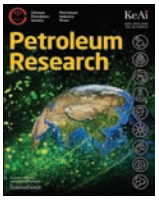
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Review Article

# 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/t$CO_2$), 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.

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## 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.

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**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 |

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.

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

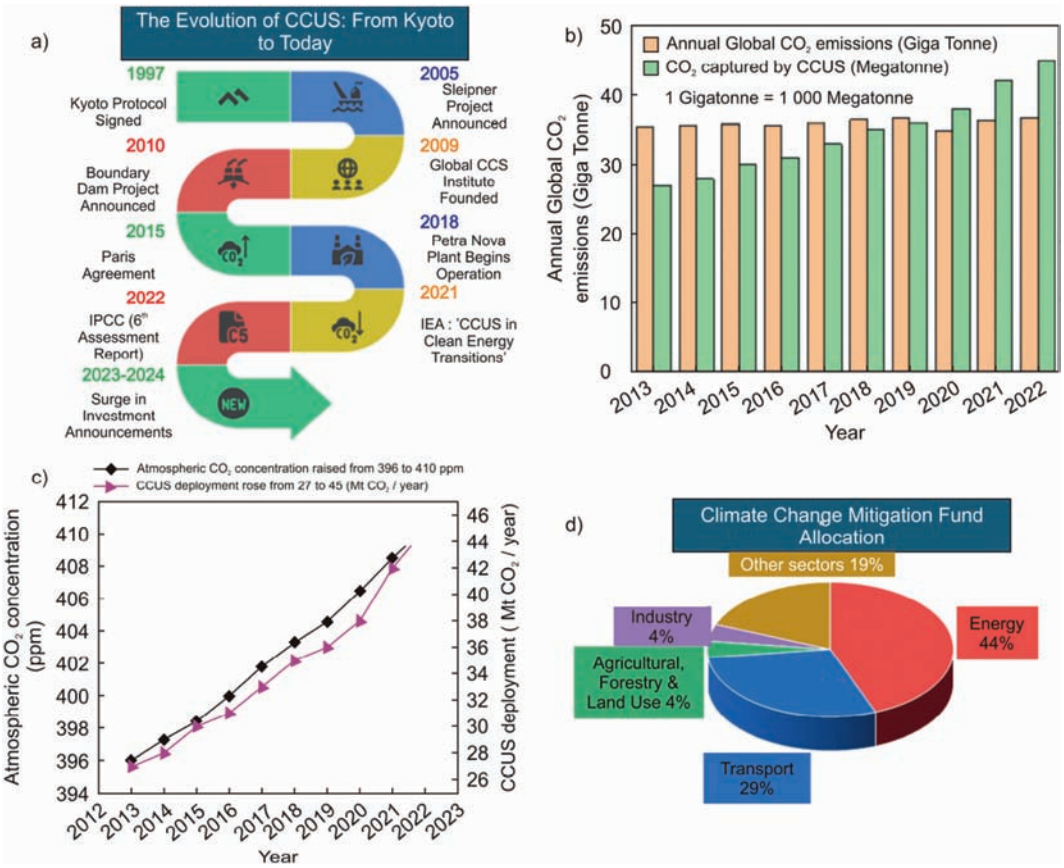



**Fig. 1. a)** Timeline of CCUS development (Global CCS Institute, 2021), **b)** Global $CO_2$ Emissions vs. $CO_2$ Captured by CCUS (2013–2022) (International Energy Agency, 2020; Liu et al., 2024), **c)** Trends in Atmospheric $CO_2$ Concentration and CCUS Deployment (2013–2022) (Rui et al., 2025;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

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.

