Exponential Temperature Sensitivity in CO_2 Capture and Release Systems

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December 16th, 2025

Abstract

Carbon dioxide capture technologies are commonly evaluated in terms of equilibrium capacity, material selectivity, and process scale. However, operational performance in practical systems is often dominated by temperature-dependent kinetics governing adsorption, regeneration, and material degradation. Here, we show that CO_2 capture efficiency and energy cost in widely deployed and proposed capture systems exhibit exponential sensitivity to operating temperature, such that modest thermal changes produce disproportionate impacts on capture capacity, regeneration energy, and lifecycle performance. This behavior arises from Arrhenius-controlled adsorption and desorption kinetics and establishes hard performance constraints that cannot be eliminated by scale or materials optimization alone. By synthesizing results from direct air capture, amine scrubbing, and solid sorbent systems, we identify temperature as the dominant control variable governing feasibility and efficiency. This framework provides a minimal, physics-grounded lens for evaluating CO_2 capture claims and designing systems that remain viable under realistic thermal conditions.

Introduction

Carbon dioxide capture is widely proposed as a critical component of climate mitigation strategies, with applications ranging from point-source capture to direct air capture (DAC). Over the past two decades, substantial effort has been devoted to developing materials and processes with high CO_2 selectivity and capacity. Despite this progress, large discrepancies persist between laboratory-scale performance and system-level viability.

A recurring challenge across capture technologies is the energy required for sorbent regeneration and CO_2 release. While often framed as an engineering optimization problem, regeneration fundamentally involves overcoming thermodynamic and kinetic barriers associated with CO_2 binding. These barriers introduce strong temperature dependencies that are frequently underemphasized in comparative evaluations.

In this work, we examine CO_2 capture systems through a minimal kinetic lens, focusing on the role of operating temperature in controlling capture efficiency, regeneration cost, and material stability. We show that many apparent performance limitations arise not from material inadequacy but from exponential temperature sensitivity intrinsic to adsorption–desorption processes. The intent of this work is as a constraint-framing analysis rather than a proposal of new capture architectures.

1. Central Claim

In practical CO_2 capture systems, operating temperature is the dominant control variable, imposing exponential constraints on efficiency, regeneration cost, and viability that cannot be removed by scale or materials optimization.

2. Rationale and Scope

This study does not introduce new capture materials or process architectures. Instead, it synthesizes existing experimental and operational results from established CO_2 capture systems—including aqueous amine scrubbing, solid sorbents, and direct air capture—to identify common kinetic constraints.

Previous analyses have emphasized equilibrium capacity, material selectivity, or system scale as primary determinants of feasibility. However, these metrics alone do not account for the steep performance cliffs observed during regeneration, cycling, and long-term operation. By isolating temperature as the dominant variable controlling adsorption and desorption kinetics, we provide a unifying explanation for these discrepancies.

The analysis relies exclusively on published data and established thermodynamic and kinetic principles, with the goal of providing a simple, falsifiable framework for evaluating CO_2 capture claims.

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3. Core Physical Basis

Adsorption and desorption of CO_2 in capture systems are governed by Arrhenius-type kinetics:

$$k \propto \exp\left(-\frac{E_a}{RT}\right)$$

where E_a is the activation energy associated with CO_2 binding or release. As a result:

- Capture efficiency decreases rapidly with increasing temperature once thermal energy competes with binding energy.
- Regeneration energy increases sharply as systems are driven across kinetic release thresholds.
- Small temperature differences can dominate system performance over material-specific improvements.

This behavior is observed across chemically distinct systems, including amine-based solvents, solid sorbents, and DAC architectures.

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4. Evidence Across CO_2 Capture Technologies

4.1 Amine Scrubbing Systems

Industrial amine scrubbing remains the benchmark for CO_2 capture. Despite decades of optimization, regeneration temperatures near 100–120 °C impose substantial energy penalties. Incremental reductions in regeneration temperature yield outsized improvements in system efficiency, consistent with exponential kinetic scaling.

4.2 Solid Sorbents and MOFs

Solid sorbents and metal–organic frameworks frequently demonstrate high CO_2 capacity under controlled conditions. However, capacity and cycling stability degrade rapidly outside narrow temperature windows, and regeneration often requires thermal swings that dominate lifecycle energy costs.

4.3 Direct Air Capture

DAC systems operate under extreme entropy constraints due to low atmospheric CO_2 partial pressure. Published analyses show that regeneration energy and capture efficiency are acutely sensitive to operating temperature, reinforcing that scale cannot overcome kinetic and thermodynamic limits.

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5. Implications

5.1 Evaluation of Capture Claims

Metrics that omit regeneration temperature, kinetic release rates, or thermal cycling behavior are insufficient for assessing real-world viability. Temperature sensitivity must be treated as a first-order constraint rather than an implementation detail.

5.2 System Design

Effective CO_2 capture systems must minimize thermal excursions across kinetic thresholds. Designs that rely on narrow temperature margins or high regeneration temperatures are intrinsically fragile at scale.

5.3 Deployment Strategy

Temperature sensitivity favors capture strategies coupled to low-grade heat sources or operating environments with stable thermal profiles. Conversely, systems requiring aggressive thermal management face compounding efficiency losses as scale increases.

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6. Conclusions

CO_2 capture systems across diverse architectures share a common constraint: exponential sensitivity to operating temperature governed by adsorption and desorption kinetics. This sensitivity explains why modest thermal changes produce large variations in efficiency, energy demand, and durability, and why scale alone cannot resolve performance limitations.

Temperature thus represents a high-leverage design parameter: incremental thermal optimization can compound into substantial gains in efficiency and lifecycle performance.

By reframing CO_2 capture through a minimal kinetic lens, this work provides a practical framework for evaluating capture technologies and identifying designs that remain viable under realistic operating conditions. Temperature is not a secondary parameter; it is the dominant control variable shaping the feasibility of CO_2 capture at scale.

References

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