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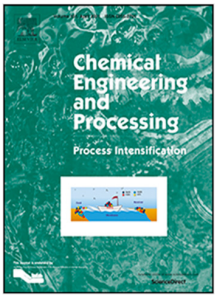


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# The steam barrier as a design constraint in carbon capture: pathways to low-temperature regeneration

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**Abstract**

Point-source carbon capture is conventionally based on steam stripping to regenerate chemical solvents, creating a dependence on high-grade thermal energy and limiting integration with low-temperature heat sources. Steam-based regeneration is highly effective because it simultaneously supplies heat, promotes $CO_2$ desorption, and facilitates production of a high-purity $CO_2$ stream. Nevertheless, the widespread use of steam stripping should not be interpreted as evidence that high-temperature regeneration is the only viable pathway for $CO_2$ release. In this Perspective, we examine solvent regeneration through the lens of energy quality and temperature-sensitive thermodynamic control variables, highlighting why $CO_2$ desorption can occur at temperatures substantially below those required for conventional steam stripping. We connect observations across buffer systems, sterically hindered and tertiary amines, thermomorphic solvents, and enzymatically assisted capture to a common underlying mechanism: temperature-dependent acid-base equilibria and phase behavior that enable equilibrium-driven desorption without vaporization. Within this framework, carbonic anhydrase emerges not as a marginal absorber-side additive, but as a kinetic enabler that becomes viable under mild, low-temperature desorption conditions. Viewed through this lens, the steam barrier is revealed as one of multiple design options rather than a physical inevitability, opening systematic pathways toward carbon capture systems compatible with low-grade heat and improved exergy efficiency.

**Keywords:** carbon capture, pH-swing, carbonic anhydrase, low-temperature desorption

# 1 Introduction: the steam barrier

Carbon capture is widely recognised as a critical component of industrial decarbonisation, yet its deployment remains strongly shaped by the availability of high-grade thermal energy [1, 2]. Most point-source capture systems rely on solvent regeneration through steam stripping at temperatures typically exceeding 120 °C, embedding boilers and steam infrastructure as implicit requirements for capture [3]. Steam stripping remains attractive not only because it supplies thermal energy, but also because steam acts as an in-situ condensable sweep gas. Following desorption, water can be readily condensed, leaving a high-purity $CO_2$ product suitable for compression, transport, and storage. This dual role partly explains the enduring dominance of steam-based regeneration. Although steam stripping is a practical solution for post-combustion capture processes, this reliance on steam, the steam barrier, has guided solvent development and process design for decades and continues to limit integration with systems dominated by low-grade heat [4]. The steam barrier is defined as:

**The steam barrier**

The implicit requirement that solvent regeneration must occur at the solvent boiling temperature rather than at the minimum equilibrium temperature for $CO_2$ release.

Recently, researchers have begun to challenge this paradigm [5, 6]. Experimental and process studies demonstrate that $CO_2$ absorption and release need not be intrinsically coupled to solvent boiling or carbamate breakdown. Examples include thermomorphic systems that exploit temperature-dependent liquid-liquid phase behaviour [7–10], electrochemical and temperature-induced pH-swing concepts [5, 11–14], and enzymatically assisted capture processes operating under mild conditions [15]. Together, these approaches show that low-temperature regeneration is feasible and already technologically diverse. However, they are typically developed as distinct solutions to specific challenges, without a unifying thermodynamic interpretation of what fundamentally enables carbon capture to move beyond steam.

From a process intensification perspective, the steam barrier reflects a mismatch between the thermodynamic requirements of $CO_2$ desorption and the high-grade heat imposed by boiling-based regeneration. Steam stripping supplies energy at temperatures determined by solvent boiling rather than by the equilibrium conditions governing $CO_2$ release, potentially contributing to avoidable exergy losses. Reframing solvent regeneration around equilibrium control and energy-quality matching highlights design pathways that reduce irreversibility and enable regeneration without phase change. In this view, overcoming the steam barrier is a thermodynamic route toward more efficient carbon capture systems.

Mechanism-based solvent screening supports this approach by identifying molecular properties, such as strong temperature-dependent equilibria or phase behaviour, that allow regeneration under mild conditions. Under these conditions, carbonic anhydrase can further intensify the process by accelerating hydration-dehydration kinetics and enabling rapid equilibration at lower temperatures. Together, non-boiling regeneration and catalytic rate enhancement illustrate how removing the steam constraint

opens practical pathways toward thermodynamically and kinetically intensified solvent regeneration.

In this perspective, we re-examine low-temperature $CO_2$ capture through the lens of temperature-sensitive thermodynamic behaviour, potentially accelerated by enzymatic catalysis or other promoters. Rather than proposing a new capture concept, we connect existing observations across buffer systems, selected amine formulations, and enzymatically assisted processes to common underlying drivers, such as temperature-dependent acid-base equilibria and phase behaviour. This focus clarifies why low-temperature regeneration is possible in these systems and how solvent choice and operating conditions determine access to low-grade heat for $CO_2$ release. Viewed in this way, the steam barrier emerges as a design choice rather than a physical inevitability, opening a broader and more systematic pathway toward integrable, low-temperature carbon capture. The goal of this work is therefore not to provide experimental validation or full-process simulation, but to establish a unifying thermodynamic framework that connects diverse observations reported across the literature and identifies systematic low-temperature regeneration pathways worthy of future process-intensification research.