### 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).

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

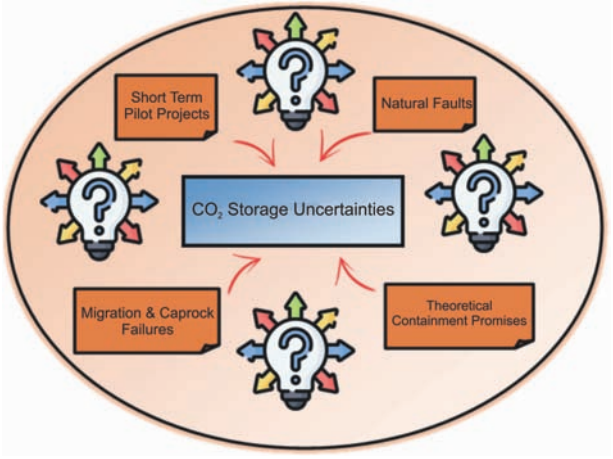



**Fig. 2.** Aspects of $CO_2$ storage uncertainties.

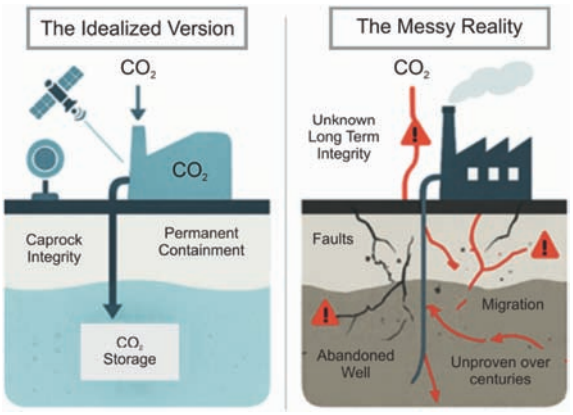



**Fig. 3.** Reality vs idealized version of $CO_2$ storage.

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).

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).

