Agile vs. Brittle Economies: Optimal CCUS Portfolios at the Abatement Wall

Introduction

Climate change, driven by the accumulation of greenhouse gases (GHGs), necessitates a rapid transition to net-zero emissions. While renewable energy deployment is accelerating, the global economy faces an ”abatement wall”—a threshold where the marginal cost of conventional decarbonization escalates dramatically due to diminishing returns. This barrier arises from a convergence of physical and economic constraints: the finite availability of land for solar and bioenergy, the exponentially rising costs of grid integration for variable renewable energy, and the thermodynamic rigidity of industrial process emissions (e.g., in cement and steel) that cannot be eliminated via electrification.

At this wall, Carbon Capture, Utilization, and Storage (CCUS) emerges not merely as a transitional technology, but as a structural necessity to address these prohibitive marginal costs (IPCC, 2005; IEA, 2021). However, the deployment of CCUS remains slow, and the economic literature often treats Carbon Utilization (CU) and Carbon Storage (CS) as a monolithic block. This study contributes to the literature by developing a theoretical framework that explicitly models the trade-offs between consuming a polluting resource, utilizing the captured carbon as a productive input (source substitution), and storing it in geological formations (end-of-pipe cleanup), as illustrated in Figure 1. We adopt a social planner perspective to determine the efficiency benchmark for deploying these technologies.

Our primary contribution is the identification of a structural dichotomy between what we term “Agile” and “Brittle” economies. We demonstrate that the optimal response to increased climate pressure (or a higher carbon price) depends critically on the economy’s structural flexibility. Counter-intuitively, in an agile economy, a higher social cost of carbon may lead to a decrease in carbon storage, as resources are reallocated toward more efficient utilization and consumption reduction.

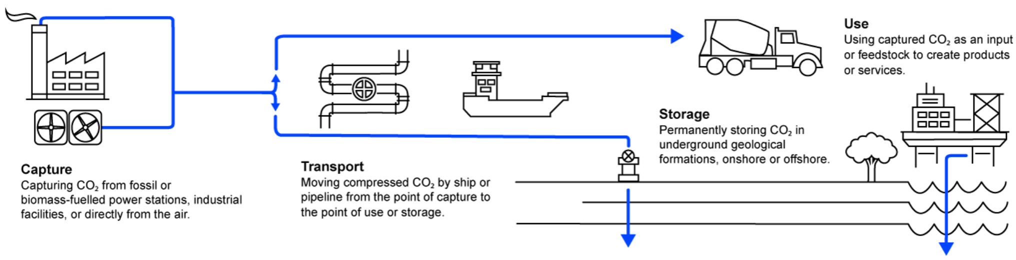

Figure 1: *Schematic of the CCUS value chain and abatement pathways (IEA, 2022).*

Method and Theory

We construct a static social planner model to analyze the optimal allocation of resources. The planner maximizes social welfare, W, which is derived from a composite consumption good, x, net of the costs of resource extraction (C_d), utilization (C_a), storage (C_s), and environmental damages (h).

The total consumption x is produced using a polluting resource, x_r, and utilized carbon, $\alpha_d a_d$, where a_d is the amount of captured CO_2 and $\alpha_d \in [0,1)$ represents the conversion efficiency. The optimization problem is defined as:

$$\max_{x,a_d,a_s} W = U(x) - C_d(x - \alpha_d a_d) - C_a(a_d) - C_s(a_s) - h(\xi(x - \alpha_d a_d) - a_s) \tag{1}$$

Subject to the constraints that net emissions cannot be negative and utilization is limited by the available carbon stock. Here, ξ represents the emissions conversion factor (intensity), effectively serving as the shadow price of pollution or a Pigovian tax. The damage function $h(\cdot)$ is strictly convex ($h'' > 0$), reflecting the increasing marginal damage of emissions.

We solve the model using the Kuhn-Tucker conditions and perform comparative statics to analyze how the optimal portfolio (x^*, a_d^*, a_s^*) responds to exogenous shocks, specifically changes in the emissions intensity (ξ) and technological efficiency (α_d).

Results: The Agile vs. Brittle Dichotomy

The analytical solution reveals that while a higher emissions penalty (ξ) unambiguously reduces polluting resource use (x_r) and increases utilization (a_d), the response of carbon storage (a_s) is ambiguous. We derive a critical threshold condition that governs this response:

$$\frac{\partial a_s^*}{\partial \xi} \geq 0 \quad \text{if and only if} \quad x_r^* \geq \frac{\xi h'}{\Delta^{-1} + C_d''} \tag{2}$$

where $\Delta \equiv \frac{\alpha_d^2}{C_a''} - \frac{1}{U''}$ represents the structural flexibility of the economy. This parameter Δ combines the efficiency of utilization technology relative to its cost convexity (α_d^2/C_a'') and the flexibility of consumer demand ($1/U''$).

