customers who want to buy it." •

Indiana Landowners Decry State Dept. of Natural Resources' Enactment of Weak Carbon Capture Rules

By **Mark Hefflinger**

NEWS JULY 16, 2025

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Busload of landowners and advocates arrive in Indianapolis to testify at IN DNR public hearing on state carbon capture rules

FOR IMMEDIATE RELEASE: June 16, 2025

Indiana Landowners Decry State Dept. of Natural Resources' Enactment of Weak Carbon Capture Rules

Busload of advocates traveled to Indianapolis last week to testify at public hearing

The new rules were obviously written to please industrial polluters, including Wabash Valley Resources which has proposed injecting 1.67 million tons of carbon dioxide annually into an underground sequestration waste dump, part of its plan to produce what the company claims will be "low-carbon-intensity" anhydrous ammonia fertilizer.

The DNR's decision to adopt these rules comes on the heels of overwhelming opposition from landowners and community members targeted by risky carbon capture and storage projects. Last week, a busload of landowners and community members traveled to Indianapolis to testify in favor of stronger protections during a public hearing held by the DNR. They called out the proposed definitions as overly vague, and voiced concerns about eminent domain abuse, and potential leaks and contamination of water sources, while calling for verification of voluntary easements signed by landowners, and pushing for stronger insurance requirements for proposed CO2 injection wells.

"The Indiana DNR passing their proposed Carbon Sequestration rules is an absolute dereliction of duty," said **Whitney Boyce, Vigo County resident**. "They purposefully ignored all requests for safety, setbacks, and meaningful regulations and even refused to clarify the process for verifying the 60% voluntary easements required before allowing Wabash Valley Resources to use eminent domain to take our land. They held hearings and meetings hours from the communities directly impacted by the State's only CCS pilot project, and refused to post the agenda 48 hours in advance as per state law. They have created nothing but obstacles to block public engagement. Wabash Valley Resources has been sneaking around behind the scenes for years and the Statehouse has denied the community directly impacted by their pilot CCS experiment a seat at the table. Tonight's decision in Indiana was nothing short of prioritizing companies over people and profits over safety in their rush to sell-out citizens and make Indiana nothing more than a dumping ground. It is clear the people making the laws in Indiana do not understand the intricacies of the issues surrounding CCS and the very real risks these dumps will bring."

The bus trip by landowners was sponsored by the Indiana Action Team, a new state-based legal co-op. The IAT, which is also supported by Bold Education Fund, was created to pool the resources of landowners who oppose eminent domain and have concerns ranging from safety and leaks – like the recent leak from ADM's CCS facility in Illinois – to the wasteful 45Q tax credits that are the financial lynchpin for projects such as Wabash Valley Resources in Indiana, which is dependent on a $1.5 billion loan guarantee made by the Dept. of Energy during the Biden administration.

Emma Schmit, Bold Alliance's Pipeline Fighters Director, stated, "The final approval of these industry-favored regulations is a disservice to the people of Indiana. These rules don't regulate the carbon capture industry – they enable it, and put the land and lives of Hoosiers at risk in the process. Attorney General Rokita must deny these rules and force the DNR to develop rules that do not undermine the rights to private property and due process."

About Indiana Action Team:
The Indiana Action Team landowners' legal co-op works to educate landowners and to support organizing those who are opposed to eminent domain for private gain, and works with attorneys to file landowner legal challenges to proposed CO2 waste dump and pipeline projects, and lawsuits and appeals including constitutional challenges and condemnation litigation. (https://indianaactionteam.org)

About Bold Alliance:
The Bold Alliance is a network of "small and mighty" groups in rural states working to protect land and water. We fight fossil fuel projects, protect landowners against eminent domain abuse, and

# # #

WATCH: Indiana DNR meeting with public testimony and vote:

Background via Indiana Dept. of Natural Resources:

Agenda Iter

BEFORE THE
NATURAL RESOURCES COMMISSION
OF THE
STATE OF INDIANA

IN THE MATTER OF:

ADMINISTRATIVE RULES GOVERNING	)	**Administrative Cause**
CARBON SEQUESTRATION PROJECTS	)	**Number: 23-OG-027**
	)	
	)	**LSA Document #24-162(F)**

REPORT ON RULE PROCESSING, PUBLIC HEARING, AND HEARING OFFICER ANALYSIS WITH RECOMMENDATIONS REGARDING FINAL ACTION

1. RULE PROCESSING

For consideration as to final action, is the proposed added rule governing carbon sequestration projects at 312 IAC that otherwise qualifies as a rule charged by the Department of Natural Resources (the "Department").

The Natural Resources Commission (the "Commission") gave preliminary adoption to the proposed permanent rul March 18, 2025.

Whitney Wampler, Deputy General Counsel for the Administration Bureau for the Department submitted the prop rule language and regulatory analysis to the Indiana Office of Management and Budget (OMB) and Indiana State Budget Agency (SBA) for review and approval. By letter dated March 12, 2025, Lisa Hershman (OMB) and Chad Ranney (SBA) authorized the Department to proceed with the proposed rules as follows:

> Pursuant to the provisions of IC 4-22-2-22.8, the Office of Management and Budget and State Budget Ag have reviewed the proposed rule that adds Article 30 to Title 312 of the Indiana Administrative Code (0M #2025-06R), which you originally submitted on March 12, 2025. After reviewing the proposed rule, the recommendation of 0MB and SBA is that the rule changes be approved. DNR is authorized to commence public comment period(s).
>
> Furthermore, if you revise the proposed rule after this approval, you must resubmit the rule to 0MB and o

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PIPELINE FIGHTERS HUB: RESOURCES TO STOP RISKY FOSSIL FUEL PROJECTS

Charles Harvey testifies on Illinois carbon sequestration leak concerns

PUBLISHED ON: APR 28 2025

Written by: Callie Ayoub

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In March, MIT Civil and Environmental Engineering Professor Charles Harvey provided testimony in support of a bill that would limit the industrial injection of carbon dioxide into wells near the Mahomet Aquifer in Illinois.

concerns about potential contamination of the region's drinking water.

"The Mahomet Aquifer is legally designated as a sole source water supply, meaning it is the only available drinking water supply for a large portion of the state," Harvey explains. The aquifer serves 1 million residents in over one hundred communities, including hospitals, businesses, and farmers.

Pam Richart, Co-Director of Eco-Justice Collaborative, a non-profit in Champaign, Illinois focused on climate and environmental issues explains, "it was designated as a sole source aquifer in 2015 by the U.S. Environmental Protection Agency (EPA), which elevates the importance of the aquifer to the region and acknowledges that if it were to be polluted there is no alternate supply of water that is feasible."

There are fifteen carbon sequestration projects operating in the United States. ADM's Illinois site is unique in that it is not used for enhanced oil recovery, a process that injects carbon dioxide underground to extract additional crude oil, which is later burned, re-releasing CO2 into the atmosphere.

ADM's sequestration facility in Decatur is the only operating EPA-approved Class VI project in the country.

"Because the EPA doesn't monitor oil fields where all the other sequestration projects are using CO2 for enhanced oil recovery, this project is the only one that is monitored," he says. The other projects rely on self-reporting in the event of a leak.

The Mt. Simon sandstone formation in Illinois apparently makes the state an ideal location for holding sequestered carbon dioxide. "The Mt. Simon is both large and porous, making it an excellent site for CO2 injection," Harvey says, "However, it lies beneath a sole source drinking water aquifer and now, despite industry assurances that it would not leak, it has leaked buoyant CO2 upward into this aquifer."

Carbon capture and storage (CCS), which aims to reduce emissions by capturing CO2 before it enters the atmosphere and storing it underground, has been widely promoted by the fossil fuel industry. However, the approach has faced growing scrutiny due to concerns such as high costs, significant energy demands, and continued reliance on fossil fuels.

"It's like we're all looking for the silver bullet to solve climate change, Richart says, but CCS is anything but that. "We try to find a way to talk about the fact that these are taxpayer subsidized projects that harm people, their land, and their water as well as risk their health and safety. Plus, CCS diverts funding for energy efficiency, renewables, and other solutions we know can curb emissions."