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

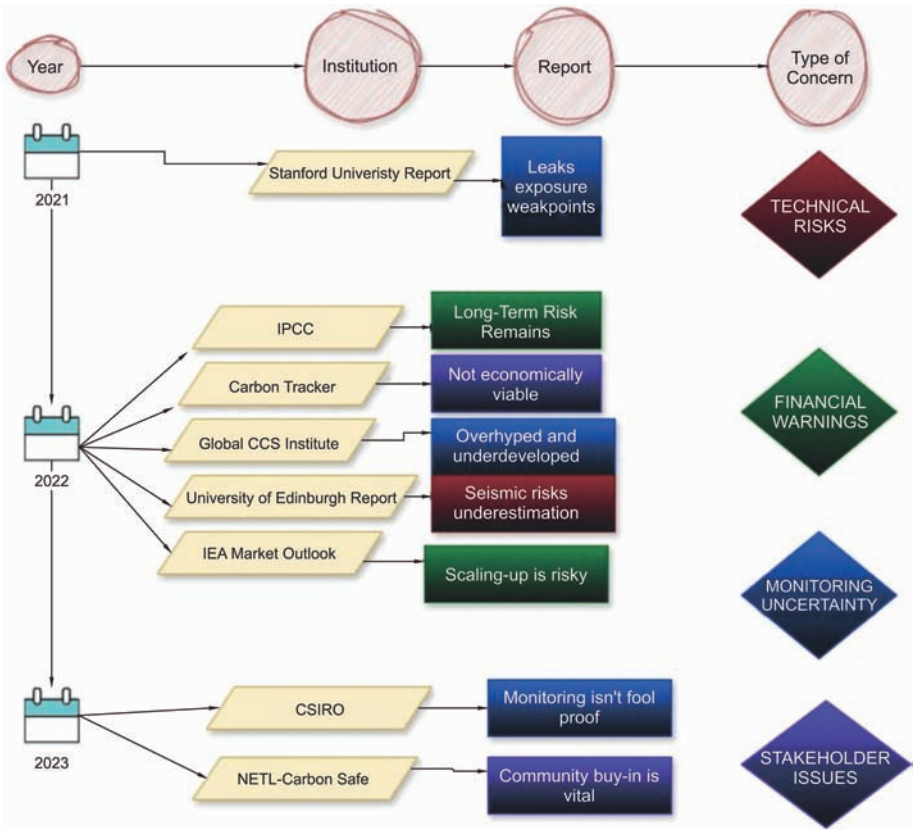



**Fig. 4.** Evidence of $CO_2$ storage failures from published reports/reviews (2021–2023).

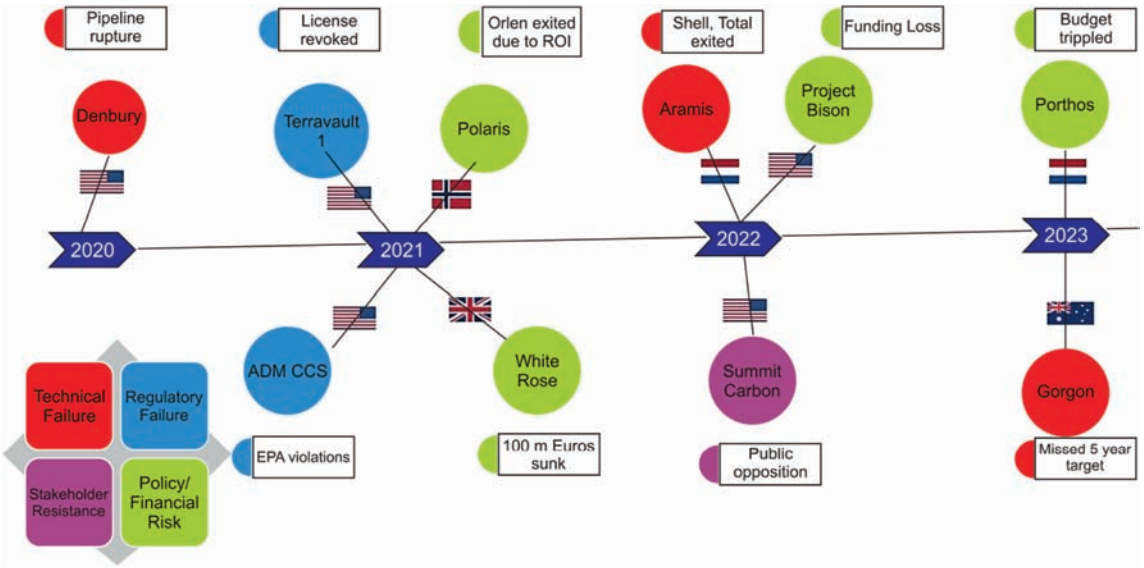



**Fig. 5.** Evidence of $CO_2$ storage failures from investigative journalism.

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.

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

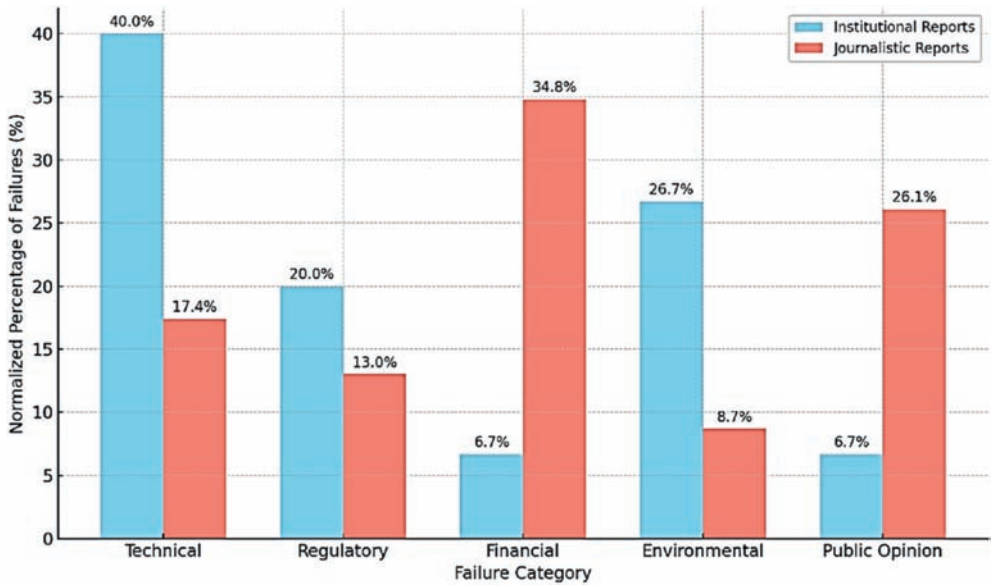



**Fig. 6.** Comparison of factors affecting $CO_2$ storage projects derived from published reports and news articles.

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.