## 2 Exergy destruction in the conventional process

A simplified flow diagram of a conventional point-source post-combustion $CO_2$ capture process is shown in Figure 1. In this configuration, solvent regeneration is achieved in a stripper column, in which a vapor phase for stripping is generated by partial evaporation of the $CO_2$-lean solvent. The generated vapor phase provides the necessary heat and driving force for $CO_2$ desorption, which is achieved by counter-current contacting with the $CO_2$-rich solvent in the stripper column. The thermodynamic phase and chemical equilibria are the key enabler for mass transfer from the liquid to the vapor phase [16, 17]. $CO_2$ absorption occurs close to ambient conditions and involves a relatively small change in chemical potential, whereas regeneration is typically conducted above 120 °C and requires evaporation of large amounts of water. This large temperature lift forces a fundamentally low-grade separation task to be driven by high-grade thermal energy, imposing an inherent thermodynamic inefficiency [16, 17], despite the heat integration between the rich and lean solvent streams (HX-1).

To assess the thermodynamic implications of this regeneration strategy, exergy provides a particularly useful thermodynamic quantity representing the maximum useful work obtainable relative to a defined environment. The specific exergy of each stream, such as feed and product streams, as well as utility streams for supplying energy can be computed as

$$e = (h - h_0) - T_0(s - s_0), \tag{1}$$

where $h$ and $s$ denote the specific enthalpy and entropy of the stream, respectively, and the subscript 0 refers to properties evaluated at the environmental reference temperature $T_0$. Unlike simple energy analysis, exergy analysis effectively accounts for both the quantity and the quality of heat flows [18]. Considering that the stripper represents the main exergy sink of the $CO_2$ capture process, an exergy balance around the

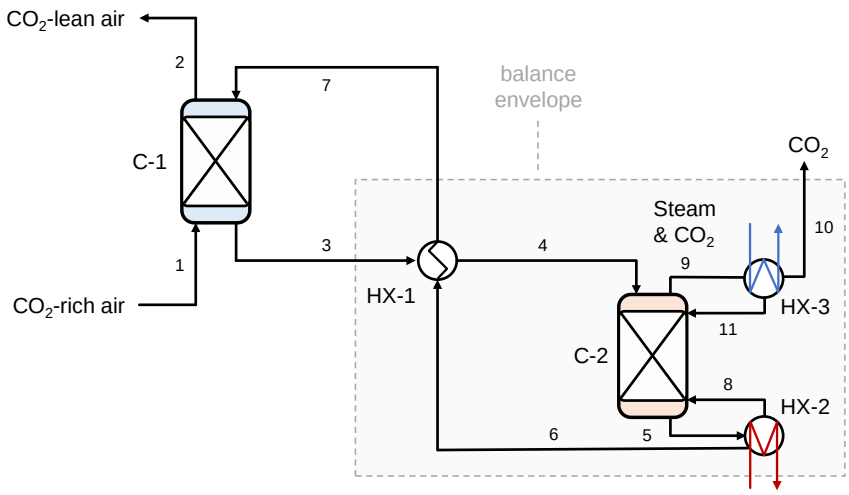



**Fig. 1**: Simplified process flow diagram of a conventional post-combustion $CO_2$ capture system based on steam-driven solvent regeneration.

stripper and the intermediate heat exchanger (HX-1) indicates that the rich solvent stream (3) and the utility stream to the reboiler (HX-2) are providing exergy to the system, while the lean solvent stream (7) and the $CO_2$ stream (10), as well as the utility in the condenser (HX-3) remove exergy from the system. Following the analysis of Tumbalam Gooty et al. [19] for general distillation columns, the high-temperature heat supplied in the reboiler to drive solvent regeneration and $CO_2$ desorption is considered the major exergy sink, while the heat that is released in the overhead partial condenser as water vapor condenses provides the dominant exergy source. For heat supply and removal the individual exergy can be calculated on the basis of the heat flow $\dot{Q}$ with the temperature $T$ in respect to the reference temperature

$$\dot{e}_{heat} = \dot{Q}\left(1 - \frac{T_0}{T}\right). \tag{2}$$

Therefore, even if the heat flows at the reboiler and partial condenser are almost equivalent, the high-temperature reboiler duty carries a higher exergy content than the low-temperature condenser duty. As a result, the stripper effectively acts as a heat quality degrader and constitutes the dominant site of exergy destruction in the process. Figure 2 illustrates the effect of the temperature over a range from 60 °C to 200 °C, with Figure 2a showing the exergy content of water as a function of temperature and pressure, highlighting the substantial exergy associated with the heat of vaporization. As discussed in the context of general distillation columns by Tumbalam Gooty et al. [19], it is of imminent importance to utilize the exergy of the heat flow

from the condenser to improve the energy efficiency of the process. However, the low temperature of the condenser impairs a direct utilization at the reboiler, which only becomes possible via the integration of an additional heat pump [19]. Such concepts have so far however received limited attention in the context of carbon capture and storage, as e.g. explored in the recent study of Jensen et al. [20]. Even if such heat integration can be established, the heat and exergy demand for the reboiler should be kept as low as possible.