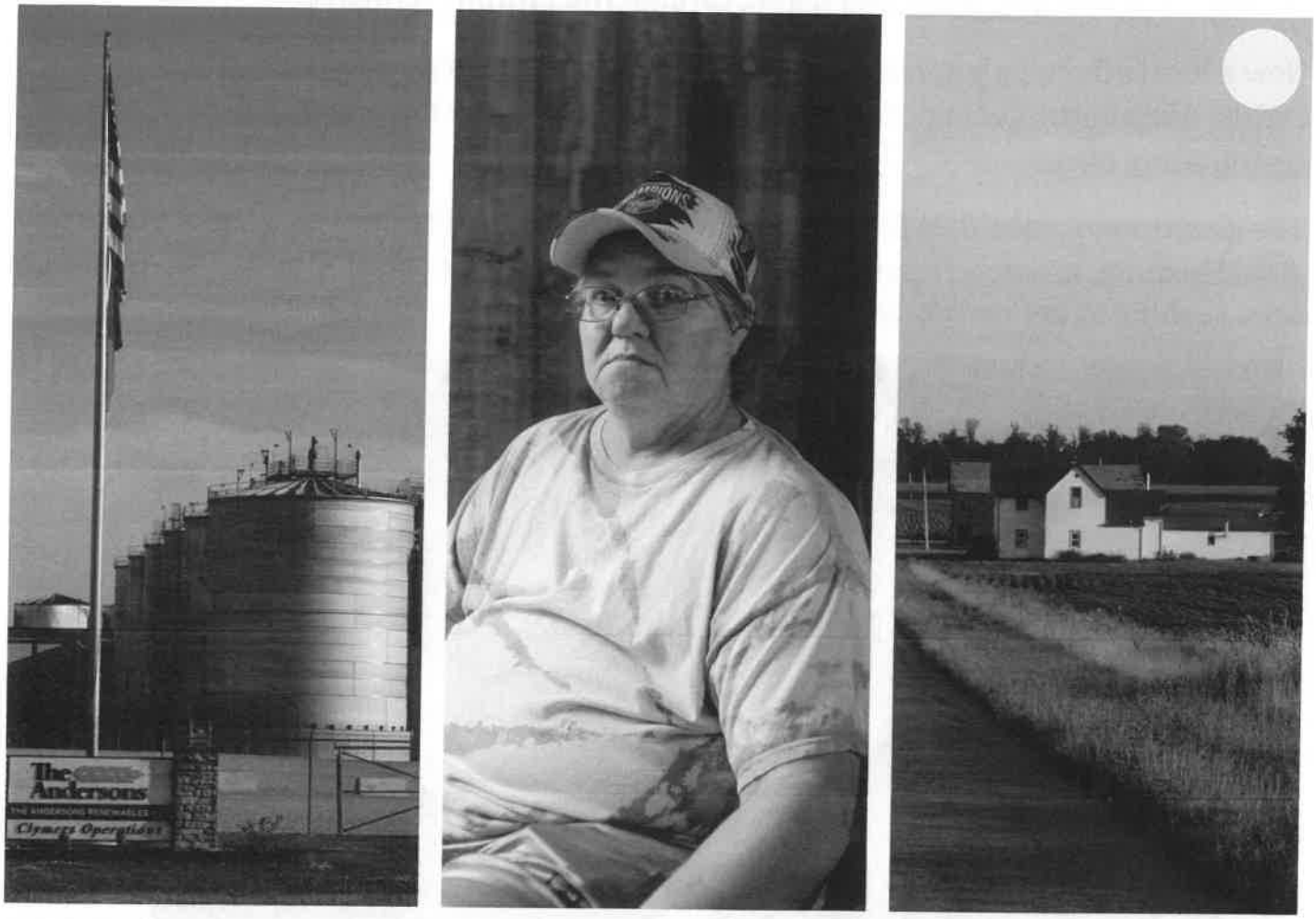
In 2024, Harvey, along with leading climate experts, formed the Science Roundtable on Carbon Capture and Storage. The roundtable aims to provide a unified voice among technical experts on the challenges of CCS, elevating the science and data for decision makers, press, and other stakeholders. None of the roundtable members accept funding from oil companies, enabling them to speak with a unique and unbiased voice.

The Illinois State Senate unanimously approved the bill that bans the injection of CO2 through and storage of it under the Mahomet Aquifer. The bill will now move to the Illinois House for a vote.

America's dirty divide Carbon capture and storage (CCS)

'Huge wave' of carbon storage projects causes alarm in small-town USA as oil firms eye billions in subsidies

Dozens of projects are in development across US despite concerns over environmental and health risks



L-R: The Andersons ethanol plant and grain elevator in Clymers, Indiana. Melissa Harrison sits in her 'She Shed' behind her home in Clymers. Farmland near the Andersons ethanol plant. Composite: Kaiti Sullivan/The Guardian

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the guardian .org

About this content

Erin McCormick *in Cass county, Indiana, with photographs by Kaiti Sullivan*

Sun 12 Jul 2026 08.00 EDT

Prefer the Guardian on Google

The plan to bury carbon under remote Indiana farmland is supposed to be a slam dunk for the climate, according to its supporters – all generously funded by US tax dollars.

But as far as Melissa Harrison and some other residents of Clymers, Indiana, are concerned, it just might be the end of their town. "This is our place," she says. Generations of her family are buried in the cemetery, and she is raising her five grandchildren in one of several dozen white-clapboard homes among cornfields and industrial plants serving the farming industry.

Now a local ethanol plant has spearheaded a project to bury vast stores of carbon deep in the geologic formation that runs under the town and surrounding farms.

The government subsidies for the plan, which is supposed to help prevent global heating, are so generous that companies all over the country have been rushing to get permission for similar projects.

Melissa Harrison, left, holds her grandson, Aedan, while her grandchildren, Michael (left), Derris (center) and Mary Lee, play outside their home in Clymers, Indiana, on 7 July 2026.

But residents around some of these carbon sequestration projects are organizing to stop them, making Clymers a center of emerging national tensions around these projects.

While international climate monitors say carbon sequestration projects could be secondary tools to help contain global warming, they also say the main focus must be on urgent and deep cuts to fossil fuels. Some environmental

groups question the benefits of carbon sequestration and are concerned it could delay the transition to clean energy and pose risks to surrounding communities.

Harrison said the town of Clymers was already overburdened by hazards from industrial agriculture facilities including a fertilizer supplier, a hazardous waste recycling company and the giant ethanol plant that is proposing the project. She said the community faced contaminated well water, a lack of sewage facilities and high poverty rates.

Warmly remembered as once having been a thriving "heartland" community with a beautiful white church, two grocery stores, a Chevy dealer and a diner, the town is now struggling. Its school is closed; the old Methodist church has been demolished and the playground is surrounded by fertilizer tanks on trailers, which the fertilizer company rents to nearby farms.

Harrison, like other residents in the area, received a letter about the project. Some were asked to accept $150 a year in exchange for having the carbon sink under their properties.

Melissa Harrison visits a family burial site in the Clymers cemetery on 7 July 2026. Most of her deceased family members are buried here.

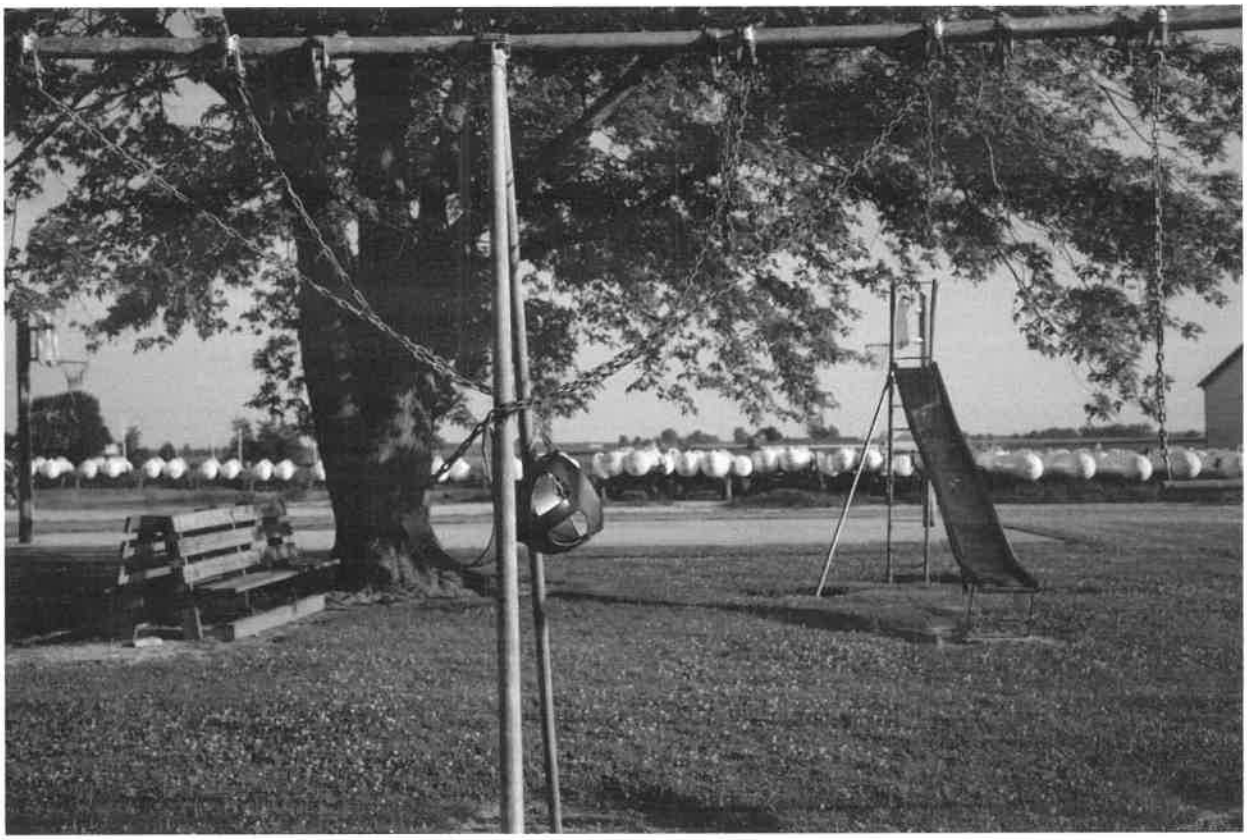
"If they make Clymers bad enough that no one wants to live here, they can take over the whole town, real cheap," she said.