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

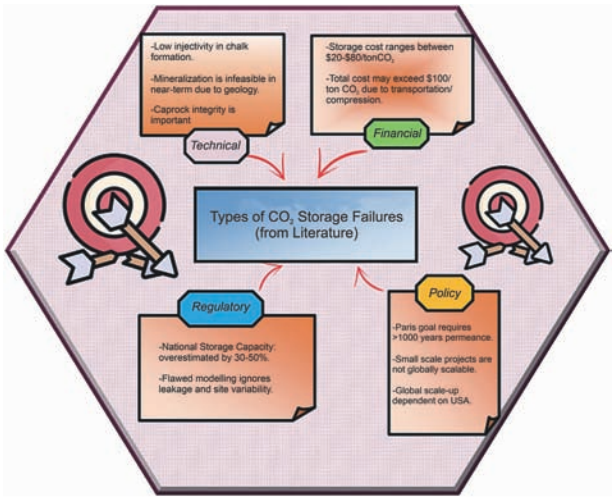



**Fig. 7.** Factors contributing to $CO_2$ storage failures gathered from literature.

**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 Acid Interaction in Subsurface $CO_2$ Injection | 50% strength loss near wells | Salt crystallization weakens geology | Storage integrity threatened over time | Nooraiepour et al. (2024) |
| 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) |

they actually affect the feasibility and deployment of any $CO_2$ storage related project.

*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).

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.

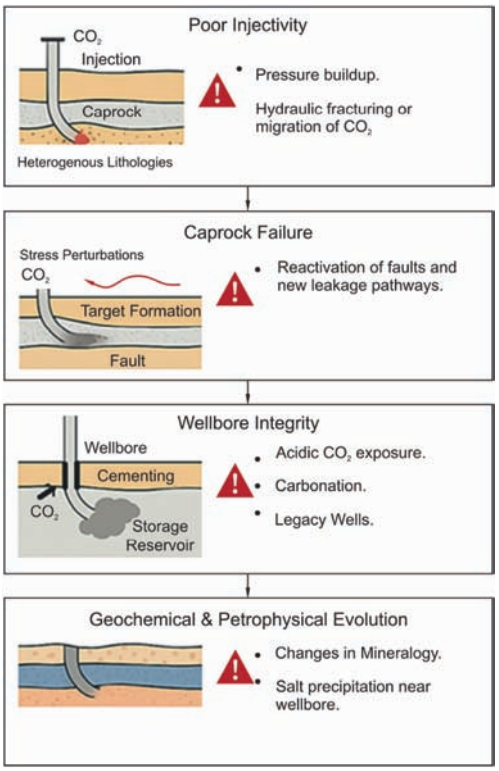



**Fig. 8.** Possible technical failures during underground $CO_2$ sequestration.

*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).

*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

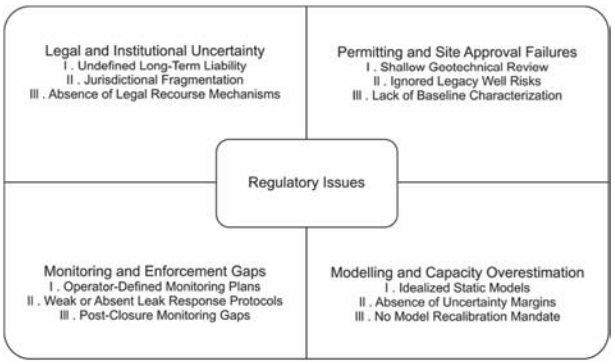



**Fig. 9.** Regulatory barriers for $CO_2$ storage related projects.

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).

*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).

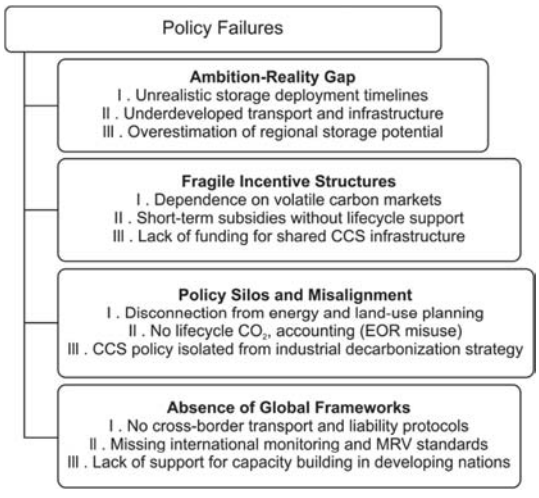



**Fig. 10.** Policy failures for $CO_2$ storage related projects.

*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).