If a heat flow $\dot{Q}$ is supplied at temperature $T$ to drive a process that could, in principle, occur at a lower minimum temperature $T_{\min}$, the associated excess in temperature results in an unnecessarily wasted exergy destruction that can be calculated as:

$$\dot{e}_{dest} = \dot{Q}\left(\frac{T_0}{T_{\min}} - \frac{T_0}{T}\right). \tag{3}$$

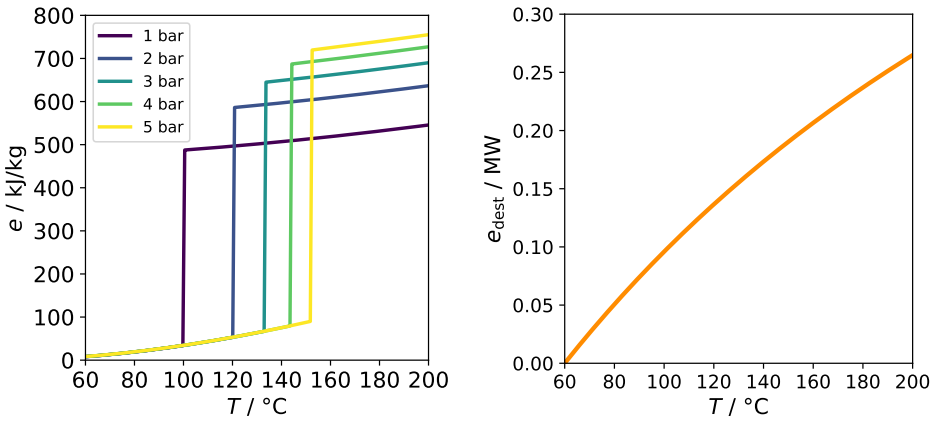
This expression isolates temperature mismatch as a fundamental source of irreversibility, highlighting the importance of minimum approach temperatures in the heat exchangers. Even in the absence of equipment-specific losses, exergy losses arise solely from supplying high-grade thermal energy to a task that could be accomplished using lower-grade heat. Of course, it must be considered that practical implications do require some temperature excess beyond the thermodynamic minimum in order to provide a sufficient driving force for heat transfer, but that does not impair the current analysis.

In conventional steam-driven solvent regeneration, $T$ has to be at least as high as the boiling temperature of the evaporating rich solvent in the reboiler $T_{\min}$. However, if solvent regeneration is not driven by partial evaporation of the rich solvent $T_{\min}$ could be further reduced to represent the minimum temperature required for $CO_2$ desorption [16, 18]. Figure 2b indicates the resulting excess energy for supplying heat at different temperatures relative to an assumed minimum desorption temperature of 60 °C [5], showing that in relation to supplying heat at 130 °C, as in conventional amine scrubbing processes, would result in a reduced exergy supply of approximately 0.16 MW per MW of heat input [16, 21].

The high temperature requirement is intrinsically linked to the boiling temperature of the rich solvent in the stripper, and not necessarily required to shift the chemical equilibria governing $CO_2$ release. Consequently, regeneration temperature is dictated by the solvent boiling point rather than by the minimum thermodynamic requirements for $CO_2$ desorption resulting from the chemical reactions. Thus, the steam requirement is embedded as a structural feature of conventional carbon capture systems rather than a necessity imposed by $CO_2$ chemistry itself [17, 18]. As a consequence, alternative low temperature concepts for solvent recovery possess a large potential to reduce the exergy destruction.

An important technical limitation that should be noted is that a significant engineering challenge in transitioning to low-temperature capture is the effective management of heat transfer under small thermal driving forces. While the use of low-grade heat reduces exergy destruction, it also results in a smaller temperature difference ($\Delta T$) between the heating utility and the solvent. According to fundamental heat transfer principles, reduced approach temperatures require substantially larger heat-transfer surfaces to maintain the same duty, which in turn increases equipment

size and capital expenditure. Consequently, the design of low-temperature capture systems becomes a techno-economic optimization problem: the operational benefits associated with improved thermodynamic efficiency and lower utility costs must be weighed against the higher investment costs associated with larger and potentially more complex heat exchanger networks.




(a) (b)

**Fig. 2**: (a) The exergy of water and steam at different temperatures and pressures. (b) The exergy destruction associated with 1 MW of heat transfer at different temperatures that could have been achieved at 60 °C. The methodology for these calculations is provided in the supporting information.

## 3 The role of solvent chemistry

Solvent chemistry fundamentally influences both the thermodynamic efficiency and energy demand of point source $CO_2$ capture. In conventional amine systems, primary and secondary amines such as monoethanolamine (MEA) and diethanolamine (DEA) react with $CO_2$ to form carbamates:

$$RNH_2 + CO_2 \rightleftharpoons RNHCOO^- + H^+ \quad (4)$$

$$R_2NH + CO_2 \rightleftharpoons R_2NCOO^- + H^+. \quad (5)$$

Carbamate formation is highly exothermic, and reversing these reactions during solvent regeneration requires substantial energy input to overcome the reaction enthalpy, thereby motivating the use of high-temperature steam stripping as the conventional regeneration strategy [1, 22–24].