In a statement to the Guardian, the company proposing the project, the Andersons Renewables, said it "is a safe, established technology, with a rigorous permitting, engineering, and monitoring process to protect groundwater, public health, and the surrounding environment".

"The proposed project would capture carbon dioxide from the ethanol production process, compress it, and then inject it deep underground, more than 3,000 feet, into geologic formations identified for permanent storage," said the statement.

"We were able to determine the site's suitability through seismic analysis and by drilling a test well," it added.

The company, which was partly owned by a subsidiary of Marathon Oil at the time it proposed the project, said in its statement that it understood why residents might be concerned, but it planned to work transparently with the community to allay those worries.



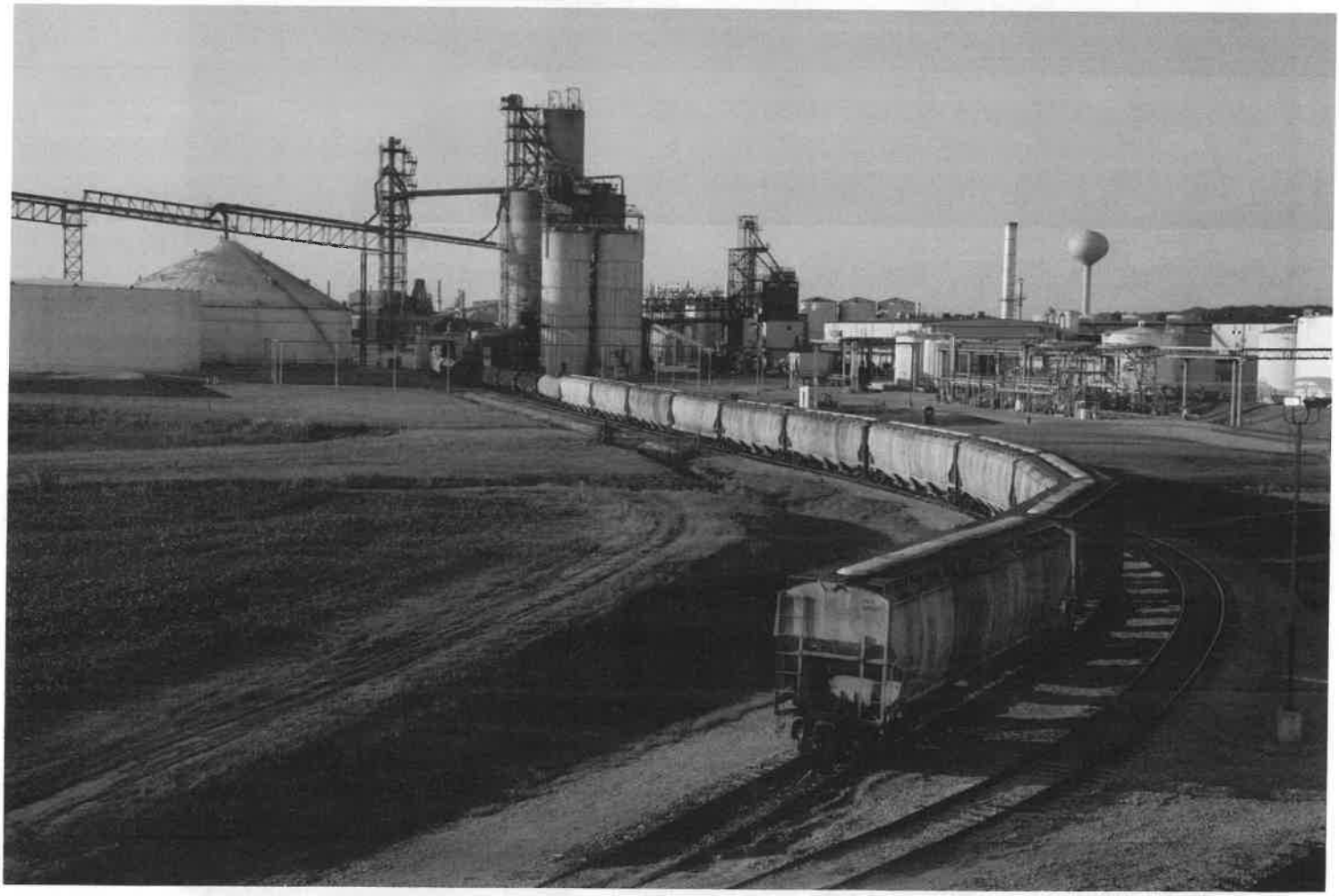
Anhydrous ammonia is stored near a park in Clymers, Indiana, on 7 July 2026.

The undertaking is one of dozens of carbon sequestration projects expected to be given the green light for construction in the US by the Environmental Protection Agency and state environmental regulators in the next year - as a flood of corporate permit applications reach the end of their approval processes. Oil industry companies are often sponsors and benefactors of these projects.

Carbon sequestration involves capturing industrial CO_2 emissions that would normally be vented to the atmosphere before they can contribute to global

heating, and burying them in rock formations thousands of feet underground for what proponents say is permanent storage.

The Intergovernmental Panel on Climate Change has said carbon capture storage (CCS) is one mitigation option that could help keep global heating in check, assuming it supports deep fossil fuel cuts, but has warned it should not be over-relied on. Both Democratic and Republican presidential administrations have supported such plans in past years. The Biden administration authorized a lucrative tax credit reimbursement program for them as part of the Inflation Reduction Act.



The Andersons ethanol plant and grain elevator in Clymers, Indiana, on 7 July 2026.

The Trump administration, which has called the climate crisis "a hoax" and canceled funding for many other types of climate projects, continued this tax credit, which often benefits energy companies that are already using underground technology such as fracking. It offers companies $85 in transferable tax credits for each ton of point-source carbon stored - a bounty that has set off what some call "a carbon-capture gold rush".

Since even the smallest projects expect to store hundreds of thousands of tons of carbon each year, the tax credits could be hugely profitable, said Brad Johnston, an analyst with Enverus, an energy industry market research company and data company that tracks permits for this type of project. Many

are proposed for ethanol plants, which emit a nearly pure stream of CO_2, making their emissions simpler to capture and put underground.

While only a handful of projects are operating, a "huge wave" is about to be approved, Johnston said.

The Cass county fair in Logansport, Indiana, on 7 July 2026.

Experts say the money brought in to these companies by tax credits from these carbon projects can rival the revenues from selling the actual ethanol itself, thereby potentially doubling a plant's earnings.

Many environmental groups criticize the projects, saying they merely subsidize oil and gas industry companies and don't reliably cut emissions at scale.

For instance, a small project that sequesters 200,000 metric tons of carbon per year can earn $17m annually through a tax credit called 45Q. Larger projects plan to sequester tens of millions of tons of carbon, said Kerwin Olson, executive director of the Indiana group Citizens Action Coalition, which has helped residents in the state organize against the many projects proposed there.

"You can do the math," he said. "That is a lot of cash - an enormous amount of cash."

"You're talking billions of dollars."

Main Street in Clymers, Indiana.

Environmental experts say the risks of carbon storage include earthquakes, water table contamination and potentially deadly carbon leaks, and point to several cases where carbon has leaked.

In 2024, the nation's first commercial carbon capture project, under a lake that provides drinking water for large parts of central Illinois, developed two

leaks. The state subsequently banned new CCS projects under one of the state's biggest aquifers.

In 2020, a pipeline carrying carbon dioxide ruptured in rural Mississippi, creating a mass poisoning that resulted in 45 people being hospitalized and 200 evacuated. Emergency responders found people lying on the ground unable to breathe and didn't know what was happening. "It looked like you were going through the zombie apocalypse," Jack Willingham, emergency director for the affected county, told NPR.

Melissa Harrison outside her home in Clymers, Indiana.

Charles Harvey, a professor of civil and environmental engineering at MIT, helped to start one of the world's first companies devoted to sequestering carbon to prevent global heating in the early 2000s. But since then, he has

become a staunch opponent of the strategy, and acknowledged experiencing guilt akin to what J Robert Oppenheimer felt over inventing the atomic bomb.

"It's just the stupidest way to reduce emissions," said Harvey. Oil companies are lobbying hard for the projects, he said, but he believes CO_2 emissions could be best tackled if the money was spent on renewable energy.

"It is loved by the industry because it's a subsidy for whatever they're already doing," he said.

Johnston, the Enverus analyst, said that, given the setbacks caused by the Illinois leaks, his sense was that companies were being extra careful to engineer their projects to avoid any further problems.

"I think any additional setback from a leak or a failure of one of these wells would be pretty detrimental to the CCS industry," he said. "So I think a lot of these operators are very diligent about doing it right and probably overbuilding a lot of these systems."

Farmland near the Andersons ethanol plant and grain elevator in Clymers, Indiana.

The Clymers project's sponsoring companies called a meeting of residents and landowners in the area and told them that the carbon storage was perfectly safe and couldn't leak.

"I said that's bullcrap. I'm worried about my well," said farmer Dennis Crume, who refused to sign the form offering him $150 an acre to accept the

plan. But Indiana state law essentially strips individual landowners of the right to reject these proposals, experts say.