*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

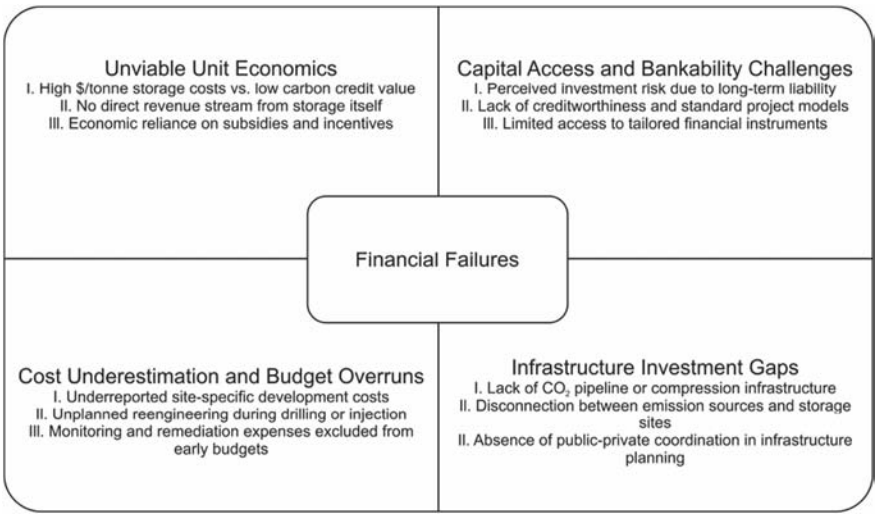



**Fig. 11.** Financial constraints for $CO_2$ storage related projects.

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.

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).

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 Tables 2 and 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).

**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 |

**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 |
| 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 |

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).

### 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

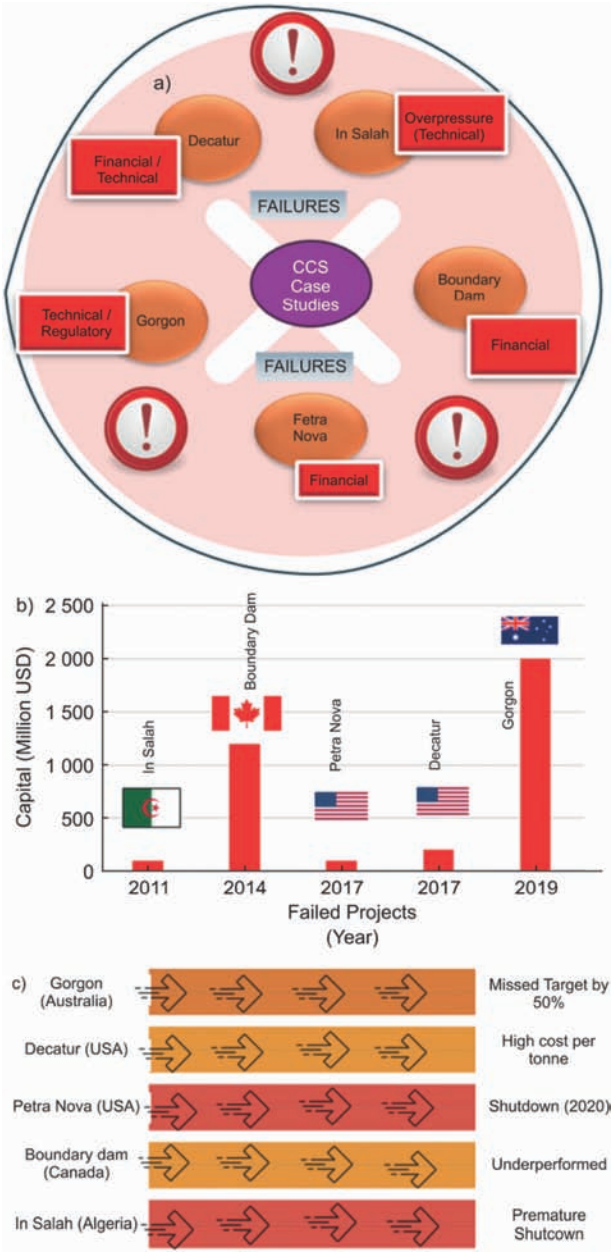



**Fig. 12.** Case studies of failed CCS projects, a) various aspects of CCS projects failures, b) capital invested in failed CCS projects globally, c) reasons of CCS projects failures.

