# Balancing Carbon Dioxide Removal Options: Lessons Learned from Techno-Economic Modelling on Resource Trade-Offs and Sustainable Energy Transitions?

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## Overview

Achieving net-zero carbon emissions by around 2050 is crucial to limiting global temperature rise to 1.5°C by the end of the century. This ambitious target requires a rapid transition to clean energy production alongside the deployment of Carbon Dioxide Removal (CDR) technologies[1]. CDR encompasses natural solutions, technology-based methods, or a combination of both. In the face of pressing challenges such as climate change and biodiversity loss, climate scientists are increasingly emphasizing Natural Climate Solutions (NCS) [2, p. 303]. Such activities like afforestation, reforestation, and forest management contribute approximately 2,000 $MtCO_2$/year in removals over the period 2013–2022, depending on the emission accounting method employed [3, p. 132]. Meanwhile, technology-based CDR methods, such as Direct Air Capture (DAC) and Bioenergy with Carbon Capture and Storage (BECCS), are projected to scale to multi-gigatons levels by 2050 and beyond [4]. Unlike NCS, which provide temporary $CO_2$ storage, these technologies offer more permanent storage solutions through Carbon Capture and Storage (CCS). However, their widespread adoption faces challenges including high costs, resource intensity, and social acceptability concerns. Integrated Assessment Models (IAMs) play a critical role in ensuring coherence across energy, land, water, and climate systems in CDR-driven pathways. These models are particularly valuable in evaluating net-zero emissions strategies aligned with mid-century targets set by various countries or regions through their Nationally Determined Contributions (NDCs), such as Australia, the USA, Canada, Europe, Brazil, South Korea, China (targeting net-zero by 2060), and India (by 2070). IAMs also support the assessment of less emissive energy systems, such as biogenic energy production, and explore emissions reduction and carbon dioxide removal opportunities, including improved land management practices.
This study addresses critical research gaps by adopting a comprehensive approach to operationalize a suite of CDR strategies. It explores their deployment through the lenses of policy, environmental impact (e.g., water and land use), and sustainability, extending beyond techno-economic considerations to facilitate large-scale implementation. By highlighting biophysical aspects of CDR into the modeling of net-zero pathways, this research contributes to advancing climate change mitigation efforts.

## Methods

Long-term prospective modelling assesses plausible energy system evolutions to support early strategic decisions. Built on mathematical optimization, such models link economic and technological systems with environmental impacts, determining optimal technology configurations and associated emissions under projected scenarios. We use the TIAM-FR, the CMA's version of the TIMES Integrated Assessment Model, representing the world energy system in 15 regions. TIMES is a methodological corpus developed under the IEA's Energy Technology Systems Analysis Program (ETSAP)[1]. This bottom-up optimization model gives a detailed description of technologies and end-uses constituting the Reference Energy System (RES) linking the different sectors and optimizing investments, operations, energy supply, and trade at minimal global cost. By using the demand projection functions of TIMES, this model uses the inputs from the Shared Socio-economic Pathways (SSPs) [5], and a climate module that we parametrize according to [6]. To address the role of the AFOLU sector, we soft-link TIAM-FR with GLOBIOM of the International Institute for Applied Systems Analysis (IIASA). GLOBIOM is a global economic land use model, and we use a model emulation. The idea is that achieving a reduction of greenhouse gases (GHG) through the AFOLU sector and evaluating biomass for bioenergy potentials involves biophysical and technical measures to be ensured. Additionally, we include a water allocation module to assess water use in electricity generation and carbon removal (BECCS, DACS), and the water footprint of biocrops. This is meant for addressing resource trade-offs and ensuring sustainable energy transitions.

## Results

The implementation of climate policies is essential for achieving net-zero emission targets. By leveraging both technical and political frameworks, we analyze the future global energy mix required to meet decarbonization goals, with a particular focus on the long-term need for CDR under these constraints. Using TIAM-FR, we project the global

[1] www.iea-etsap.org

energy system's activity through 2100 under two scenarios aligned with the Paris Agreement, incorporating countries' NDCs and net-zero commitments to reflect current policies.
The first scenario follows a middle-of-the-road SSP2-45 pathway, corresponding to a Representative Concentration Pathway (RCP) that limits temperature rise to 2°C. The second scenario, also aligned with the Paris Agreement, follows SSP2-19, which targets a more ambitious temperature limit of 1.5°C. These scenarios provide a comprehensive framework for evaluating the transitions required to achieve global climate goals.

The shares of afforestation, reforestation, deforestation reduction and forest management are implemented for carbon removal. Moreover, BECCS and DACS deployment are explored, and a techno-economic arbitration is presented. We evaluate the cost implications of bioenergy crops, electricity production and storage, land availability, and policy support. Additionally, we explore sustainable pathways for bioenergy by investigating feedstock options, including regional availability, trade dynamics, and environmental constraints. This allows for a detailed discussion on BECCS technologies, focusing on balancing their limitations and synergies. By addressing these aspects, we aim to reconcile various solutions in a long-term strategy, providing a realistic and enriched assessment of the evolution of the global energy system. By addressing their limitations and synergies, we aim to reconciliate between these solutions in a long-term discussion for an enriched and realistic assessment of the evolution of the world energy system. Furthermore, the arbitration between the vast portfolio of CDR options (related to AFOLU, to technologies or a combination) includes an analysis of the various effects of these options on sustainable development through the Sustainable Development Goals (here SDG 2, 6, 12, 13 and 15).

## Conclusions

The presented work highlights the role of CDR, with a special focus natural climate solution, under varying levels of climate mitigation. In context of net-zero targets, reliable sequestration needs to be deployed with a comprehensive outlook. Through scientific-based decisions it is possible to implement effective policies and mechanisms that ensure these solutions viability. Integrating TIAM-FR and GLOBIOM adds a cross-sectoral and interdisciplinary perspective. Also, with TIAM-FR water allocation and utilization of climate parameters, we apply a realistic approach for assessing the environmental impacts and temperature variation while accounting to $CO_2$ and non-$CO_2$ emissions. The results would allow to conduct a technical and policy-oriented discussion and address other issues relevant to climate change mitigation like integrating natural solutions and technology-based CDR in carbon markets or using natural solutions for climate change adaptation.

## References


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