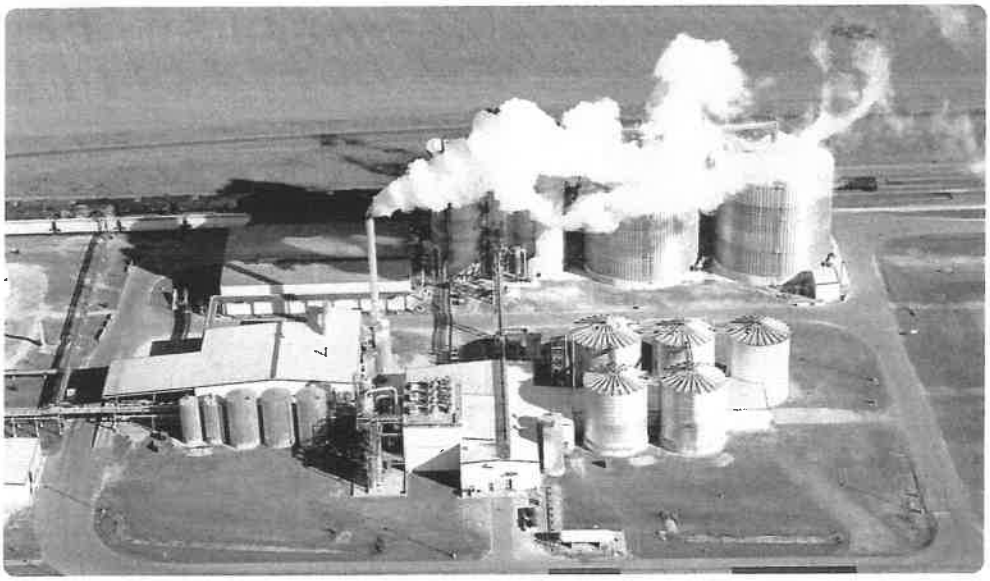
Crume grows soybeans and corn on several plots of land skirting Clymers, some of which he leases from other owners. He raises a few cows in a grassy field behind his house and tries to grow everything his family eats in his garden. But he worries about the pollution he sees cropping up all around him.

"I'm trying to look out for our grandkids," said Crume, who has 11 of them living nearby. "We've got to do something for the environment."

Most viewed

CARBON pipelines

By **Alex Gray**
New Products Editor
alex.gray@agriculture.com



GLOSSARY:
CCS: Carbon capture and sequestration
CI: Carbon intensity
CO2: Carbon dioxide
GHG: Greenhouse gas
GREET: The Department of Energy's Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies model
IRA: Inflation Reduction Act of 2022
LUC: Land-use changes
NAS: National Academy of Science
RFA: Renewable Fuels Association
RFS: Renewable Fuel Standard

From Well to Wheels

A look at ethanol's life cycle emissions.

Corn ethanol has been the standard for biofuels in the United States since the Renewable Fuel Standard (RFS) was introduced in 2005.

Carbon pipelines have been positioned as the next step the ethanol industry needs to sequester carbon, receive tax credits, and be poised for growth, including in new areas such as sustainable aviation fuel. In our series on carbon pipelines, we have covered how companies are working to establish pipelines across the Midwest. We also looked at how farmers can navigate eminent domain use when pipeline construction comes closer to reality.

For this story, we set out to directly compare the life cycle of greenhouse gas (GHG) emissions — from well to wheels — of ethanol and gasoline, and how carbon pipelines factor into the future of ethanol as a viable, low-emission fuel.

This turned out to be more difficult than expected. Few recent independent studies have been conducted removed from the goal of adopting ethanol as a clean energy source in the U.S.

There are so many different approaches to measure well-to-wheel emissions, it's almost impossible to find an agreed-upon carbon intensity (CI) score among various studies and stakeholders. The U.S. government uses the Department of Energy's Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) model.

Mark Heckman is vice president of sales and marketing at Edeniq, Inc., a California-based biotechnology company, and formerly ethanol services director at EcoEngineers, an Iowa-based engineering consultant. "In the carbon world, people talk about system boundaries — the handoff of where emission measurement starts and when it stops," Heckman said. "The GREET model is a quick tool that pulls all these emission factors into it, and uses the science that's coming out of the Department of Energy and Argonne National Laboratory to state acceptable practices or levels to use, if you take farm practices as a whole."

Emissions From Well to Wheels

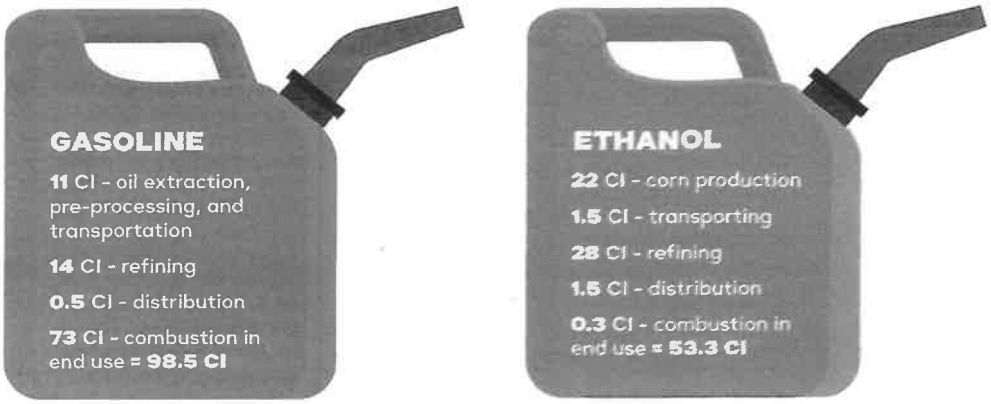
Congress created the RFS clean fuel policy in 2005 and expanded it with the Energy Independence and Security Act of 2007, with the goal of reducing GHG emissions and U.S. reliance on imported oil. President Biden's Inflation Reduction Act (IRA) of 2022 made reducing CI via carbon capture and sequestration (CCS), either on-site or by pipeline transport, vital to access tax credits for ethanol production.

Typically, carbon dioxide emissions are standardized to Carbon Intensity (CI) scores. CI is measured in →

Photography: BanksPhotos, Getty Images

This is the third part in our series on carbon pipelines. Read the first article by scanning the smart code.

THE LIFE CYCLE EMISSIONS FOR GASOLINE AND ETHANOL FROM "WELL TO WHEELS"



Gasoline: The oil extraction, pre-processing, and transportation to the refinery generates 11 CI. Refining generates 14 CI. Distribution is another 0.5 CI. Combustion in end-use generates 73 CI. This results in a total **98.5 CI.**

Ethanol: Corn production generates 22 CI. Transporting the corn generates 1.5 CI. Production at the ethanol refinery generates 28 CI. Distribution of ethanol generates 1.5 CI. Combustion in end-use generates 0.3 CI. This results in a total **53.3 CI.**

grams of carbon dioxide equivalent per megajoule of energy.

To comply with the RFS's required GHG emission reductions, renewable fuels derived from corn must have a CI at least 20% below the gasoline baseline of 93.1 CI the RFS established in 2005. The RFS's 2010 regulatory impact analysis projected ethanol fuel's life cycle carbon emissions would have a 73.2 CI by 2022, a 21.4% reduction from gasoline, in line with the reduction target. The baseline CI estimate for ethanol's life cycle emissions is 53.6, which aligns with the Renewable Fuels Association (RFA) assessment, a 2024 study by the nonprofit think tank EFI Foundation, and a 2019 study by the USDA. The RFA breaks down the life cycle emissions for gasoline and ethanol from well to wheels as follows:

Gasoline: The oil extraction, pre-processing, and transportation to the refinery generates 11 CI. Refining generates 14 CI. Distribution is another 0.5 CI. Combustion in end-use generates 73 CI. This results in a total 98.5 CI.

Ethanol: Corn production generates 22 CI. Transporting the corn generates 1.5 CI. Production at the ethanol refinery generates 28 CI. Distribution of ethanol generates 1.5 CI. Combustion in end-use generates 0.3 CI. This results in a total 53.3 CI.

The EFI Foundation reported ethanol facilities' CI scores ranging from 48–68 CI. Ethanol fermentation emissions CCS could decrease this by 30.5 CI.

The study estimates ethanol emissions' CCS cost to be $37 per ton of carbon dioxide (CO_2) — lower than the $85 per ton the 45Q tax credit offers.

"There are essentially three components to measure," Heckman said. "The energy to produce the crop, the energy to get the crop to the production plant, and then the transportation costs to get the feedstock to the dispenser."

Heckman added that he believes pipelines are imperative for ethanol to eventually bring the carbon cycle to net-zero.

"If you're burning ethanol, you're taking carbon that's been trapped someplace and putting it into the atmosphere," Heckman said. "Somehow, some way, we've gotta get it back into the ground."

Research Studies

A USDA study published in 2019 found greenhouse gas emissions from corn ethanol were 39%–43% lower than gasoline, about a 56.6 CI score compared with the gasoline baseline. The score could be reduced as much as 43% when refined at natural-gas-powered refineries. A major contributor to the reduction was an updated assessment of land use change (LUC).