Hindered and tertiary amines, such as 2-amino-2-methyl-1-propanol (AMP) or triethanolamine (TEA), react with $CO_2$ predominantly to form bicarbonate or carbonate

species:

$$R_2NH + H_2O + CO_2 \rightleftharpoons R_2NH_2^+ + HCO_3^- \quad (6)$$

$$R_3N + H_2O + CO_2 \rightleftharpoons R_3NH^+ + HCO_3^-. \quad (7)$$

These pathways are generally less exothermic than carbamate formation, which can reduce the heat of regeneration and thus lower energy requirements compared to primary/secondary amines [25, 26].

Beyond conventional chemistries, a class of thermomorphic solvents has emerged that exploit temperature-dependent phase behaviour to reduce regeneration energy. In these systems, a $CO_2$-loaded homogeneous solution undergoes a thermally induced liquid–liquid phase separation at elevated temperatures. The resulting $CO_2$-rich phase can be selectively desorbed, often at temperatures well below the boiling point of aqueous amine solutions (e.g., 80–90 °C), enabling regeneration with low-grade heat. Because only the $CO_2$-rich phase requires regeneration, the sensible and latent heat duties associated with heating the entire solvent inventory are significantly reduced, lowering the overall energy penalty of the capture cycle. Recent work has demonstrated thermomorphic absorbents that regenerate with high $CO_2$ desorption efficiency near 50 °C using phase separation driven by differences in polarity between co-solvent layers [27–29].

Thermomorphic biphasic amine solvents have been shown to achieve both high cyclic $CO_2$ loading and the ability to use low-value heat for desorption by shifting between homogeneous and biphasic states as a function of temperature. Such behaviour exemplifies how solvent design, specifically tuning the interplay between chemical reactivity and phase behaviour, can decouple $CO_2$ desorption from high-temperature steam stripping, offering a pathway to reduce exergy destruction associated with conventional thermal regeneration.

## 4 Insights from Decades of Solvent Screening

More than three decades of solvent screening for point source $CO_2$ capture reveal a consistent pattern: most efficiency gains attributed to "advanced" amines arise from suppressing stable carbamate formation rather than from fundamentally altering the separation mechanism [1]. Sterically hindered and tertiary amines—including 2-amino-2-methyl-1-propanol (AMP), 2-amino-2-methyl-1,3-propanediol (AMPD), 2-amino-2-ethyl-1,3-propanediol (AEPD), methyldiethanolamine (MDEA), triethanolamine (TEA), and tris(hydroxymethyl)aminomethane (Tris, AHPD)—store $CO_2$ primarily as bicarbonate and physically dissolved $CO_2$, enabling higher cyclic capacities and lower heats of desorption than primary amines such as monoethanolamine (MEA) [30–32]. Among sterically hindered amines, those with large p$K_a$, such as AHPD and AMPD repeatedly demonstrate high equilibrium loadings approaching 1 mol $CO_2$/mol amine, favorable regeneration efficiencies, and reduced reaction enthalpies, reflecting the instability or absence of carbamate species. These thermodynamic advantages, however, are consistently offset by slower absorption kinetics, often

necessitating promoters such as piperazine or carbonic anhydrase to achieve industrially relevant mass-transfer rates [33, 34]. Importantly, decades of work show that such kinetic enhancements accelerate hydration and proton-transfer steps without altering equilibrium chemistry, and therefore do not eliminate the fundamental energy penalty associated with boiling-based regeneration.

A second, less appreciated lesson is that most solvent screening studies implicitly accept steam stripping as a fixed boundary condition. Even solvents explicitly identified as "easy to regenerate" are almost universally evaluated in absorber-stripper configurations operating above 120-150 °C, where regeneration temperature is dictated by boiling rather than by the minimum thermodynamic requirement for $CO_2$ release [3, 35]. As a result, improvements in cyclic capacity or reaction enthalpy translate only weakly into system-level energy savings. The literature on sterically hindered amines-including AMP, AMPD, AHPD, and their blends—contains repeated evidence of strong temperature-dependent equilibria, pH shifts, and favorable bicarbonate chemistry [36, 37], yet these features have rarely been exploited to enable regeneration below the boiling point of water. The same solvents identified as "regeneration-friendly" in classical studies are therefore precisely those best suited for alternative regeneration paradigms—such as temperature-induced pH swing, thermomorphic solvents (as recently demonstrated experimentally [7–9]), or hybrid capture-conversion schemes—that decouple $CO_2$ release from vaporization. In this light, the long history of solvent screening does not argue for incremental solvent optimization within steam-based architectures, but instead points toward a structural redesign of the regeneration step itself. An overview of the characteristics of different amine solvents is given in Table 1.

This distinction is particularly important for low-temperature and non-boiling regeneration concepts. Primary and secondary amines such as MEA and DEA form relatively stable carbamate species that require substantial thermal driving force to decompose, making efficient $CO_2$ release difficult under mild regeneration conditions. Their favorable absorption kinetics therefore come at the expense of stronger chemical binding and higher effective regeneration barriers. In contrast, bicarbonate-forming systems exhibit weaker $CO_2$ binding and stronger equilibrium sensitivity to moderate temperature and pH changes, allowing regeneration to proceed at substantially lower temperatures without relying on intensive steam stripping. From this perspective, carbamate suppression is not merely a route toward incremental energy reduction, but a prerequisite for enabling fundamentally different regeneration architectures based on low-grade heat integration.