Agile Economies: An economy is defined as ”Agile” when Δ is high. This occurs when utilization technologies are highly efficient or consumption preferences are flexible. In this regime, the threshold in Eq. (2) is high. Consequently, an increase in climate damages (ξ) induces a substitution away from storage ($\partial a_s^*/\partial \xi < 0$) in favor of efficient utilization and output reduction. The economy ”leaps” over the abatement wall by restructuring production rather than relying on end-of-pipe solutions.

Brittle Economies: Conversely, a ”Brittle” economy is characterized by low Δ (rigid demand, inefficient utilization) or high extraction cost convexity (C_d''). Here, the threshold is low. Facing an abatement wall, the planner has no viable alternative but to expand storage capacity ($\partial a_s^*/\partial \xi > 0$) to mitigate rising damages. This mirrors the situation of resource-dependent nations bound by rigid export contracts or industries with immovable process emissions. This economic logic is visualized in **Figure 2**, which demonstrates how the social planner switches between consumption reduction, utilization, and storage based on the intersection of the marginal benefit of utilization and the marginal social cost of the resource.

Furthermore, our results indicate that innovation policies targeting utilization efficiency (α_d) act as productivity enhancers. An increase in α_d expands the production frontier, allowing for higher consumption (x^*) while simultaneously reducing reliance on both the polluting resource and geological storage. This contrasts with storage support, which acts strictly as a cost-management tool for residual emissions.

Conclusions

This study challenges the view that Carbon Storage must strictly increase with carbon pricing. We show that the optimal abatement portfolio is contingent on the economy’s structural agility. In agile economies, innovation in utilization allows for a decoupling of economic activity from waste generation, rendering massive storage expansion redundant. However, for brittle economies—and specifically for hard-to-abate sectors—storage remains an indispensable backstop.

Policy frameworks must therefore be differentiated. For agile sectors (e.g., chemicals, synthetic fuels), subsidies should target R&D to lower utilization costs (ϕ_a) and improve efficiency (α_d), effectively creating value from waste. For brittle sectors (e.g., cement, waste-to-energy), policy must focus on

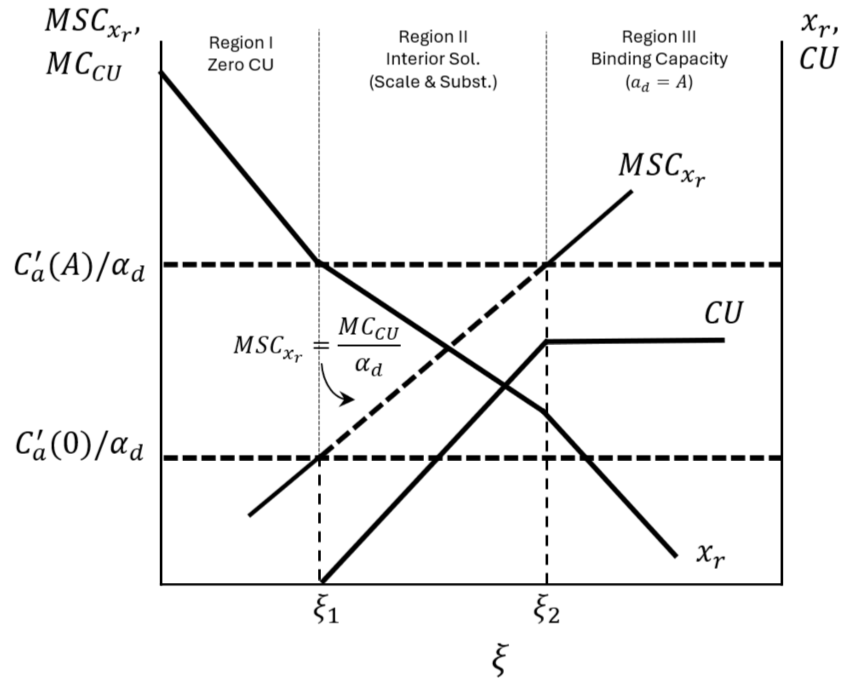

Figure 2: *Impact of Emissions Conversion Factor on Marginal Costs and Resource Substitution. The diagram illustrates how the social planner switches between consumption reduction, utilization, and storage based on the intersection of marginal benefits and costs.*

de-risking transport and storage infrastructure to lower the effective cost of storage (ϕ_s). By recognizing CCUS not as a monolithic solution but as a diversified portfolio, policymakers can minimize the total social cost of the net-zero transition.

References

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