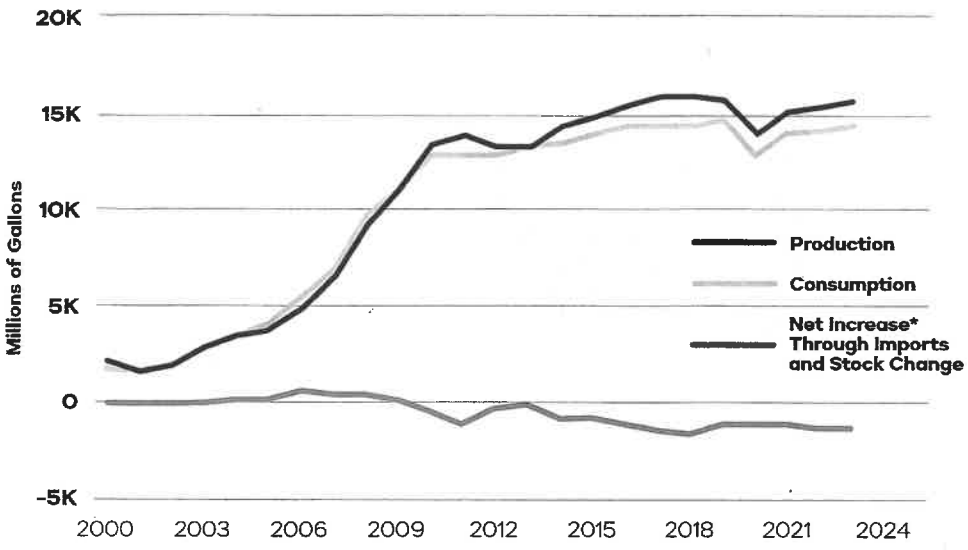
While previous estimates projected farmers bringing more land into production as a result of increased corn prices, the USDA study found only a modest increase. This takes into account additional refinery improvements, as well as farm practices such as reduced tillage and cover crops. The study also projects possible scenarios showing ethanol life cycle emissions becoming 47%–70% lower than gasoline.

Conversely, ethanol production spurred by the RFS likely had at least 24% higher GHG emissions than standard gasoline, according to a National Academy of Sciences (NAS) study published in 2022. The study solely looked at the effects of →

Source: Renewable Fuels Association

Illustration: Kolonko, Getty Images

U.S. PRODUCTION, CONSUMPTION, AND TRADE OF ETHANOL



LUC, and the causal change that would have on emissions projected by the RFS's 2010 regulatory impact analysis.

This research found the RFS increased corn prices by 30%, and the prices of other crops by 20%. This expanded U.S. corn production by 6.9 million acres, and total cropland by 5.1 million acres. Both were higher than the USDA's 2019 research of 3.65 million acres and 1.44 million acres, respectively. These changes also led to 3%–8% increased annual nationwide fertilizer use, and increased water quality degradants 3%–5%.

With their analysis, the score for ethanol increased to 115.7 CI, 24% higher than the baseline 93.1 CI score for gasoline established in 2005 — failing to meet the RFS's proposed 20% reduction. Even accounting for a 30.5 CI reduction from CCS, this would only lower ethanol to 85.2 CI, about an 8.5% reduction from gasoline.

"Domestic LUC emissions spurred by the RFS undermine the GHG benefits of using ethanol as transportation fuel," the NAS study states.

"In our case, we looked at the RFS policy associated with ethanol production and said, 'What impact did that policy in particular have on crop prices?'" said Tyler Lark, co-author of the article and a scientist at the University of Wisconsin-Madison's Center for Sustainability and the Global Environment. "We looked at the influence crop prices had on LUC and resulting emissions, as well as the carbon intensity in the fuel."

Lark said this research centered on the impacts from the growth of land use in ethanol production. Maintaining current production levels won't induce additional land use or further alter the product's CI. The U.S. has increased ethanol production capacity from 13.6 billion gallons per year in 2011 to 18 billion gallons per year as of January 2024, according to the U.S. Energy Information Administration.

U.S. renewable fuel associations largely discredited the National Academy of Science study. The RFA cited a 2021 study by the Argonne National Laboratory, showing a reduction in ethanol emissions from 58 CI in 2005 to 45 CI in 2019 — a 44% reduction from baseline gasoline emissions. The RFA also sourced farmland data from the USDA showing the amount of land planted for corn in 2021 was essentially the same as in 2007, before the RFS revision was adopted.

The RFA's largest criticism fell on the NAS study's methodology, saying its use of "error-prone" USDA Cropland Data Layer satellite imagery provided unreliable data. The study claims farmers converted native grasslands with high carbon storage into corn production because of RFS, but the imagery cannot distinguish land covered in grass from pastureland, hay grass, Conservation Reserve Program land, or native grassland. •

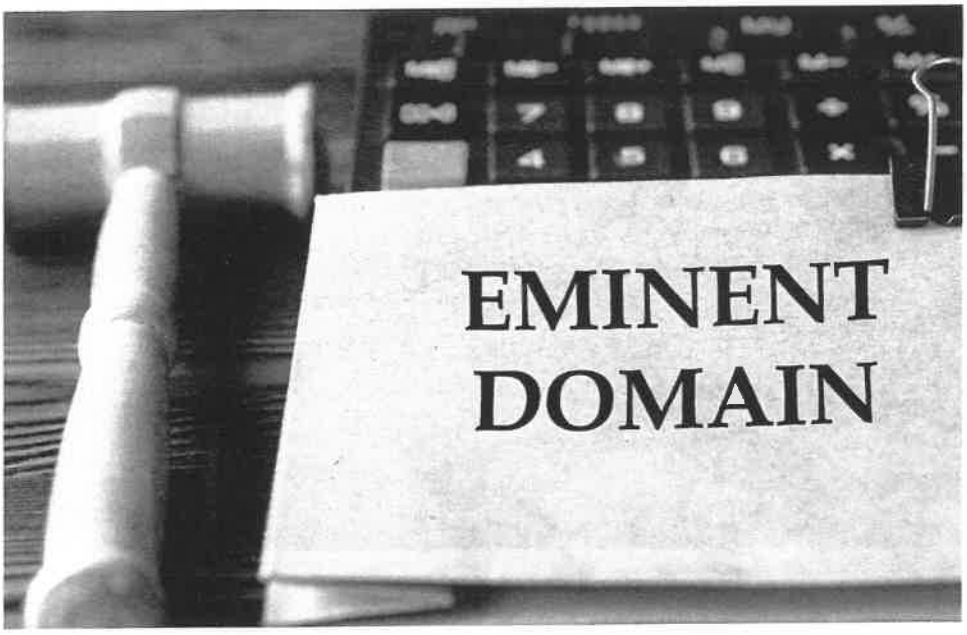
Tax Credit Refresher

The 45Q tax credit was expanded under President Biden's Inflation Reduction Act (IRA) in 2022. This credit incentivizes carbon capture and sequestration (CCS), with the government providing $85 per metric ton (17¢ per gallon of ethanol) for carbon dioxide (CO2) permanently sequestered underground, and $60 per metric ton (12¢ per gallon of ethanol) for CO2 used for enhanced oil recovery or other industrial uses, according to documentation from the Iowa Corn Growers Association.

The 45Z tax credit specifically incentivizes fuel producers to lower their CI scores to 50 or lower. For on-road vehicles, pending final regulations, 45Z offers 2¢ per gallon up to $1 per gallon for every CI point reduction below 50 CI. For sustainable aviation fuel, the 45Z offers 3½¢ per gallon, up to $1.75 per gallon for every CI point reduction below 50 CI. •

* Last updated October 2024
Source: U.S. Energy Information Administration

This is the second part in our series on carbon pipelines. Read the first article by scanning the smartcode.



THE BATTLE OVER LAND

Navigating eminent domain use for carbon pipelines.

By **Cassidy Walter,** Business Management Editor
cassidy.walter@agriculture.com | @CassidyARWalter

The question of eminent domain has hung like a black cloud over carbon capture and sequestration (CCS) pipeline projects. This guide attempts to clear up some of the fog on the topic.

What Is Eminent Domain?

"Eminent domain has been a part of the United States since the Constitution was ratified," says Rusty Rumley, senior staff attorney at the National Agricultural Law Center. The Fifth Amendment of the U.S. Constitution says "... nor shall private property be taken for public use, without just compensation."

"That's actually talking about the power of eminent domain," Rumley says.

Rumley defines eminent domain — also known as condemnation — as the right of the government to acquire property for the public good in exchange for just compensation.

The definition of "public use" expanded in 2005, when the U.S. Supreme Court ruled eminent domain could be used for private projects that would foster a community's economic benefit. Following this ruling, Rumley says, some states began changing their laws to prevent eminent domain from being used this way. Today, laws vary by state.

Follow the Money

Some question if it is legal for private companies to use eminent domain to benefit financially. Kristine Tidgren, director of the Center for Agricultural Law and Taxation at Iowa State University, explains the question of profit is not relevant in determining if eminent domain can be used. The pertinent questions are:

- **Is the project for a public use such as a road or park?/Is the company a common carrier?**
- **Are landowners being justly compensated?**

If You Face Eminent Domain

Because eminent domain laws vary, check with your attorney if you have specific questions. That said, here are some tips from experts, and a farmer who went through the process.

- **Don't ignore it.**

Rumley says if you are approached about a project and you are not coming together on an easement, don't think refusing to sign something will get rid of it.