**Table 1**: Key lessons from decades of solvent screening for point sou

| **Solvent class** | **Dominant $CO_2$ species** | **Key advantage** | **P** |
|---|---|---|---|
| Primary amines | Carbamate | Fast absorption kinetics | H |
| Secondary amines | Carbamate / bicarbonate | Moderate cyclic capacity | Pa |
| Sterically hindered amines | Bicarbonate / $CO_2$(aq) | High cyclic capacity, low $\Delta H$ | Sl |
| Tertiary amines | Bicarbonate | Very low regeneration enthalpy | Ve |
| Promoted systems (e.g. PZ, CA) | Same as base solvent | Accelerated absorption | N |

## 5 Temperature-induced pH swings

A recently described and very promising route to low-temperature $CO_2$ desorption is to exploit the strong temperature dependence of acid–base equilibria in aqueous solvents [5]. In alkaline solutions, absorbed $CO_2$ is stored predominantly as bicarbonate and carbonate species. Increasing temperature lowers the solution pH through changes in water dissociation and solute protonation equilibria, shifting speciation toward dissolved $CO_2$ and enabling desorption without reliance on carbamate breakdown or solvent boiling. This mechanism suggests that solvents exhibiting a large temperature dependence of protonation equilibria, quantified by a high $d\mathrm{p}K_\mathrm{a}/dT$, may enable cyclic capture processes operating entirely below 90 °C.

Sterically hindered and tertiary amines such as AMP, AMPD, and AHPD (Tris) have long been investigated as alternatives to primary and secondary amines because they form unstable or no carbamates, resulting in lower heats of regeneration. Historically, however, these solvents have been deployed within conventional absorber–stripper flowsheets operating above 120 °C, with research emphasis placed on absorption kinetics and enzymatic enhancement via carbonic anhydrase (CA) [34, 39, 40]. Only recently has their suitability for low-temperature, non-boiling regeneration begun to receive focused attention [5].

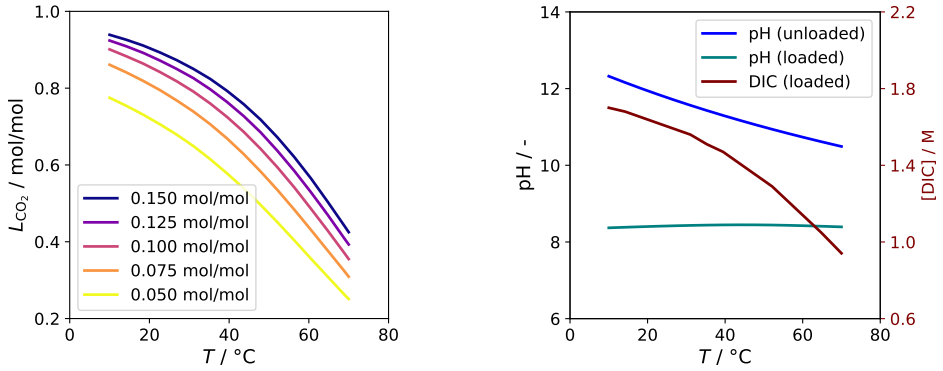
Temperature-induced pH-swing strategies directly leverage these chemical properties. Moderate heating induces a measurable decrease in solution pH, shifting carbonate–bicarbonate equilibria toward molecular $CO_2$ without the need for high-grade thermal input. Unlike primary and secondary amines, which require substantial energy to reverse strongly bound carbamates, hindered and tertiary amines predominantly bind $CO_2$ through weaker acid–base interactions. When coupled with temperature-sensitive protonation equilibria, this enables efficient $CO_2$ release at temperatures potentially below 80 °C, substantially reducing exergy losses, mitigating solvent degradation, and improving compatibility with low-grade heat sources.

Figure 3 examines the gas–liquid equilibrium behavior of aqueous AMP in contact with simulated flue gas. The recently developed AMP elec-NRTL model by Morlando et al. [41] was used to examine the behavior of an aqueous solution with 2 M concentration at low temperatures. Gas-liquid equilibria were calculated using the flash2 unit in ASPEN Plus V14. The methodology is presented in the supporting information. Figure 3a shows the equilibrium $CO_2$ loading of a 2 M aqueous AMP solution as a function of temperature for different flue-gas compositions represented as a binary mixture of $CO_2$ and $N_2$. The loading capacity, defined as the moles of $CO_2$ absorbed per mole of solvent at equilibrium,

$$L_{\mathrm{CO_2}} = \frac{[\mathrm{DIC}]}{[\mathrm{Amine}]} = \frac{[\mathrm{CO_2(aq)}] + [\mathrm{HCO_3^-}] + [\mathrm{CO_3^{2-}}]}{[\mathrm{Amine}]}, \tag{8}$$

captures the thermodynamic storage potential of the solvent independent of a specific process cycle. Maximum loading is achieved at low temperatures and decreases sharply upon heating, consistent with temperature-driven speciation shifts toward $CO_2$ release. When full regeneration is achieved, the loading capacity converges to the cyclic capacity.