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*

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 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 (Figs. 13 and 14) (Ringrose, 2018; Singh et al., 2025).

#### 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)

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

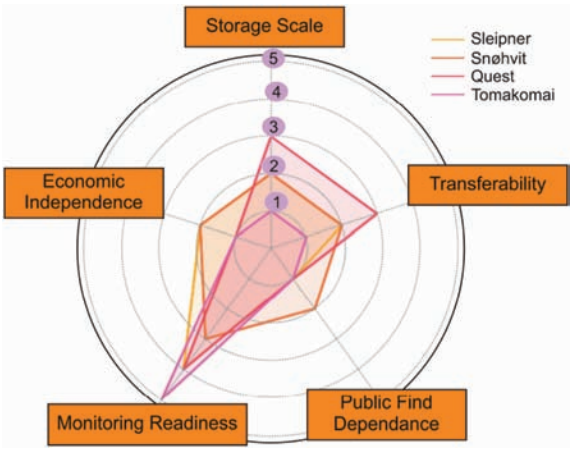



**Fig. 13.** Radar map of 'successful' CCS projects evaluated on parameters like storage, transferability, economic independence, monitoring readiness and public funding dependency.

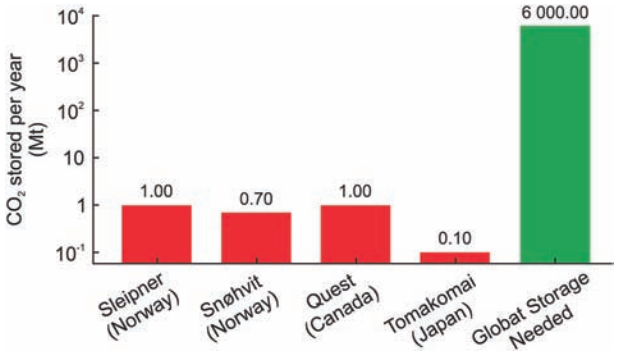



**Fig. 14.** Global $CO_2$ storage needed vs $CO_2$ stored in 'successful' CCS projects.

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).

In combination, Figs. 14 and 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

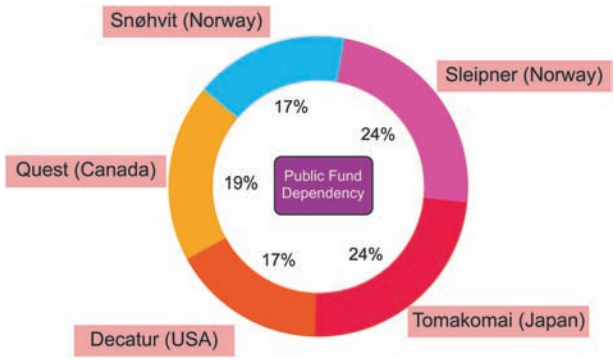



**Fig. 15.** Public fund dependency of CCS projects.

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.

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

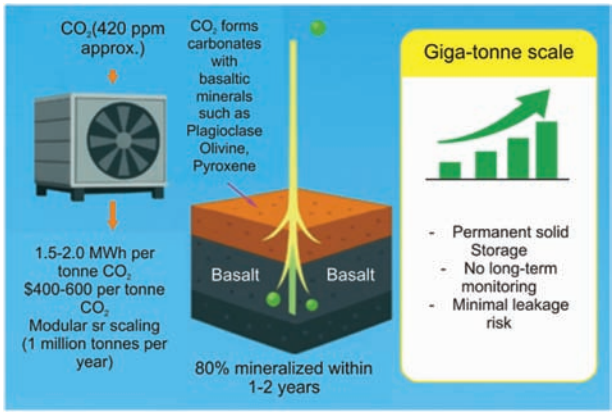



**Fig. 16.** DAC coupled with in-situ mineralization.

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).

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).

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

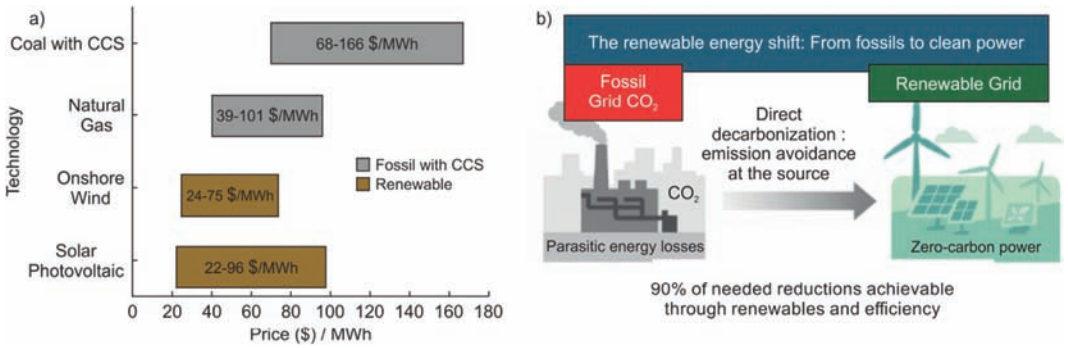



**Fig. 17.** Renewable energy reliance as an alternative to CCS for combatting climate change.

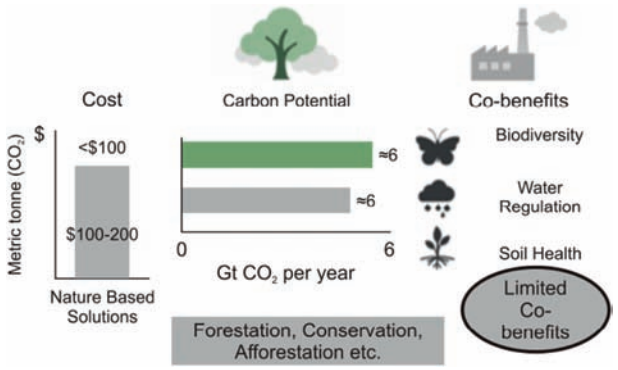



**Fig. 18.** Nature based solution as a CCS alternative.

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).

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).

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

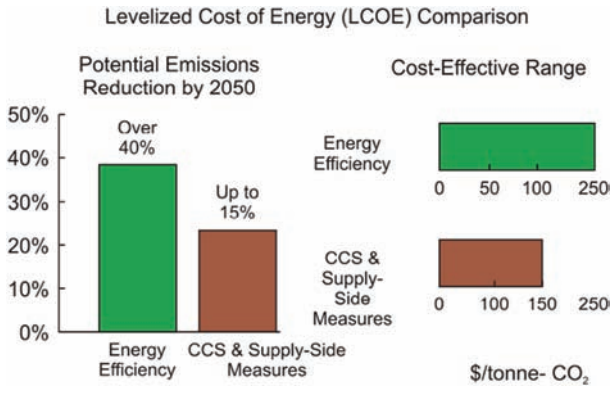



**Fig. 19.** Reduction in energy demand as a CCS alternative.

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).

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).

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

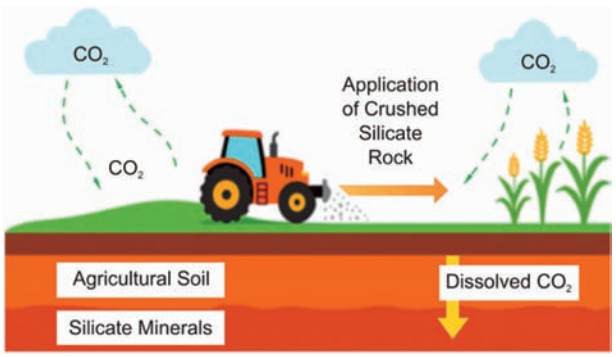



**Fig. 20.** Enhanced weathering as a conventional CCS alternative.

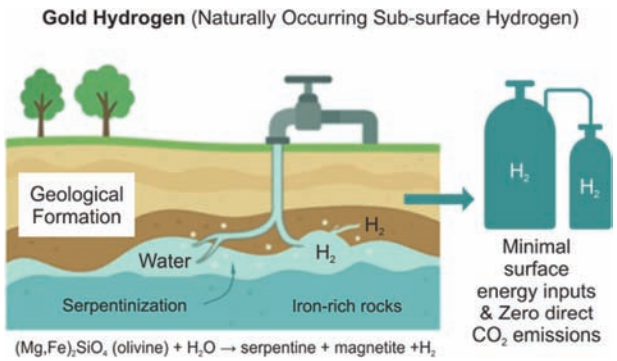



**Fig. 21.** Gold hydrogen as a viable CCS alternative for combatting climate change.

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).

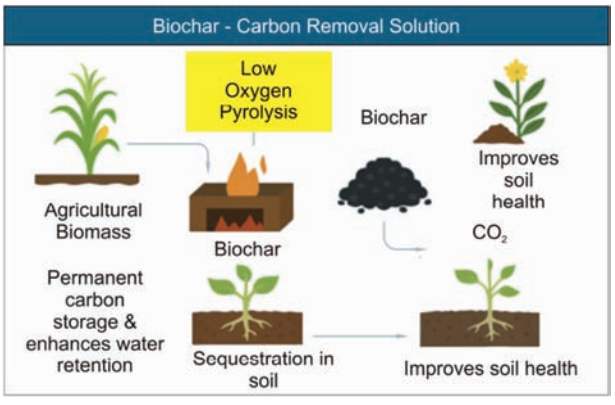



**Fig. 22.** Biochar for carbon removal as a CCS alternative.

**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.

## 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

**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 |
| 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 |

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.

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.

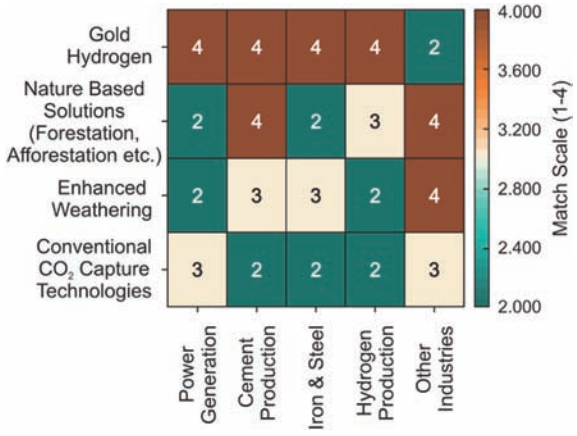



**Fig. 23.** Heatmap of alignment scores (1–4) between sectoral $CO_2$ sources and mitigation options, spanning capture and capture-avoidance/removal pathways (higher = stronger fit). "Other Industries" groups heterogeneous emitters (e.g., chemicals, aluminium/glass, textiles, food & beverage). Gold (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.

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).

#### 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.

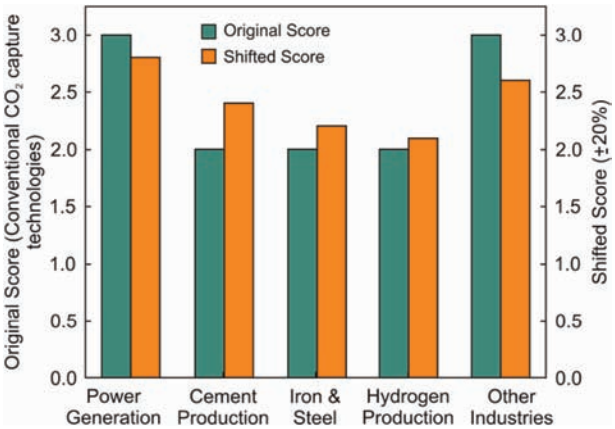



**Fig. 24.** Sensitivity analysis of conventional $CO_2$ capture technologies (as an example) match scores across sectors under ±20% parameter shifts. Bars show original predictive scores (teal) and shifted scores (orange), demonstrating that while absolute values fluctuate slightly, relative rankings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

## 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

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ptlrs.2025.09.005.

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