"If they're going to use eminent domain and they're at the point where they can ... they'll take the land, and then they'll worry about compensation later on," he says. "The farmer will be compensated; whether they think it's fair or not, that's for interpretation."

- **Understand the process.**

Processes will vary by state, but let's look at Iowa as a case study.

By Iowa law, each county board of supervisors chooses at least 28 individuals to serve on compensation commissions. When a case arises, six are chosen for the deciding commission. The commission convenes a public hearing at which the landowner has an opportunity to speak.

Ultimately, Tidgren says, the commission must decide the difference between the land's fair market value before and after the easement. If either party is unsatisfied with the commission's decision, they can appeal through the courts.

Seek legal counsel to gain a deeper understanding of the process in your area.

- **Don't fear it.**

Garth Griffin, a farmer from New Hampton, Iowa, went through an eminent domain proceeding more than 20 years ago, when ▸

Photography: Zhanna Hapanovich, Getty Images

a road-expansion project was set to cut through his property. He says he was offered less compensation than businesses in town. The compensation commission agreed that a higher payment was justified.

His legal fees were also covered. Iowa law stipulates that if the commission finds the property owner is due more than 10% over what was originally offered, the party seeking the condemnation must also cover the property owner's legal fees in addition to the cost of an appraisal.

Griffin says farmers shouldn't fear the process if they believe the offered compensation isn't fair.

• Not a question of if, but how much

In most cases, Rumley says, it is clear the project in question has the right to use eminent domain and it is difficult to stop it, such as with public roads. Typically the dispute is over the level of compensation. And there is a limited answer.

"[The compensation commission doesn't] have the right to say, 'Oh, we feel bad for you; we're going to give you a windfall,'" Tidgren says. "They have to stick with fair market value."

The Quandary of Carbon Pipelines

For CCS pipelines, Tidgren and Rumley agree the question of the right to use eminent domain is largely unanswered.

In Iowa the answer appears to be yes. In late August the Iowa Utilities Commission (IUC) granted Summit Carbon Solutions, a company seeking to build a multi-state CCS pipeline, a construction permit.

In its decision the IUC cited Iowa Supreme Court case precedent asserting eminent domain use is allowed only for transferring private property to public ownership, such as in the case of a road or hospital, or to a private entity that is a common carrier. The IUC considered several factors before deciding the common carrier definition applied to Summit based on Iowa law and case precedent.

"... Summit Carbon is a 'for hire' company with its primary business being the transportation of carbon dioxide for the independent ethanol plants and those who will do business with Summit Carbon under the transportation service agreement or as a walk-up shipper," the IUC concluded.

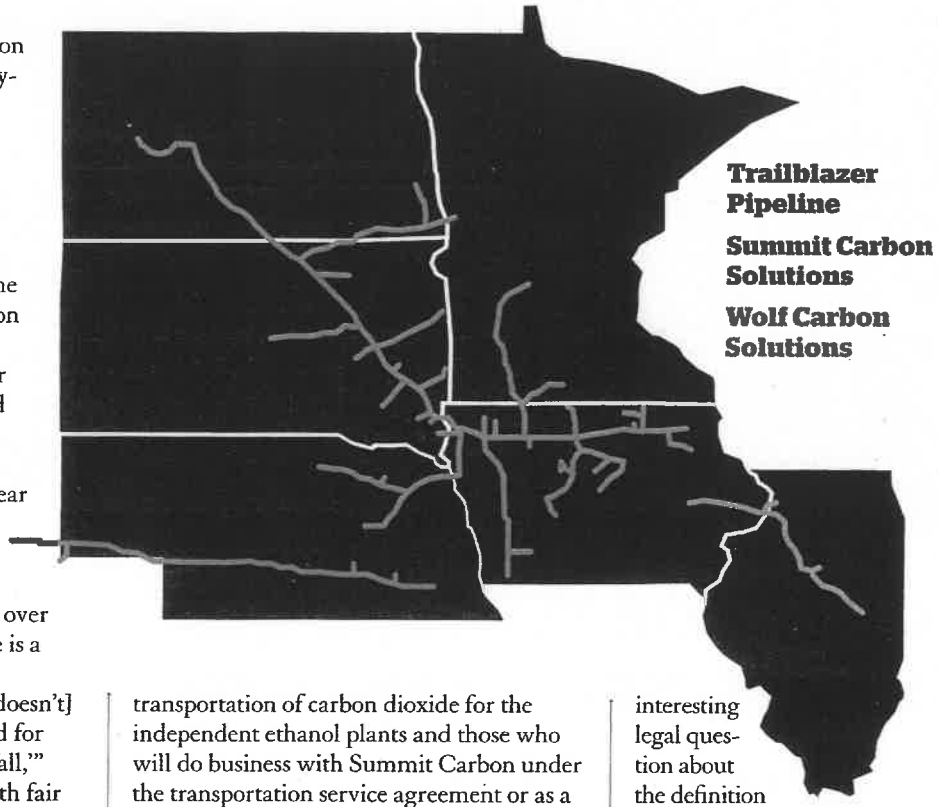
Summit faces the question of whether it qualifies to use eminent domain in each state in which it seeks to build, based on those states' laws. The IUC also ruled Summit cannot start construction in Iowa until South Dakota and North Dakota — two other states slated to house the pipeline — have also approved construction.

• Up for debate

Tidgren says while being deemed a common carrier means the company is open to public use of its transportation services, traditionally there is a public market for the commodity being transported. For example there is a public market for electricity or crude oil. "This project is designed to transport CO2 from ethanol plants to North Dakota for permanent storage, pursuant to private contracts," she says. "It is unclear whether a public market for this CO2 transport will arise outside of the private contracts, even if the pipeline offers to ship for the public." She says this raises an interesting legal question about the definition of a common carrier the courts will ultimately answer.

Rumley echo's Tidgren's sentiment. "The argument for common carriers," he says, "is: 'You may not like the electric line going through your property, but everybody likes having electricity, and you're benefiting yourself and everybody else by putting up with electric lines coming through.' This one is a little bit trickier.... The companies are making the argument that they're benefiting society as a whole because they're taking carbon dioxide out of the air. But you don't have that long, traditional usage, like you do with utilities." SF

PROPOSED MIDWEST CO2 PIPELINE PROJECTS



Map: Summit Carbon Solutions website; Iowa Renewable Fuels Association, Comparative Economics of Carbon Sequestration for Iowa Ethanol Plants. Prepared by Decision Innovation Solutions, LLC, 2023

Margaret Keen gave Ohio unspoiled land. 28 years later, state allowing it to be violated

Briones Bedell
Updated Wed, April 3, 2024 at 4:46 PM EDT
3 min read
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Since the Commission decided to open our already-limited public lands to the oil and gas industry, more and more requests to drill have been submitted.

Trust being broken

This 2023 file photos shows a well pad in Guernsey County. Ohio is opening up more than 8,200 acres of a wildlife area in southeastern Ohio and another 500 acres of Salt Fork State Park for fracking

Take the example of the 84-acre Keen Wildlife Area. Established in 1996 with land from the estate of Margaret Keen, the preserve is used for hiking, nature study, birdwatching, and hunting, giving Ohioans priceless opportunities to recreate in our natural spaces.

A private citizen entrusted this land to our state under the assumption that it would be preserved for the benefit of the ecosystem and the people who access it.

It shouldn't happen again. One of worst methane gas leaks in US history happened in Ohio.

Only 28 years later, that commitment has been walked back by the opening of this preserve to leasing nominations from the fracking industry.

What is fracking?

It has become clear that fracking is not just an environmental issue. It is also a moral one, and it is clear that this decision is a grave misuse of Ohio's public lands.

Fracking is the process of extracting natural gas from under the ground, and emissions from this fossil fuel produce methane, a chemical 80 times more effective at trapping heat in the atmosphere than carbon dioxide.

The fracking process can contaminate drinking water and soil, exposing communities to toxins linked to cancers, endocrine disorders, asthma, and complications in pregnancy. It threatens our air quality. The heavy, loud, and ugly machinery used in fracking operations will disturb wildlife and decrease the natural beauty of our landscapes.

Officials must understand the danger

A fracking explosion in Belmont County in February 2018 created one of the worst methane leaks in U.S. history. For 20 days after workers lost control of the horizontal gas well, a raging fire released harmful methane emissions into the air around the eastern Ohio community. [Provided Ohio State Highway Patrol Aviation Section]
More

Our decision-makers now rank the interests of out-of-state fossil fuel corporations above Ohioans' rights to unspoiled natural spaces.

The request to frack in the 18,0011-acre Egypt Valley Wildlife Area in Belmont County is as disappointing as what is planned for Keen.

Conservationist groups — including the Conservation Fund, Ducks Unlimited, the National Wild Turkey Federation, and the Ruffed Grouse Society — banded together to create this preserve.

A park composed of land recovering from extensive surface coal-mining, the recent proposition to begin fracking on this preserve adds insult to injury. It hampers decades of efforts to restore critical habitat, reintroduce native plant and animal populations, and provide recreational space.

Briones Bedell

We protect public lands for practical reasons, like carbon sequestration, habitat restoration, and tourism.

But the intangible things that nature preserves provide us — respite from the troubles of everyday life, connection with the world around us, appreciation of our natural heritage — are just as valuable.

Fracking on our public lands is a bad deal for people and the planet alike. It's time our decision-makers understand this.

Briones Bedell is a nonprofit fundraiser and communications professional residing in Columbus.

This article originally appeared on The Columbus Dispatch: Fracking in Ohio betraying trust of those who gifted cherished land

Ranchers reported abandoned oil wells spewing wastewater. A new study blames fracking.

An SMU study is the first scientific proof of a phenomenon local landowners have long warned was occurring.

BY DYLAN BADDOUR, INSIDE CLIMATE NEWS AND **CARLOS NOGUERAS RAMOS** THE TEXAS TRIBUNEAUG. 7, 2024, 5:00 A.M. CENTRALUPDATED AUG. 7, 2024, 5:00 A.M. CENTRAL

Fracking wastewater, injected underground for permanent disposal, traveled 12 miles through geological faults before bursting to the surface through a previously plugged West Texas oil well in 2022, according to a new study from Southern Methodist University.

It's the first study to draw specific links between wastewater injection and recent blowouts in the Permian Basin, the nation's top producing oil field, where old oil wells have lately begun to spray salty water.

It raises concerns about the possibility of widespread groundwater contamination in West Texas and increases the urgency for oil producers to find alternative outlets for the millions of gallons of toxic wastewater that come from Permian Basin oil wells every day.

"We established a significant link between wastewater injection and oil well blowouts in the Permian Basin," wrote the authors of the study, funded in part by NASA and published last month in the journal Geophysical Research Letters. The finding suggests "a potential for more blowouts in the near future," it said.

For years, the Texas agency that regulates the oil and gas extraction industry has refrained from putting forth an explanation for the blowout phenomenon, even as a chorus of local landowners alleged that wastewater injections were driving the flows of gassy brine onto the surface of their properties since about 2022.

Injection disposal is currently the primary outlet for the tremendous amount of oilfield wastewater, also known as produced water, that flows from fracked oil wells in West Texas. Thousands of injection wells dot the Permian Basin, each reviewed and permitted by Texas' oilfield regulator, the Texas Railroad Commission.

Oil producers are exploring alternatives — a small portion of produced water is reused in fracking, and Texas is in the process of permitting facilities that will treat produced water and release it into rivers and streams. Still, underground injection remains the cheapest and most popular method by far.

A scientific connection has solidified between the practice of injection disposal and the increasing strength and frequency of earthquakes nearby. In the Permian Basin, a steady crescendo of tremors peaked last November with magnitude 5.4 earthquake, the state's strongest in 30 years, triggering heightened restrictions on injections in the area.

The link between injections and surface blowouts, however, has remained unconfirmed, despite widespread suspicions. The latest study marks a big step forward in scientific documentation.

"It just validates what we've been saying," Sarah Stogner, an oil and gas attorney who ran an unsuccessful campaign for a seat on the Railroad Commission in 2022, said about the latest study.

For the last three years, Stogner has represented the Antina Cattle Ranch, where dozens of abandoned oil wells have been spraying back to life. Stogner persistently alleged that nearby wastewater injection was responsible. But she couldn't prove it.

Now a scientific consensus is beginning to fall in behind her.

"Our work independently comes to this same conclusion in different areas [of the Permian Basin]," said Katie Smye, a geologist with the Center for Injection and Seismicity Research at the University of Texas at Austin, citing several upcoming papers she and her colleagues will release at major geoscience conferences in the coming year. "There is a link between injection and surface flows in some cases."

In a study published December 2023, Smye and others reported "linear surface deformation features" in parts of the Permian Basin — the ground was swelling along channels that suggested pressure moving through underground faults. Some of those were ancient geological faults, Smye said; others appeared to be created by recent human activity. Many of them were growing, heaving and bulging, the research showed.

When that channel of underground pressure hits an old oil well that is broken or improperly plugged, it can shoot to the surface.

"This is reaching a critical point in the Permian Basin," Smye said. "The scale of injection needs is increasing."

About 15 million barrels, or 630 million gallons, of produced water are injected for disposal in the Permian Basin every day, Smye said.

A Railroad Commission spokesperson, Patty Ramon, said in a statement the agency is "talking to operators in the Crane County area regarding geology and other data they maintain, reviewing satellite imagery, and analyzing RRC records such as well plugging information.

"We will be continuing this type of analysis in our commitment to ensuring environmental protection," Ramon said.

Blowout in 2022 sparks study

The SMU study examined a January 2022 blowout in Crane County that gushed almost 15 million gallons of brine before it was capped, according to the paper. That would fill about 23 Olympic-sized swimming pools.

The study traced the cause of the blowout to a cluster of nine injection wells about 12 miles to the northeast. Researchers pulled publicly available data on injection volumes at those wells and found they lined up closely to surface swelling that preceded the blowout. Seven of the wells belong to Goodnight Midstream and two belong to Blackbeard Operating, according to Railroad Commission records.

A spokesperson for Blackbeard said the company "is committed to ensuring prudent operations" and "will continue to operate its assets in accordance with all applicable laws and in coordination with all applicable regulatory agencies."

A spokesperson for Goodnight said the company is dedicated to operating its facilities responsibly and in full compliance with legal requirements.

"We work proactively with regulatory agencies and industry workgroups to ensure our operations are at the forefront of geologically sustainable solutions," the spokesperson said. "Our commitment to safety, environmental stewardship, and community engagement is the foundation for everything we do."

According to the paper, injection at those nine wells began in 2018 at a rate of about 362,000 gallons per day and doubled to 720,000 gallons per day in late 2019. In late 2020 it doubled again to 1.5 million gallons — two Olympic-sized swimming pools crammed underground everyday — which is when the ground near the blowout site began to inflate.

The study found that the volume injected matched the volume of the surface bulge 12 miles away.

"These observations suggest that this group of injection wells to the NW of the study area, injecting into the San Andres and Glorieta formations, is responsible for the surface deformation in the region," the study said.

Those wells reached a depth between 4,300 and 3,300 feet. But the SMU study found that the source of the bulge in the earth was much shallower, between 2,300 and 1,600 feet underground.

"This suggests the leakage of wastewater from the San Andres or Glorieta formations to the shallow formations," the study said.

The bottom of the Rustler Aquifer, the lowest usable source of groundwater in the Permian, sits between 800 and 1,000 feet underground. The SMU study did not examine the possibility of groundwater contamination.

"Our findings highlight the need for stricter regulations on wastewater injection practices and proper management of abandoned wells," the study said.

Todd Staples, president of the Texas Oil and Gas Association, said the Railroad Commission "is taking appropriate action by thoroughly gathering and reviewing data to address the issues experienced in Crane County."

He said the industry cooperates with the Railroad Commission by providing data to help analyze geological formations. "In addition, the industry and academia continue to explore alternatives to wastewater injection through market-based water reuse and recycling as well as innovative pilot programs," Staples said.

Ranchers report damaged land

West Texas ranchers who own land where contaminated water is seeping from underground are beginning to worry it will soon become uninhabitable.

Last February, saltwater flooded parts of Bill Wight's ranch, about 50 miles southwest of Odessa. The lifelong rancher purchased the land in 2012, hoping to pass it on to his kids. He told The Texas Tribune he wasn't sure how much of the ranch would survive the leaking wells.

When it was clear the flow of water threatened the property last December, he asked the Railroad Commission to seal the well the water had leaked from. It took the commission months and millions of dollars to plug the well.

His brother, Schuyler Wight, faces a similar predicament at his ranch roughly 60 miles to the west in Pecos County. He has asked the Railroad Commission for years to investigate the multiple abandoned leaking wells on his property. The liquid has eroded the equipment on the surface and killed the plants. After the water dried up, the ground was crusted white from salt.

"It's what we've known all along," Schuyler Wight said. "What we're doing is not sustainable."

Ashley Watt, owner of a ranch 50 miles east of Schuyler Wight's ranch in Crane County, told the Texas Railroad Commission during a 2022 meeting that she believed excessive injection by nearby oil producers was causing the fluids to spray from abandoned oil wells on her property.

A Railroad Commission staff member said the agency asked operators to check for a source of the leak. The operators told the commission they did not find any. The Railroad Commission during the meeting also said they did not find a well in the agency's database, and that the nearest injection wells were less than two miles away.

The agency instructed staff to prevent truckers from accessing those injection sites, telling operators to find others "until further notice."

The wells continue to leak.

Laura Briggs, who also owns a ranch in Pecos County less than half a mile east of Schuyler Wight's place, said she has seen five old wells start leaking water since 2015. The Railroad Commission plugged two of them, she said, but one began to leak through the seal again.

Briggs has repeatedly given testimony and submitted documentation to the Railroad Commission asking for help. Based on her experience, she believes the subterranean problems in West Texas are much more than what the Railroad Commission can handle.

"If I could do one thing differently, we would have gotten a mobile home so it was easier to get the hell out of here," Briggs said. "If this [ranch] goes leaking, we just have to leave and nobody will buy the property, no insurance will cover it, you're just done."

Despite those problems, the Railroad Commission approved 400 new disposal wells in the Permian Basin alone in 2021, according to agency documents, and 480 in 2022.

Threats to groundwater

The use of injection wells for disposal has expanded immensely with the practice of fracking, according to Dominic DiGiulio, a geoscientist who worked for 30 years at the U.S. Environmental Protection Agency. But DiGiulio said these wells are still regulated under rules from the 1970s and '80s. Increasingly, he said, those rules appear insufficient.

"West Texas isn't the only place where this is happening," DiGiulio said. "Overpressurization of aquifers due to disposal of produced water is a problem."

In 2022, DiGiulio conducted a review of Ohio's wastewater injection program for the group Physicians, Scientists, and Engineers for Healthy Energy and found the same two problems there: Injected fluids were leaking from some formations meant to contain them, and excessive injections were causing other formations to become overpressurized.

There was one big difference with Texas. In November 2021, DiGiulio's study said, Ohio had just 228 injection wells for wastewater disposal. Texas, meanwhile, had 13,585 in 2022, according to Railroad Commission documents.

The primary threat posed by produced water migrating from injection wells is groundwater contamination. If deep formations fail to contain the toxic waste injected into them, that waste could end up in shallow freshwater aquifers.

It could happen two ways, DiGiulio said. If the wastewater enters the inside of an old oil well through corroded holes in the casing, it can travel up the steel pipe to the surface, spilling and seeping into the ground. If the wastewater moves up the outside of an old oil well, through the cement that surrounds the steel pipe, it could already be flowing into the aquifer.

That would be bad news for West Texas, which depends almost entirely on groundwater for drinking and crop irrigation.

"Once groundwater contamination happens, it's too expensive to remediate," DiGiulio said. "So when it occurs, that's basically it. You've ruined that resource."

NATIONAL & WORLD

The chance of a major earthquake in or near Indiana may surprise you

By: Tyler Sebree

Posted: Jul 25, 2019 11:27 AM EDT

When you hear the word earthquake, Indiana may not be the first state that comes to mind. However, the state sits near two major fault lines and seismic zones:

- New Madrid Seismic Zone
- Wabash Valley Seismic Zone

The latter may come as a surprise as it is less known than the New Madrid. Regardless, both have a history of producing earthquakes -- some that were strong to even extreme.

And both have the legitimate potential to produce another

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TOP STORIES

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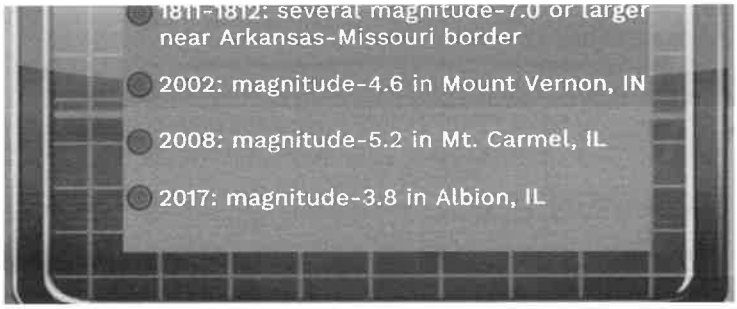
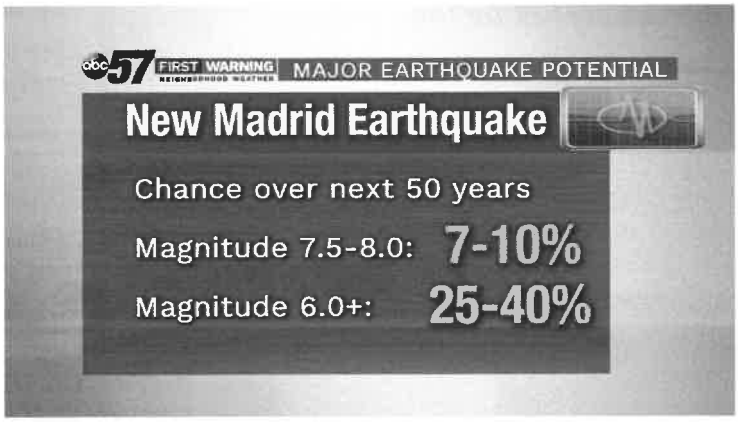


The most notable recent earthquakes in this geographical region occurred back in the early 19th century when multiple strong earthquakes shook parts of Missouri, Arkansas, Tennessee, Kentucky, Illinois, and Indiana. Three major quakes of magnitude-7.3 or stronger hit within a 3-month span.

Since then, there have been many weaker earthquakes in this region, but none quite as intense as those. For example, a strong M 5.2 quake hit Mt. Carmel, Illinois, back in 2008.

For perspective, that particular earthquake was felt across 18 states, and did cause structural damage.



USGS

It's clear that major, destructive and deadly earthquakes are few and far between in the Midwest and Ohio Valley region. According to the USGS, there is a roughly 500-year interval between ones as intense as what occurred in 1811-1812.

So that means we're safe for another 300 years, right?

Put simply, the answer to that question is ***no***. In fact, data suggest that there is a 25-40% chance of an earthquake with a magnitude of at least 6.0 striking in the New Madrid area in

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Carson Kvapil wins his first O'Reilly Auto Parts Series win at the Indianapolis Motor

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Potential casualties (injuries + fatalities) from a M 7.5 earthquake striking in the Wabash Valley Seismic Zone.

USGS/ArcGIS/FEMA

Injuries and fatalities could occur in nearly every Indiana county. That would include most of Michiana. The most substantial number of deaths and injuries would likely occur along the Indiana-Illinois state line, in addition to areas in and around Indianapolis.

The interactive map displaying the potential injuries and fatalities can be found here, and was put together by ArcGIS. It uses the Hazus Earthquake Model along with the simulated M 7.5 earthquake.

This, of course, is a hypothetical scenario in the Wabash Valley Seismic Zone. It is very possible that a major earthquake strikes in the New Madrid Seismic Zone, just a bit farther south.

Back in 2008, a study was released to show the impacts of a M 7.7 quake in the New Madrid region. Impacts, some great, would be felt in Indiana from such a disaster.

It's always a good idea to be prepared for a significant earthquake. For more on that, click here.

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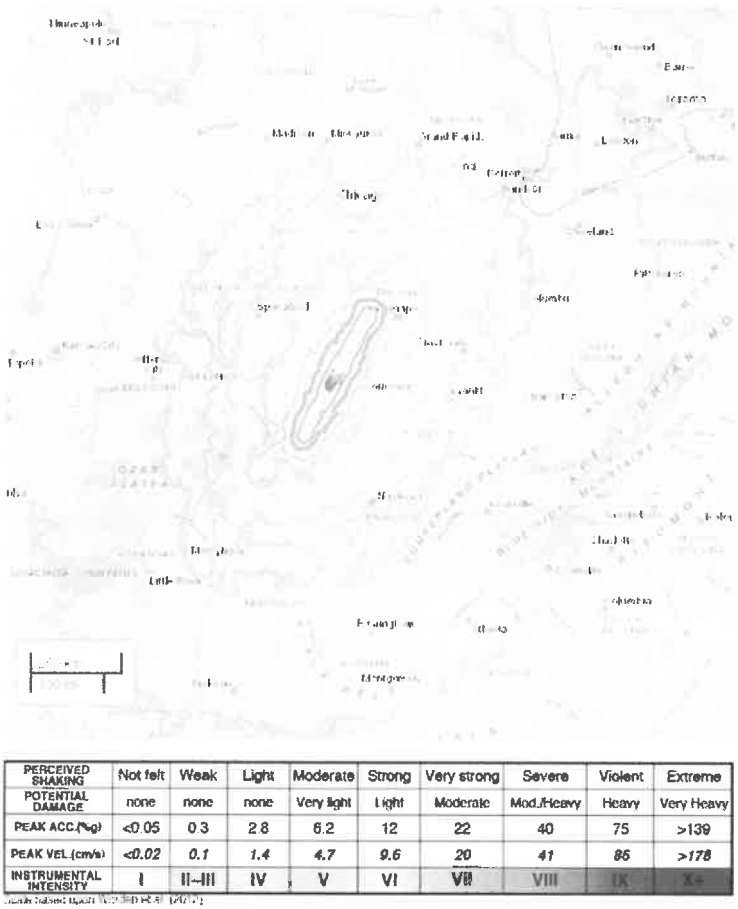

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Mod./Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<0.05	0.3	2.8	6.2	12	22	40	75	>139
PEAK VEL.(cm/s)	<0.02	0.1	1.4	4.7	9.6	20	41	86	>178
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Shake map from a hypothetical M 7.5 earthquake striking in the Wabash Valley Seismic Zone.

USGS

While those probabilities are coincided with the New Madrid Seismic Zone, there is a legitimate risk of a major, destructive quake in the Wabash Valley Seismic Zone, which is partially in Indiana. The USGS created a hypothetical scenario for a M 7.5 earthquake in the Wabash Valley Seismic Zone back in 2017.

If such an earthquake were to strike just west of Vincennes, Indiana, shaking could be felt as far away as Birmingham, Kansas City, Green Bay, and Pittsburgh.

Damage would occur across most of Indiana, Illinois and western Kentucky. That damage could be "Moderate" to "Heavy" in locations such as Kokomo, Lafayette, Indianapolis, Terre Haute, Evansville, and Paducah.

1 Ludacris Opens Elkhart County 4-H Fair Concert Series Amid Ticket Resale Concerns

2 U.S. 31 to close lanes due to overhead box truss installations

3 Vehicle allegedly dumped in St Joseph River in South Bend

ABC57 INVESTIGATES

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