The underlying pH response is illustrated in Figure 3b. For unloaded AMP solutions, pH decreases strongly with temperature, reflecting the temperature sensitivity of its p$K_a$. In contrast, $CO_2$-loaded solutions exhibit a more buffered pH response and remains near neutral across a broad temperature range. Importantly, this operating window overlaps with the optimal activity range of carbonic anhydrase (typically below 60 °C and pH 7–11), allowing enzymatic acceleration of $CO_2$ hydration and dehydration without exposing the enzyme to thermal deactivation [42, 43]. In this context, temperature-induced pH swings provide a thermodynamic foundation upon which kinetic enhancers can operate, rather than serving as a standalone capture mechanism. Viewed through this lens, low-temperature regeneration emerges as a consequence of solvent chemistry and equilibrium control, consistent with the broader reframing of the steam barrier developed in this Perspective.

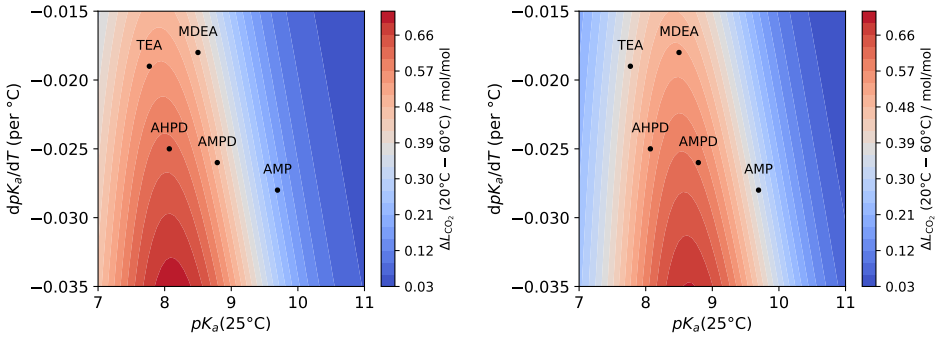



(a) (b)

**Fig. 3**: (a) $CO_2$ loading estimates (moles $CO_2$ per mole AMP) against temperature for different $CO_2$ mole fractions in the gas phase. (b) Loaded and unloaded solvent pH and dissolved inorganic carbon and speciation estimates for 2 M AMP for a flue gas with a 0.15 mol/mol $CO_2$ mole fraction

In order to screen solvents for which rigorous thermodynamic models are not available, a custom Python model was developed to compute gas–liquid and chemical equilibria for $CO_2$ absorption in lean (low concentrations and ionic strengths) aqueous amine solutions. Electrolyte concentrations were kept below 0.5 M, and for this reason, the non-ideal solution behavior was described using the semi-empirical Davies activity model, with comparisons to Debye–Hückel and ideal-solution assumptions showing only minor deviations (cf. supporting information). The model accounts for $CO_2$ dissolution, carbonate equilibria, and solvent acid–base reactions, with temperature-dependent equilibrium constants evaluated over 20–60 °C using standard thermodynamic relationships. Gas–liquid equilibrium was represented via Henry's law, and solution speciation was obtained by iteratively solving the charge balance while

updating ionic strength and activity coefficients until convergence. The approach was used to calculate $CO_2$ loading differences between 20 and 60 °C as a function of key thermodynamic parameters of the solvents, such as $pK_a$ and $dpK_a/dT$. The results are shown in Figures 4a and 4b for different solvent concentrations. It is interesting to note that $dpK_a/dT$ was found to strongly affect the loading differences, with more temperature sensitive solvents leading to a more pronounced change in loading. Further, the optimal $pK_a$ value depended on solvent concentration and increased with increasing solvent concentration. Some of the commonly studied solvents (that mostly form bicarbonate) are presented on Figures 4a and 4b as points.




(a) (b)

**Fig. 4**: (a) $CO_2$ loading estimates differences between 20 and 60 °C for an aqueous solvent with 0.1 M concentration in equilibrium with flue gas containing 0.15 mol/mol $CO_2$. (b) $CO_2$ loading estimates differences between 20 and 60 °C for an aqueous solvent with 0.5 M concentration in equilibrium with flue gas containing 0.15 mol/mol $CO_2$. The methodology for the calculations is given in the supporting information.

It is important to note that, although the simulations in Aspen Plus were performed at industrially relevant concentrations of up to 2 M, the simplified screening model developed in Python is intentionally restricted to dilute conditions ($<$ 0.5 M) using the semi-empirical Davies model. This reduced-complexity framework is intended to provide qualitative insights into thermodynamic trends without introducing the additional computational and parameterization challenges associated with high-ionic-strength interactions. Accordingly, the model should be regarded as a preliminary, low-level solvent screening tool that provides approximate estimates rather than quantitatively rigorous predictions under industrial operating conditions.

## 6 Carbonic anhydrase as a kinetic enabler

While the thermodynamic analysis demonstrates that $CO_2$ release is feasible at temperatures significantly below the solvent boiling point, the practical realization of such

processes must contend with inherently slower desorption kinetics. At reduced temperatures, the driving force for chemical reaction and mass transfer is diminished, which may necessitate significantly larger regenerator volumes to achieve industrial throughput. Consequently, non-boiling regeneration might require the use of promoters and intensified contacting strategies, such as membrane contactors with high surface-area-to-volume ratios, to compensate for lower reaction rates and avoid impractically large capital footprints.

Carbonic anhydrase (CA) is often used as a promoter in absorption systems employing tertiary or hindered amines because these solvents exhibit inherently slow reaction kinetics with $CO_2$. CA is a highly efficient metalloenzyme that catalyzes the reversible hydration of $CO_2$ to bicarbonate, dramatically accelerating the otherwise slow reaction in aqueous solutions[44]:

$$CO_2 + H_2O \overset{CA}{\rightleftharpoons} HCO_3^- + H^+. \tag{9}$$

By accelerating this kinetically limiting step, CA can substantially reduce absorber and desorber residence times, particularly in solvent systems where $CO_2$ is stored predominantly as bicarbonate rather than as strongly bound carbamates.These bicarbonate-forming systems often exhibit intrinsically slower absorption and desorption kinetics, making them particularly well suited for coupling with CA-based catalytic enhancement. Maintaining enzyme activity over repeated capture cycles remains a key challenge, motivating strategies such as enzyme immobilization, formulation optimization, and the development of CA mimics [45]. Prior studies have demonstrated that CA can enhance $CO_2$ absorption rates in amine-based systems, although its long-term stability is compromised under the high temperatures and strongly alkaline conditions typical of steam-stripping regeneration [39, 40, 43, 46–48].

Low-temperature capture concepts fundamentally change this trade-off. Temperature- and pH-swing processes operating below 60-80 °C can remain within the optimal activity window of CA (pH 7-11), allowing the enzyme to function across both absorption and desorption stages rather than being confined to the absorber [42, 43]. Interestingly, the case study for AMP in Figure 3b shows that even though the pH of the unloaded solvent might vary a lot, the pH of the loaded solvent remains more or less constant, and close to the optimal pH for CA. In such regimes, CA shifts from a marginal kinetic aid to a potential central enabler of process intensification, ensuring rapid equilibration while avoiding the thermal and chemical stresses that drive enzyme deactivation. This alignment between mild operating conditions, bicarbonate-based solvent chemistry, and enzymatic catalysis suggests that CA is intrinsically better suited to low-temperature point-source carbon capture than to conventional steam-driven systems. More broadly, it opens pathways toward integrated capture-conversion schemes in which bicarbonate-rich streams are routed directly to enzymatic or catalytic upgrading, replacing thermal desorption altogether.

Therefore, lowering regeneration temperatures below 80 °C significantly reduces thermal degradation compared to conventional steam stripping. However, solvent degradation remains a risk in the presence of flue gas impurities. Furthermore, while

mild temperatures preserve the structural integrity of carbonic anhydrase, its long-term stability against pH fluctuations and mechanical or oxidative stress during continuous industrial cycling requires further experimental validation[49].

## 7 Regeneration without boiling: strategies and technical aspects

Figure 5 schematically illustrates three approaches for $CO_2$ desorption from amine-based solvents: conventional steam stripping, inert-gas-assisted desorption (including condensable carriers), and membrane-based desorption.

Traditional $CO_2$ desorption in amine-based capture systems is dominated by steam stripping, where high-temperature steam is passed through the loaded solvent to promote $CO_2$ release. This method relies on thermal energy to overcome adsorption equilibria, typically requiring temperatures of 120-150 °C for aqueous amine solutions [1, 22, 23]. While well-established and industrially mature, steam stripping incurs substantial energy penalties and contributes significantly to the operational cost of carbon capture.

$CO_2$ desorption can alternatively be driven by introducing an inert gas such as hydrogen (with the idea of utilizing the resulting mixture of $CO_2$ and $H_2$ downstream), which lowers the partial pressure of $CO_2$ in the gas phase and shifts the equilibrium toward desorption [50, 51]. Volatile, condensable species such as HFE-7100 could potentially also serve as inert carriers (although their suitability requires further investigation). Their low boiling points enable the desorbed $CO_2$ to be co-extracted and subsequently condensed, allowing the carrier solvent to be recycled and reducing overall energy consumption [52, 53]. Compared to steam stripping, inert-based methods can achieve desorption at lower temperatures while minimizing thermal degradation of the solvent. Nevertheless, this advantage must be evaluated at the process-system level, because non-condensable sweep gases in separation-only pathways may shift the exergy penalty downstream by generating dilute $CO_2$-containing mixtures that require energy-intensive purification. This penalty can be mitigated, however, if the sweep gas is directly integrated into a subsequent utilization step; for example, using $H_2$ as a sweep agent could avoid downstream $H_2/CO_2$ separation when the resulting mixture is further converted to methanol, thereby providing an additional opportunity for process intensification. For applications targeting purified $CO_2$, condensable sweep agents such as hydrofluoroethers are therefore preferred, as they can be recovered by condensation and reduce the need for mechanical downstream separation.

Membrane contactors offer a non-thermal route for $CO_2$ desorption. Gas-permeable membranes selectively transport $CO_2$ from the solvent into a sweep gas or vacuum stream, maintaining a driving force for desorption without bulk heating [40, 54]. Membrane systems are modular, minimize solvent degradation, and can be integrated with low-temperature heat sources or electrically driven processes to improve overall process efficiency. When permanent $CO_2$ storage is desired, the conventional desorption step can be replaced by a salt formation pathway, in which the absorbed $CO_2$ is converted into thermodynamically stable carbonate or bicarbonate solids.

Collectively, these approaches demonstrate that $CO_2$ desorption can be realized via thermal, inert-gas, or membrane-assisted strategies, enabling lower energy consumption and greater operational flexibility compared to conventional boiling-based regeneration [39, 50]. Nevertheless, these non-boiling pathways may require auxiliary purification to satisfy downstream $CO_2$ specifications or manage flue gas impurities. Additionally, rigorous water-balance control is essential to counteract moisture carryover and ensure stable solvent concentrations.

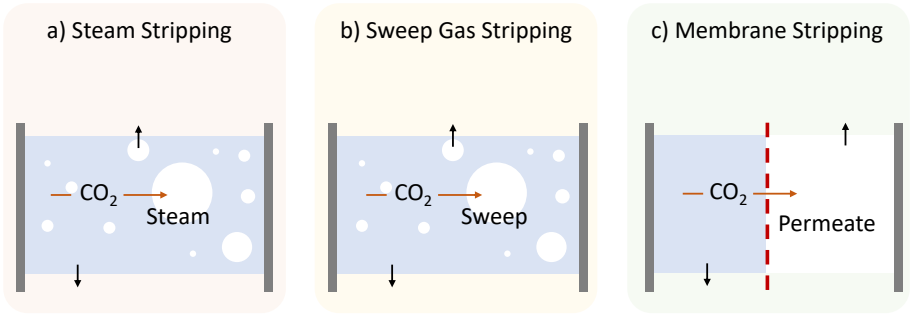



**Fig. 5**: Three different methods of $CO_2$ stripping.

A comparison of the three principal desorption routes highlights important differences in energy intensity and operational suitability. Steam stripping typically operates at elevated temperatures of 120–150 °C, enabling rapid and effective solvent regeneration; however, it is associated with substantial thermal energy demand and significant exergy losses due to the high-temperature heat input required. In contrast, sweep/inert gas desorption generally operates at lower temperatures of 60–90 °C, which reduces thermal degradation of the solvent and lowers overall thermal stress while improving energy efficiency. Membrane contactor-based desorption can operate at near-ambient to moderate temperatures depending on pressure gradients and membrane configuration, offering modularity, compact system design, and lower direct thermal energy requirements. Nevertheless, its effectiveness depends strongly on membrane transport characteristics and mass-transfer resistance.

## 8 Open Challenges and Research Priorities

Overcoming the limitations of conventional steam-based $CO_2$ desorption requires not only experimental exploration of novel solvents but also a fundamental rethinking of carbon capture strategies. The overarching goal is to enable effective desorption using the lowest possible grade heat, thereby minimizing energy consumption and improving process sustainability. Based on current knowledge, the following research priorities are highlighted:

**Research Priorities**

- Development of temperature-responsive solvents: Identifying and designing solvents whose properties change favorably with temperature to enhance $CO_2$ desorption without excessive thermal input.
- Exploration of alternative temperature-sensitive mechanisms: Beyond the discussed metrics such as p$K_a$ and miscibility, conceptualizing and investigating other molecular or physical properties that can be exploited to trigger desorption.
- Investigation of the system behavior of low-temperature carbon capture processes.
- Evaluation of synergies with enzymatic catalysis: Testing the ability of different solvents to coexist with carbonic anhydrase is important.
- Experimental validation of desorption strategies: Systematically testing the feasibility, efficiency, and scalability of different desorption methods, including inert-gas-assisted, condensable solvent-assisted, and membrane-based approaches.

Addressing these challenges is essential to advance low-energy carbon capture technologies and to transition from conventional steam-reliant processes to more sustainable, flexible regeneration methods.

## 9 Conclusions and Outlook

Low-temperature $CO_2$ capture strategies, including temperature- and pH-swing processes, catalytic enhancements, and membrane- or inert-gas-assisted desorption, offer a pathway to decouple regeneration from high-grade heat and reduce exergy losses. However, low-temperature regeneration is not inherently process-intensified at the apparatus level, as reduced driving forces may require larger heat-transfer areas and regenerator volumes. Its relevance to process intensification must therefore be evaluated at the process-system level, where increased equipment size may be offset by improved heat-source matching, reduced high-grade heat demand, lower solvent degradation, simplified utility integration, and reduced environmental impact. Future work should focus on optimizing solvent chemistry, ensuring catalyst or enzyme stability, and developing integrated process models that capture thermodynamics, kinetics, and mass transfer. Scaling these approaches and linking them to downstream $CO_2$ utilization will be critical to realize their full potential. Overall, these advances bear considerable potential to enable a flexible platform for carbon management and an improved exergy efficiency. A pathway to breaking the steam barrier could be distilled to:

**Breaking the steam barrier**

1. Selection of solvents with temperature-sensitive thermodynamic properties.
2. Acceleration of the reaction kinetics with carbonic anhydrase or other activators.
3. Implementation of technical solutions for low-temperature desorption or biochemical utilization of $CO_2$.

**Supplementary information.** A separate document with supporting information is provided as a pdf. The Python code for the thermodynamic models to produce all figures both in the main article and in the supporting information is provided on TORE. It can be accessed with the following DOI:
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**Declaration of interests**

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: