



Land–energy nexus to assess the contribution of carbon dioxide removal in net-zero emission pathways

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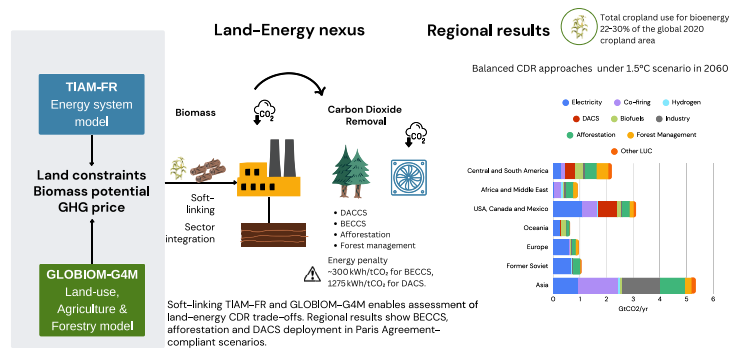
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HIGHLIGHTS

- Novel TIAM-FR and GLOBIOM-G4M link quantifies land-energy CDR interactions.
- CDR strategies assessed for emission cuts with reduced cropland pressure.
- China and the Americas show the most diversified CDR portfolios.
- BECCS deployment depends on sectoral integration and biomass supply.
- GHG and biomass pricing drive the cost-effectiveness and regional allocation of CDR strategies.

GRAPHICAL ABSTRACT



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ABSTRACT

The land and energy sectors can provide efficient mitigation solutions for climate change through different types of solutions including Carbon Dioxide Removal. Given the strong interdependencies between these sectors, an integrated assessment is relevant to ensure both physical feasibility and economic viability. To achieve the temperature increase limitations set out in the Paris Agreement, biomass-based solutions constitute a potential avenue for the sectoral decarbonization of the energy system. This study addresses these interactions by linking two Integrated Assessment Models (IAMs): TIAM-FR, which represents the global energy system, and GLOBIOM-G4M, which models global land-use dynamics. The analysis examines the key factors affecting bioenergy expansion to achieve negative emissions, including the deployment of dedicated energy crops, which supply 54–55 EJ yr⁻¹ of bioenergy and will occupy around 215 million hectares of land in the net-zero year (2060),

Abbreviations: A/R, Afforestation/Reforestation; IAM, Integrated Assessment Model; IEA, International Energy Agency; TIAM-FR, TIMES Integrated Assessment Model – France version; TIMES, The Integrated MARKAL-EFOM System; GAEZ, Global Agro-Ecological Zones; GLOBIOM, Global Biosphere Management Model; G4M, Global Forestry Model; BECCS, Bioenergy with Carbon Capture and Storage; CDR, Carbon Dioxide Removal; DACS, Direct Air Carbon Capture and Storage; CCS, Carbon Capture and Storage; CCU, Carbon Capture and Utilization; CHI, China; CSA, Central and South America; MACC, Marginal Abatement Cost Curve; LUC, Land-Use Change; LP, Linear Programming; AFOLU, Agriculture, Forestry and Other Land Use; SSP2, Shared Socioeconomic Pathway 2; RCP, Representative Concentration Pathway; GHG, Greenhouse Gas; SDGs, Sustainable Development Goals; RES, Renewable Energy Sources; Mt, Million tons; t DM/yr, Tons dry matter per year; NDC, Nationally Determined Contribution; NETs, Negative Emission Technologies; ODA, Other Developing Asia; USA, United States of America; UNFCCC, United Nations Framework Convention on Climate Change.

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excluding additional cropland used for conventional bioenergy feedstocks. Net global CO₂ emissions are reduced by about 88% in the 2 °C pathway, whereas the 1.5 °C scenario exceeds a 100% reduction, corresponding to net-negative emissions of around $-4 \text{ GtCO}_2 \text{ yr}^{-1}$. Cost-relevant trade-offs are reflected in CDR energy requirements, with 1275 kWh tCO₂⁻¹ for direct air capture and storage and $\sim 300 \text{ kWh tCO}_2^{-1}$ for bioenergy carbon capture and storage. The study also provides a replicable framework for assessing trade-offs between bioenergy deployment and land-use sustainability.

1. Introduction

Achieving net-zero emissions, which is crucial to limiting global warming to 1.5 degrees Celsius (°C), involves rapid emissions reductions across all sectors alongside scaling up Carbon Dioxide Removal (CDR) [1]. The latter is particularly relevant to the abatement of incompressible emissions and is also an option in carbon trading mechanisms under Article 6 of the Paris Agreement, which promotes higher ambitions in mitigation, adaptation, and sustainable development. Current research relies increasingly on IAMs, which combine energy, land use, economics, and climate to evaluate the pathways for meeting climate objectives and determine the required levels of mitigation solutions including CDR in the future trajectories of these systems.

CDR strategies such as afforestation and bioenergy with carbon capture and storage (BECCS) help remove carbon from the atmosphere and influence the sustainability of land use [2–4]. Evaluating the energy–land nexus is essential because these strategies rely on land and biomass resources, which are limited and often compete with other land uses such as food production and biodiversity conservation.

Furthermore, studies highlight that afforestation is a cost-efficient method for carbon removal at lower carbon prices, while bioenergy with CCS becomes competitive at higher prices, showcasing the importance of pricing mechanisms in driving land-based mitigation strategies [5]. Such topics, discussed below, can be analyzed through global IAMs that include energy system interactions with the other sectors and systems mentioned previously.

Hence, in this work, the land use sector is integrated into the TIMES Integrated Assessment Model of the global energy system, developed by the Centre for Applied Mathematics (CMA), TIAM-FR. TIMES, a methodological framework developed under the Energy Technology Systems Analysis Program (ETSAP) of the International Energy Agency (IEA), offers a comprehensive approach to energy systems modeling [6]. The global version of this model was initially introduced in [7] where the foundational description of TIMES/TIAM structure and optimization are detailed. This structure serves as a basis for TIAM-FR and has been gradually developed to take into account the complexity and challenges of systems (such as water management in heat and power generation [8], detailed representation of biomass [9], and possibilities of cement sector decarbonization [10]). The Global Biosphere Management Model (GLOBIOM) coupled with the Global Forestry Model (G4M) emulated in [3] is employed with a soft-link approach for the land use part, described in detail in this article.

1.1. Research question and contribution

This paper develops a cross-scale soft-linking framework that coordinates independently optimized global land-use and energy system models through explicit biomass and carbon price signals, enabling a transparent assessment of land–energy constraints on CDR pathways. IAM frameworks such as GCAM [11,12] and MESSAGEix–GLOBIOM [13] already represent land–energy interactions, but within unified modeling architectures. The approach developed here preserves independent model optimization and allows land-use constraints and economic signals to be imposed externally on the energy system.

The core contribution of this manuscript is twofold:

- (i) the development of a methodological extension based on price- and constraint-driven soft-linking, which enables the identification of binding land–energy constraints on CDR deployment; and
- (ii) new insights into how land scarcity and economic signals jointly shape the feasibility, cost, and composition of CDR portfolios under mitigation scenarios.

More specifically, this methodological framework is implemented in the TIAM-FR energy system model to coordinate land-use constraints and land-based CDR options. To this end, TIAM-FR model is linked to the GLOBIOM-G4M emulation, which is a dataset combining biomass and greenhouse gas (GHG) price trajectories for the Shared Socioeconomic Pathway SSP2, a middle-of-the road trajectory described in [14]. Elaborating the linking method is very useful for enhancing modeling approaches. While biomass supply was previously represented in TIAM-FR mainly through techno-economic potentials [9], the coupling with GLOBIOM introduces land-use, biophysical, and sustainability constraints modeled in the land-use system and propagated to the energy system optimizations. To date, no TIAM model has been linked to a land-use model in this manner.

This association embeds land-use feasibility and bioenergy supply limits in the energy model through explicit biomass pricing and carbon pricing mechanisms, which are common parameters across IAMs. It further enables a systematic assessment of how land-based CDR options affect energy supply, mitigation portfolios, and trade-offs like applying land-use efficiency. The analysis also determines bottlenecks (land competition in feedstocks, energy penalties for capture, etc.) and sustainability constraints. Finally, the aim is also to provide policy-relevant implications and a framework that is reproducible and extensible to additional constraints like water consumption.

2. Land-based CDR as a critical component of mitigation pathways

Incorporating CDR, in particular land-based solutions, enhances the effectiveness of climate change mitigation efforts through exploring cross-sectoral synergies. Their role of these solutions is highlighted in [1] as strategies to achieve carbon neutrality by 2050 and GHG emission neutrality at a later date, to counterbalance residual emissions, and to achieve net-negative emissions [4]. The land-related CDR methods covered in this study are the reduction of deforestation, the increase in afforestation, the improvement of forest management, and BECCS.

Integrating and improving our comprehension of the interactions between the land-use sector and the energy system not only provides important strategies for mitigating climate change, but it also constitutes a steppingstone toward representing the remaining CDR options. These remaining options include agroforestry, biochar in agriculture, soil carbon sequestration and enhanced rock weathering (ERW) [15]. Recent field and modeling studies indicate that ERW on cropland can couple durable CO₂ removal with yield and soil-pH benefits, thereby mitigating land-use conflict by delivering CDR on existing farmland [16,17]. Moreover, soil carbon sequestration practices provide co-benefits for productivity and resilience, supporting sustainable food production alongside mitigation [18]. While some integrated assessment and sectoral modeling frameworks have begun to represent practice-based CDR options such as agroforestry, biochar, or enhanced weathering [12,19], these options are not explicitly represented in the present framework, as

they are not endogenously modeled in GLOBIOM-G4M. The discussion of these options here therefore serves to situate the contribution of this work within the broader CDR landscape and to highlight potential extensions enabled by improved land–energy integration.

Nevertheless, IAM assessment in land-based mitigation options can be limited due to coarse regional aggregation, which entails averaging yields, land and management and thus eradicating intra-regional heterogeneity in climate, soils, and accessibility. In contrast, high-resolution datasets reveal whether biomass productivity is high or low at the kilometer scale. Yield representation is also affected by reduced-form response functions and by the limited set of crop/vegetation models employed in IAMs. Currently, bioenergy yield maps based on machine learning can show detailed climate and soil properties [20]. Moreover, supply chain modeling shows that ignoring multi-year spatial and temporal variation in yields can significantly underestimate delivered biomass costs and risks to plant operation [21].

Land pressure is defined by the strain placed on land resources due to anthropogenic activities, which have already altered 70% of the Earth's ice-free land surface according to [22]. While land use can mitigate climate challenges through carbon sequestration, ecosystem restoration, and regulatory policy instruments, extensive or single-technique deployment of negative emissions technologies may have significant land impacts. Expanding biomass production for bioenergy and afforestation has serious consequences. The report notes that expanding biomass via fertilizer and irrigation or monoculture plantations can increase local land degradation risks. At the same time, food systems are responsible for 80% of global deforestation caused by agriculture, which also accounts for 70% of the world's freshwater use. The report highlights five key pillars shaping land-based management techniques: mitigation, adaptation, desertification, land degradation and food security.

In this work, land-based carbon removal is placed in the mitigation context through relying on both TIAM-FR and GLOBIOM-G4M. Two mitigation pathways are explored by establishing hypotheses where policy targets are screened and translated into mathematical constraints. Socioeconomic and forcing parameters from SSPs and Representative Concentration Pathways (RCP) are considered to shape the mitigation solution simultaneously (Section 2.1). Looking at representative IAMs in Section 2.2, some models are found to either co-optimize energy and land use, provide a detailed land-use and forestry representation with land allocation and forest management, or produce carbon price trajectories with varying biomass availability. This review highlights the need for timely deployment of CDR options to meet climate goals and emphasizes the need for a diversified set of CDR options given technical and ecological uncertainties.

2.1. Scenario design and assumptions

Focusing on net-zero emissions trajectories, the energy–land contributions are studied through two scenarios that align the temperature increase by the end of the century to 1.5 °C and 2 °C as per the Paris Agreement. The “middle-of-the road” pathway SSP2 is chosen for the sectoral drivers until 2100 as it provides balanced assumptions regarding population, economic growth, land-use pressures, and technological change [14,23]. SSP2 represents an intermediate path between the high-productivity, low land-pressure conditions of SSP1 and the high land-pressure, lower-productivity characteristics of SSP3 [24]. This makes SSP2 suitable for isolating the effects of CDR deployment and land–energy interactions, without the structural socioeconomic shifts introduced in sustainability-oriented (SSP1) or fragmentation-oriented (SSP3) pathways [25].

The analysis further concentrates on climate-stringent pathways in which CDR deployment and land-use constraints play an active role in shaping mitigation outcomes. As highlighted by the IPCC AR6 assessment, large-scale CDR deployment and binding land-use constraints emerge predominantly in pathways limiting warming to well below

2 °C, whereas higher-warming stabilization pathways (e.g., RCP6.0 type scenarios, represented in CMIP6 by SSP4–6.0 [26]) exhibit weaker land–energy interactions and typically rely only marginally on engineered CDR. Also, medium-term NDC trajectories and current policy pathways remain substantially above Paris targets and do not systematically require coordinated land–energy strategies for CDR deployment. This focus enables a transparent assessment of land–energy coordination under conditions where land availability, biomass supply, and land-use emissions become system-relevant.

Nevertheless, we include an emissions trajectory that follows the Nationally Determined Contributions (NDCs) considering the documents submitted to the United Nations Framework Convention on Climate Change (UNFCCC) registry, including the net-zero emissions featuring in the NDCs of specific counties. Further details are provided in Appendix C.

The designed scenarios are essentially used to assess the energy system evolution of TIAM-FR, enriched with land use contributions from GLOBIOM and assumptions that are elaborated as inputs and constraints in the energy model. As explained in the TIAM-FR method section, the baseline version integrates the agriculture and forestry sectors for energy purposes. The energy plantation potential is calculated endogenously by the model based on the input concerning land use requirements and the processes for extraction and for transforming crops into bioenergy feedstocks. The remaining biomass feedstocks are exogenous while accounting for the surface availability, based on [9]. With the integration of GLOBIOM, the level of primary bioenergy available considers the global Agriculture Forestry and Other Land Uses (AFOLU) sector, and thus these values are all replaced with GLOBIOM inputs.

Based on the above, two scenarios aligning with the Paris Agreement are developed:

- “2 °C”: assumes a temperature increase limited to 2 °C by the end of the century, with allowed overshoot, NDCs guiding emissions trajectories, and CO₂ concentrations following SSP2–26 with a nominal 2.6 W/m² radiative forcing level by 2100.
- “1.5 °C”: assumes a temperature increase limited to 1.5 °C by the end of the century, with allowed overshoot, and CO₂ concentrations following SSP2–19 with a nominal 1.9 W/m² radiative forcing level by 2100. This illustrates a net-zero pathway where GHG emissions achieve net zero by mid-century.

Although both scenarios allow a temperature overshoot, the resulting variation shown in Fig. 1 did not yield any excess with respect to the temperature limitation. For both cases, radiative forcing, which is a measure of the incoming solar radiation and outgoing thermal radiation in the Earth's atmosphere, peaks in 2040. This can be caused by various GHG, and it is assumed in the model's climate module that the contribution of these gases is additive. The magnitude of the temperature increase is proportional to the radiative forcing, although the exact relationship is complex and includes uncertainties due to the climate system feedback. More details on the equations can be found in [27]. A steep decline is noted for the 1.5 °C scenario between 2040 and 2080 which reflects in a slight decrease in temperature variation (Fig. 1) despite a general stabilization.

2.2. Implementing land mitigation in the energy system

In [28], the scenarios studied from different IAMs all include CDR with cumulative values varying from 500 GtCO₂ to 800 GtCO₂ in 2100, depending on the model and scenarios. The study of these scenarios shows that CDR plays multiple roles in accelerating early emissions reductions, offsetting residual emissions to achieve and sustain temperature stabilization, and reducing CO₂ forcing after peak warming is reached. Furthermore, deploying CDR is related to the decarbonization of the energy system because it employs bioenergy with CCS for electricity and fuel production [2].

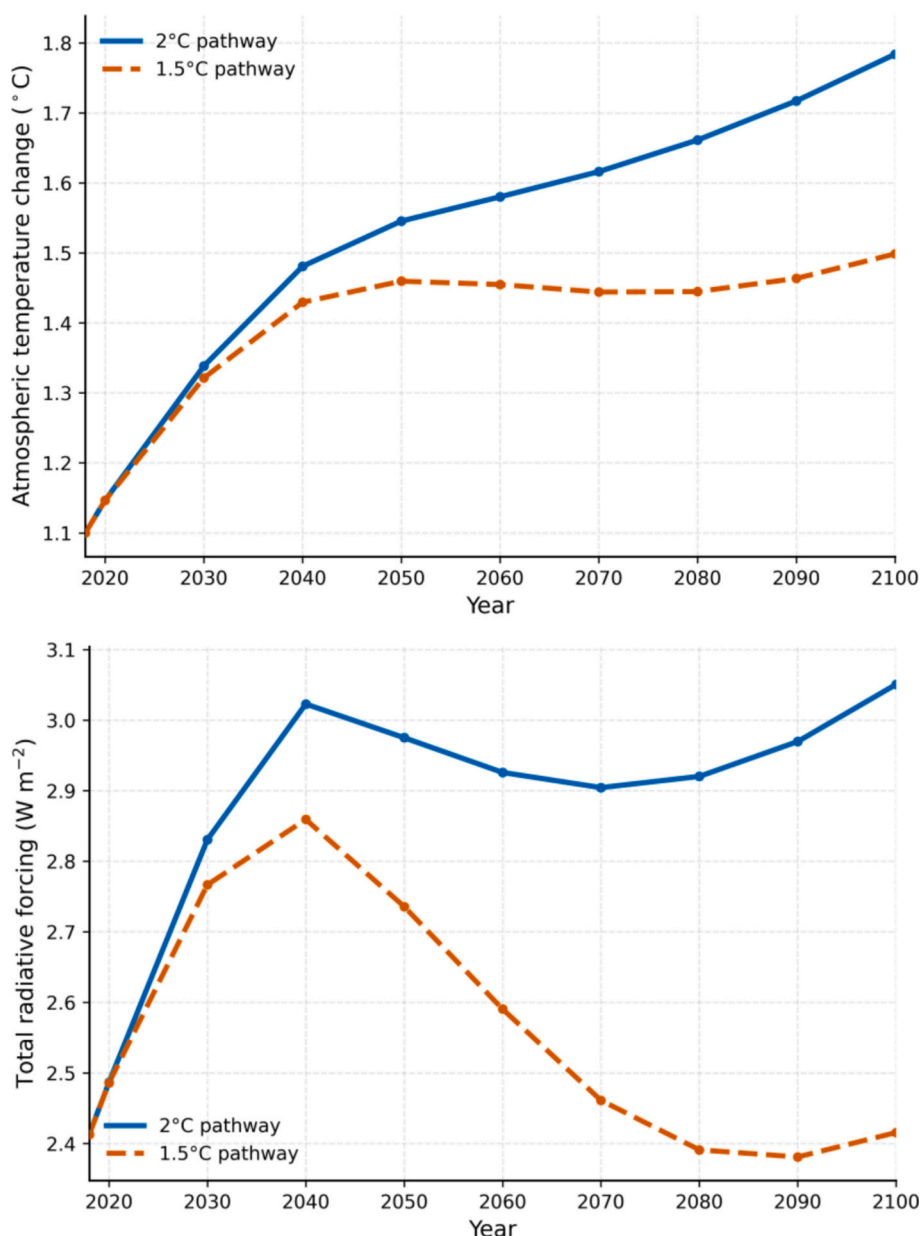


Fig. 1. Climate outcomes under the 2 °C and 1.5 °C pathways. 1a. Atmospheric temperature change, under the 2 °C and 1.5 °C pathways. 1b- Evolution of total radiative forcing under the 2 °C and 1.5 °C pathways. Panel (a): Global mean atmospheric temperature change (°C). Panel (b): Total radiative forcing ($W m^{-2}$). Values for the model base year (2018) are included in the data but omitted from the axis labels for visual clarity.

Biomass plays a critical role in the carbon cycle due to its biogenic nature, linking GHG emissions and removals. Unlike fossil fuel combustion, biomass combustion is considered to release carbon previously absorbed during growth, maintaining a balanced biogenic carbon cycle when sustainably managed, in other words, when ensuring that biomass extraction does not exceed the rate of the plants' regrowth. This is critical to ensure that the carbon released during biomass conversion is reabsorbed by new plant growth. Moreover, responsible forest management and ecosystem conservation should protect habitats and carbon stocks. Nevertheless, the utilization of organic waste and residues needs to be prioritized, as well as the use of advanced technologies. Biomass contributes to emission removal and serves as a key energy resource, with feedstocks sourced primarily from agriculture, forestry, waste, energy crops, and roundwood production, particularly in Europe [29], where biomass uses for energy have increased sharply, accounting for 22% of total uses [30]. Europe's bioeconomy footprint has also increased, which is impacting ecosystem services such as pollutant

filtration and carbon sequestration, affected by biomass production ecosystems. The trade of biomass also supports supply and economic benefits, with regional variations depending on feedstock availability.

Recent studies confirm the importance of linking biomass supply, abatement options, and GHG prices in integrated assessment. Multi-model analyses using MESSAGEix-GLOBIOM and REMIND-MAgPIE show that carbon price trajectories strongly influence the allocation of land-based mitigation between BECCS and afforestation, with outcomes highly sensitive to biomass supply curves and land constraints [31,32]. Model documentation from GLOBIOM [33] further highlights how price-responsive biomass and AFOLU abatement cost curves enable consistent transmission of carbon price signals into land-use outcomes. Global scenario frameworks such as [34] similarly demonstrate how rising carbon prices propagate through energy-land linkages, reshaping the balance between bioenergy deployment and alternative CDR options. Studies highlight that biomass supply varies significantly between models globally and regionally [35]. It appears that various factors

influence the opportunity cost of producing modern biomass, such as land allocation, which affects land used for growing food. Other benefits and costs are affected, such as emissions, land use, and management. Consistent with recent integrated assessment of CDR portfolios (BECCS, A/R, Direct Air Capture and Storage (DACs), biochar, enhanced weathering), diversified mixes reduce land–energy trade-offs and system risks compared to single-option strategies, with portfolio composition varying strongly by region [36].

To date, two methods have proved to enhance our understanding of biomass supply in climate mitigation pathways [35]. They involve either setting scenarios for bioenergy demand with GHG costs or using biomass supply curves with exogenously specified biomass prices. GHG pricing or carbon pricing is used to set an emissions cost in order to incentivize reductions and can depend on various factors. This price is influenced by the combined effect of the incorporated policies, which can vary widely. Examples of studies highlighting the abatement options and the interaction of biomass supply and GHG prices are presented in Table 1. It is worth noting that the SSPs are developed using these models among others [37], providing general narratives and key socioeconomic developments. A middle of the road development storyline which concerns both mitigation and adaptation was developed with MESSAGEix-GLOBIOM. This option represents the marker quantification for the SSP2, where it assumes key elements related to the AFOLU sector, like forest loss of 1% by 2050, moderate crop yield growth (0.51% per annum in the North and 0.66% in the South), and moderate growth in food demand [14].

The study [3] is based on a land-use model, i.e. GLOBIOM [33], whose outputs can be used in different IAMs. GLOBIOM is usually linked to MESSAGEix as part of IIASA's integrated assessment modeling framework consisting of 5 different modules or models. It provides MESSAGEix, whose objective is to optimize an energy system, with information on land use, bioenergy, AFOLU costs, and availability. GCAM and REMIND-MAGPIE, mentioned in Table 1, integrate the energy, land, and water sectors. They are also used to assess mitigation options; however, each model is linked to or integrates land use differently.

GCAM [32] incorporates endogenous land-use dynamics, simulating decisions based on factors such as historical land use, vegetation carbon density, and profit rates [11]. Climate mitigation strategies related to the land use module include bioenergy potential and its impact on ecosystems, effects of carbon taxes and trading on land use decisions (see Table 1), and sustainable agricultural practices. While effective for integrated assessments, its structure limits flexibility in adapting land-use outputs to external energy system models. REMIND-MagPIE [38,39] employs a soft-link approach, iteratively exchanging information between models to capture interactions between land use and economic factors, where MagPIE provides the availability of biomass and total emissions from land-use. It also influences agricultural production and land-use decisions, resulting in increased computational complexity for this iterative process. BENOPTex [19] and PyPSA [40,41] based applications integrate biomass supply and BECCS directly within energy system optimization, resulting in hard-linked representations of technological and carbon removal options. BENOPTex endogenously chooses among pre-defined land-use and management options (e.g. specific energy crops versus alternative uses) but relies on scenario-level assumptions for the magnitude and sustainability of land availability, rather than simulating land-use transitions itself. The soft-linking approach adopted in this study occupies an intermediate position: it preserves the specialization of detailed land-use modeling while enabling transparent exchange of land constraints, emissions, and price signals with a global energy system optimization model. Table 1 situates the proposed framework within this broader modeling landscape.

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3. Methods

This part describes the optimization and functioning of the models in Sections 3.1 and 3.2, while respectively focusing on the entry points of the soft-link approach detailed in Section 3.3. TIAM-FR models energy system transitions, emissions reduction, and technology deployment, while GLOBIOM, the land-use and forestry model, provides detailed insights into agriculture, bioenergy, and carbon sequestration. The first two sub-sections related to GLOBIOM-G4M (3.2.1 and 3.2.2) present the actions in the agriculture, forestry and land use sectors, while sub-Section 3.2.3 concerns the emulation of this model used to combine the energy and AFOLU models. This approach enables a holistic assessment of land-based mitigation strategies.

3.1. TIAM-FR description

The energy system analysis is carried out with TIAM-FR, which represents the global energy system in 15 regions. This framework has been documented and applied in multiple peer-reviewed studies, including sector-specific and systems analyses (e.g., Andrade et al., 2024; Chlela and Selosse, 2024; Selosse and Ricci, 2017). These applications demonstrate TIAM-FR's capacity to assess deep-decarbonization pathways, negative-emissions integration, and resource constraints within a technology-rich optimization setting. Like other TIMES models, TIAM-FR is a partial equilibrium model, where optimization focuses on a single sector of the economy, in this case, the energy sector. The model is technology-rich and tracks the evolution of the energy system until the end of the century and interconnecting different end-uses (residential, transport, agriculture, industrial, and commercial sectors). It effectively delineates the energy sector through a series of processes that link primary energy sources with final energy demand, utilizing explicit and implicit input and output technologies, as well as commodity flows as it is horizontally and vertically integrated. Commodities can be energy carriers, materials, greenhouse gas emissions, etc.

The model is calibrated to start at the year 2018 and runs for several time periods in 10-year time steps. The year 2020 is included as a model period and does not reflect COVID-19-related disruptions. The model performs a long-term optimization, allocating investments in new technologies according to their characteristics while accounting for present and future resources and their potential. The optimization problem can be computed with Linear Programming (LP), where the objective function of the modeled energy system consists in minimizing its total discounted costs over the time horizon i.e., until 2100, and across the 15 regions (Fig. 10, Appendix A).

Table 1
Example of studies addressing the interactions between biomass supply, abatement options, and GHG prices.

Category	GLOBIOM [3]	GCAM [32]	REMIND-MAGPIE [42]	BENOPTex [19]	PyPSA (BECCS) [40,41]	MESSAGEix-GLOBIOM [13]	This study (TIAM-FR x GLOBIOM-G4M)
Core focus	Global partial equilibrium land-use model capturing land allocation and biomass supply responses	Global integrated assessment model coupling energy, land, economy, water, and climate systems	Global IAM linking macro-economic energy transformation with detailed land-use dynamics	Biomass/energy system optimization model for cost-optimal allocation of biomass across energy sectors	Energy system optimization model including BECCS as a technology option; no endogenous land dynamics	Integrated global energy system optimization coupled with land-use representation within the IIASA IAM suite	Global assessment model representing the energy system and coupled with land including an A/R climate module;
Land use mitigation & representation	A/R; forest management; BECCS; non-CO ₂ mitigation; structural agricultural mitigation; demand-side effects (endogenous)	A/R; BECCS; avoided deforestation; land management (endogenous)	BECCS; advanced bioenergy technologies (land use dynamics from MAGPIE in some scenarios coupled to marginal abatement cost curves)	Bioenergy supply allocation, AFOLU, sectoral bioenergy use. (endogenous, options for Germany)	Energy system decarbonization with BECCS as a land-based option. (limited to BECCS pathways)	Energy system decarbonization with land-use mitigation options (land use dynamics provided by GLOBIOM-G4M, based on marginal abatement cost curves)	A/R, forest management; agricultural mitigation; bioenergy pathways; demand-side land responses (exogenous, limited to emissions and removals, land occupation)
Assessment of mitigation potential	Scenario analysis under evolving carbon and biomass prices	Sensitivity to land carbon pricing; impacts on agriculture, bioenergy, and land-based CDR	Assessment of carbon pricing and biomass feedstock prices (linked to carbon content)	Cost-optimal allocation of biomass under energy and GHG constraints	Cost-optimal energy system operation and investment	Integrated assessment of land-energy mitigation under climate targets	Energy-system optimization coordinated with land-use constraints, emissions, and price signals
Contribution to net-zero	AFOLU emission reductions up to ~9.4 GtCO ₂ eq yr ⁻¹ by 2050 at 165 USD tCO ₂ eq ⁻¹	Land-based CDR intensity 7.3–18.1 tCO ₂ ha ⁻¹ yr ⁻¹	Carbon prices up to ~164 USD tCO ₂ ⁻¹ by 2050	Determines bioenergy contribution to mitigation targets	Quantifies BECCS contribution within energy-system pathways	Net-zero pathways with endogenous land-energy trade-offs	Quantifies how land constraints and land-based emissions reshape energy-system mitigation and CDR reliance
Emission pathways	AFOLU-focused mitigation pathways relative to baseline	Land-intensive mitigation pathways	Energy-system pathways under carbon budgets	Energy-sector pathways driven by biomass constraints	Energy-system pathways under CO ₂ caps or budgets	Fully integrated land-energy pathways	Consistent land and energy pathways via iterative coordination
Land-energy coupling	Stand-alone land-use model; external coupling possible	Fully integrated IAM	Integrated IAM (iterative soft-link)	Hard-linked energy-biomass optimization	Energy-system model with optional BECCS	Integrated IAM (soft-link)	Soft-linked land-energy coordination via explicit constraints and price signals
CCS representation	Outside the scope	CO ₂ transport and storage costs are regionally specific	Fixed CO ₂ transport costs. CO ₂ storage costs are regional and storage specific	Exogenous upper limits in GHG accounting, no public generic storage module is described	Geological storage potential is introduced via data as a storage unit or store with an energy cap and injection/withdrawal costs	CO ₂ transport and storage are similar across regions with one global geological reservoir considered	CO ₂ transport and storage costs are regionally specific. CCS is constrained by geological storage potential by region and CO ₂ injection rates
CDR coverage	A/R, forest management, other land-based uses	A/R, BECCS, avoided deforestation	BECCS, afforestation, direct air capture, enhanced weathering	BECCS (via bioenergy pathways), forestry, agriculture, soils, and wetlands, long-lived building materials.	BECCS, DACS (technology-based)	BECCS, A/R, land-use CDR	A/R, forest management, land-based BECCS, land-use emissions

$$NPV = \sum_r \sum_y (1 + d_{r,y})^y \times \text{Cost}_{r,y}$$

We distinguish between two representations of the biomass sector in TIAM-FR:

- The potential of woody biomass and agricultural residues is informed in the model from the production costs, which in this case are only taken as the market prices according to [43]. These quantities are exogenously determined.
- The land use of bio-crops, including energy plantations is estimated. Depending on their type (oleaginous, starch, etc.), crops are converted to solid biomass, lignite, or bio-oil through transformation processes. In this case, the biomass quantities and costs are endogenous.
- In TIAM-FR, land allocation is constrained by Global Agro-Ecological Zones (GAEZ) data [44]. Cropland, grassland, and tree-covered land are defined as exploitable categories for bioenergy expansion. The optimization explicitly accounts for competition between crops by applying a food-first principle, whereby land required for food and feed is reserved prior to allocation for energy crops. The crop supply chain is shown in Appendix B.
- According to assumptions on yield improvement and technology appropriation, the model offers three attainable levels of potential and land use as shown in Table 2 based on [9]. Another potential is added as the output of GLOBIOM-G4M integration, which is thoroughly explained in Section 3.2.

3.2. GLOBIOM-G4M description

GLOBIOM is a partial equilibrium land-use model [45] that can assess competition for land use between agriculture, bioenergy, and forestry. Thus, the main sectors covered by this model are agriculture, forestry, and production of crops, and energy crops, which are represented according to their profitability. Owing to its bottom-up approach, the model is built from the supply side through spatially explicit representation of land cover, land use, management systems, and economic cost information (bottom) to regional commodity markets (top). Demand is established at aggregate regional level. Projections for food demand consider four drivers: population growth, per-capita income growth, response to prices, and policies.

The model runs for several periods at 10-year time steps following recursive dynamic-solving techniques and can provide projections up to 2100. The optimal decision taken in time t depends on the decisions taken by agents in the previous time period $t-1$. Hence, at each start of each time period, the land-use conditions are updated with the solutions of the previous time period.

To address greenhouse gas mitigation, the model explicitly represents various GHG emissions from agricultural production, forestry, and land use changes, including CO₂ emissions from biomass changes, N₂O from fertilizer application and manure, and CH₄ from different sources (flooded rice fields, enteric fermentation etc.).

Table 2
Maximum attainable potentials for bioenergy in EJ and land use in km².

	Maximum allowable potential in EJ							Maximum allowable land use of crops for bioenergy (1000 km ²)
	Wood	Forest residues (processing)	Agricultural residues (harvest)	Agricultural residues (processing)	Logging residues	Total		
Low	2050	50.7	8.6	42.7	8.2	3.0	113.2	472
	2100	48.2	9.0	45.9	8.2	3.3	114.5	472
Medium	2050	50.0	8.6	42.7	8.2	3.0	112.5	7367
	2100	47.6	9.0	45.9	8.2	3.3	113.9	6878
High	2050	52.2	8.6	43.3	8.2	3.0	115.3	11,474
	2100	49.8	9.0	46.6	8.2	3.3	116.9	10,302

3.2.1. Mitigation in the agriculture and land use sectors

To reduce non-CO₂ emissions, the model incorporates technical mitigation options, structural changes in agriculture (crops and livestock), and consumer responses to price changes [46]. For instance, structural mitigation options for agriculture include comprehensive management systems that allow farmers to switch to more GHG-efficient practices on-site, reallocate production to more productive areas within a region, or engage in international trade across regions. In the crop sector, four different crop management systems are differentiated using the EPIC model, which enables the explicit representation of structural changes in the agricultural sector according to climate policy. Livestock sector mitigation options involve parameterizing various production systems and livestock species to decrease GHG emissions from livestock, contributing to overall AFOLU emission reductions. Technical options are mentioned in Table 1 while further details can be found in GLOBIOM documentation [33].

3.2.2. Mitigation in the forestry sector

For the forest sector, GLOBIOM uses G4M to obtain the outputs of CO₂ mitigation options [47]. These actions, which are dynamically managed by the model, are adopted by farmers together, and include decreasing the deforestation area, increasing the afforestation area, and managing forests. Market feedback and the impacts of mitigation options, like extending rotation, are considered, giving priority to wood production over carbon accumulation. Mitigation effects are achieved mainly through shifting harvesting schedules to increase sequestration and simultaneously meet market demands. CO₂ emissions from biomass and dead organic matter due to land use changes and forest management, as well as soil carbon emissions from deforestation/afforestation, are included.

3.2.3. GLOBIOM emulation

In order to link GLOBIOM to other IAMs or models, a “lookup table” is developed in [3]. This table represents an emulation of the model, thus studying different trajectories in climate change mitigation pathways. It provides a comprehensive, detailed response for the land use sector to explicitly consider dynamics and interlinkages between biomass use and AFOLU emissions, along with other important land use-related indicators. In addition, it includes a set of scenarios with 7 biomass price trajectories and 12 GHG price trajectories, which form a 2-dimensional matrix. As an example, a baseline scenario would imply no mitigation efforts with a GHG price of nil.

3.3. TIAM-FR and GLOBIOM soft linking

Soft linking enhances and adds value to results by capturing interactions between different systems or sectors. It involves connecting multiple models by using the outputs of one model as inputs for another [48], which is a cooperative characteristic of model synergies. This approach enables detailed representation of each sector while maintaining cross-sectoral consistency. This is found in particular in IAMs, where emission pathways are constructed to be compliant with the Paris Agreement, thus requiring interdependence between climate, energy,

transport, and land-use models [49]. It is also applicable for models representing the future growth of economies. For example, the ReMIND model determines the optimal mix of investments related to energy and economy sectors while accounting for emissions, given a set of technology, population, and climate constraints. It is linked to MagPIE and MAGGIC. According to [1](Annex III; Chapter 3), soft-linking between IAMs and land-use models is now a standard practice to improve internal consistency, but applications are typically unidirectional—with land-use constraints shaping energy system results—while iterative coupling to capture feedbacks from energy demand back onto land allocation remains limited. Building on this, a principal part of our methodology is the review of techno-economic characteristics and policy constraints across land and energy systems.

In this study, the soft-linking between TIAM-FR and GLOBIOM is one-directional, where the results of GLOBIOM's optimization, for SSP2, are fed into TIAM-FR. In turn, the energy model is used to determine the energy supply change following the integration of land use, particularly for bioenergy, mitigation potential (i.e., BECCS), renewable energy shares, and net-zero timing. In practice, the integration relies on GLOBIOM-G4M outputs, including the Reference Land System configuration shown in Appendix D, following the approach described in [48] to identify the main exchanges between land and energy, including biomass resources and land constraints and AFOLU-related GHG emissions (e.g., afforestation, forest management) under varying GHG and biomass price trajectories. This “mapping” step provided a consistent boundary for linking the two systems. Outputs from the land system, such as crop areas and residue availability, were translated into the energy model using harmonized units and regional definitions. In return, the energy model provided information on fuel demand and carbon emissions. Also, economic information was aligned rather than using isolated cost values based on recommendations from [48,50]. The soft-linking uses land-based cost data as the foundation to shape the supply curve of biomass for the energy system, ensuring that the economic signal of land scarcity is correctly transmitted into the energy optimization. Moreover, this workflow follows the definition of soft-linking as the transfer of information between separate models without full code integration [50]. It allows the combined analysis of land and energy systems while keeping each model independent.

3.3.1. Linking at the level of biomass feedstocks

Due to the intrinsic role of bioenergy in energy and land systems, its supply from GLOBIOM emulation is used to update the available potential in the energy model according to an association between feedstocks. As determined in the literature review, biomass and GHG prices are determinant factors for these potentials, thus the assumptions regarding their values guide the choice for finding bioenergy supply curves for TIAM-FR.

To identify the connection between GLOBIOM and TIAM-FR, associating biomass processes represents the first step. This includes reviewing the parameters that enable soft linking, such as technical parameters (i.e., the costs of producing feedstocks), primary energy supply, and environmental parameters (i.e., the GHG emissions). Table 3 shows an overview of the parameters reviewed during the first step of this soft-linking.

Data on primary bioenergy potential, measured in exajoules (EJ), are extracted from GLOBIOM, covering energy crops (mainly second-generation), roundwood, forestry industry residues, as well as agricultural and logging residues. These data correlate with processes and commodities in TIAM-FR using techno-economic parameters. Such a correlation is possible thanks to the disaggregated modeling of feedstocks in the energy system model. For instance, the information on the process representing wood logging residues (MINBIOLOG0) in TIAM-FR is matched with the corresponding logging residues from GLOBIOM. Recall that the energy crops are modeled through a value chain in TIAM-FR, encompassing land occupation, yield, costs and transformation into solid biomass, lignocellulosic biomass, and residues (Kang, 2017). Other

Table 3
Relevant parameters comparing GLOBIOM emulation and TIAM-FR.

Category	GLOBIOM	TIAM-FR
Technical Parameters	Primary energy from biomass	Biomass commodities Transformation processes
	World and regional values: 5 world regions, higher disaggregation to 10	World divided into 15 regions
	Biomass potential (land and quantity)	Biomass potential, land and quantity for energy crops
Economic Parameters	Biomass price trajectory GHG price trajectory (across all biomass types and regions)	CAPEX and OPEX costs, at regional and technological levels
Environmental Parameters	GHG emissions (CO ₂ , CH ₄ , N ₂ O) from AFOLU Abatement potential	GHG emissions (CO ₂ , CH ₄ , N ₂ O)
Policy	Climate mitigation scenarios with social cost of GHG and land use constraints following SSP2	Conservative to high biomass potential SSP2 as driver Temperature limitation or forcing scenarios

feedstocks, such as logging residues, are modeled as processes with upper bound potential and costs. Therefore, the energy crops' potential from GLOBIOM is applied to the activity processes that convert biomass quantities (in kilotons) to energy potential (EJ). Notably, energy crops in GLOBIOM mostly consist of second-generation biomass, which is generally available at higher biomass prices.

In the GLOBIOM emulation, the “look-up table” approach applies biomass prices uniformly across all biomass types. Subsequently, the second step involves defining the space consistent with TIAM-FR's representation of biomass, considering both cost and type, within a two-dimensional matrix of biomass and GHG price trajectories. In this step, biomass prices from GLOBIOM are harmonized with TIAM-FR's techno-economic parameters. To determine appropriate biomass prices, it should cover the biomass costs in TIAM-FR. For example, the costs for the MINBIOLOG0 process align with GLOBIOM's price trajectory, ranging from 0.176 USD/GJ in 2020 to 3 USD/GJ in 2100, which is denoted as 3 USD/GJ. Once this cost compatibility is established, the associated primary bioenergy potential can be retrieved from the dataset.

However, other bioenergy processes have varying cost values, requiring a detailed mapping of biomass types and costs within the energy model. Ultimately, four biomass price scenarios are retained that align with the land-use matrix, shown in Fig. 2.

In the mapped biomass trajectories, the highest biomass potential is reached with a biomass price of 13 USD/GJ in 2100, as biomass quantities increase with price. The supply curves for primary bioenergy in TIAM-FR are obtained through assigning for each type of biomass, at their specific price, a proportion of the bioenergy output of the values corresponding to 13 USD/GJ from the emulated dataset. The same method may be applied to other biomass price assumptions.

Then, these curves are implemented as maximum attainable values through the following equation:

$$\sum_{t=0}^T (E_{\text{crops } r, t}) - \text{Trade}(\text{crops } r, t) \leq E_{\text{GLOBIOM crops } r, t}$$

where E = the primary bioenergy supply. The constraint is applied to the 15 regions, aggregated according to the regional distribution in GLOBIOM and for five periods.

The implemented bioenergy potential values derived from GLOBIOM are the maximum attainable potential. This allows for studying variations in biomass end-uses through optimization and provides a comparison with the existing potential in the energy model. The remaining variable to be determined is the GHG trajectory, which is further discussed in the next section.

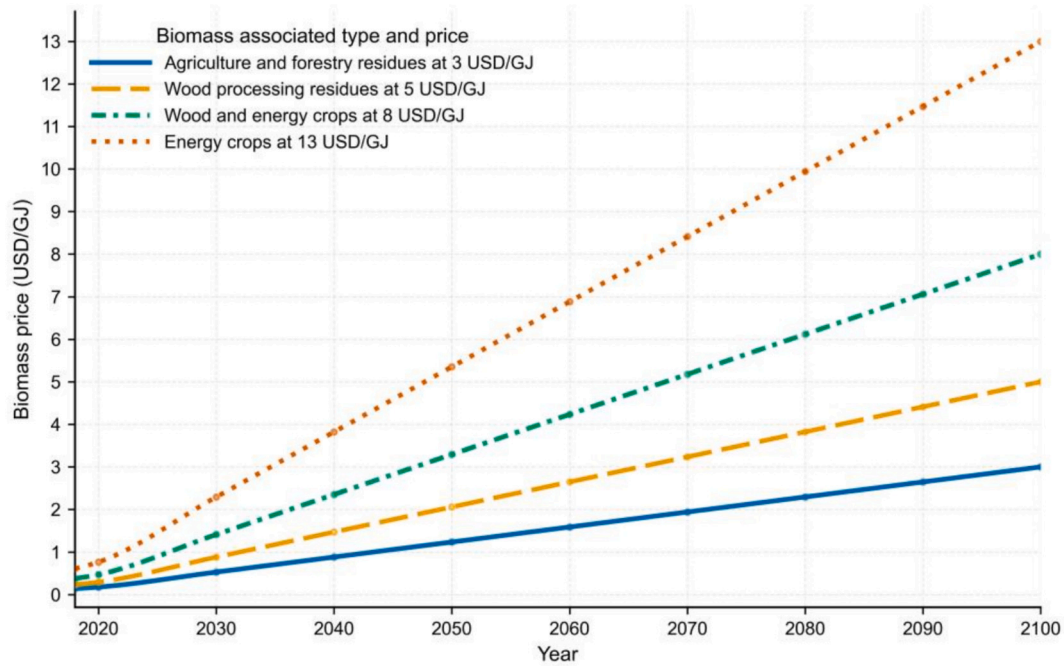


Fig. 2. Biomass price evolution across bioenergy scenarios. Values for the model base year (2018) are included in the data but omitted from the axis labels for visual clarity.

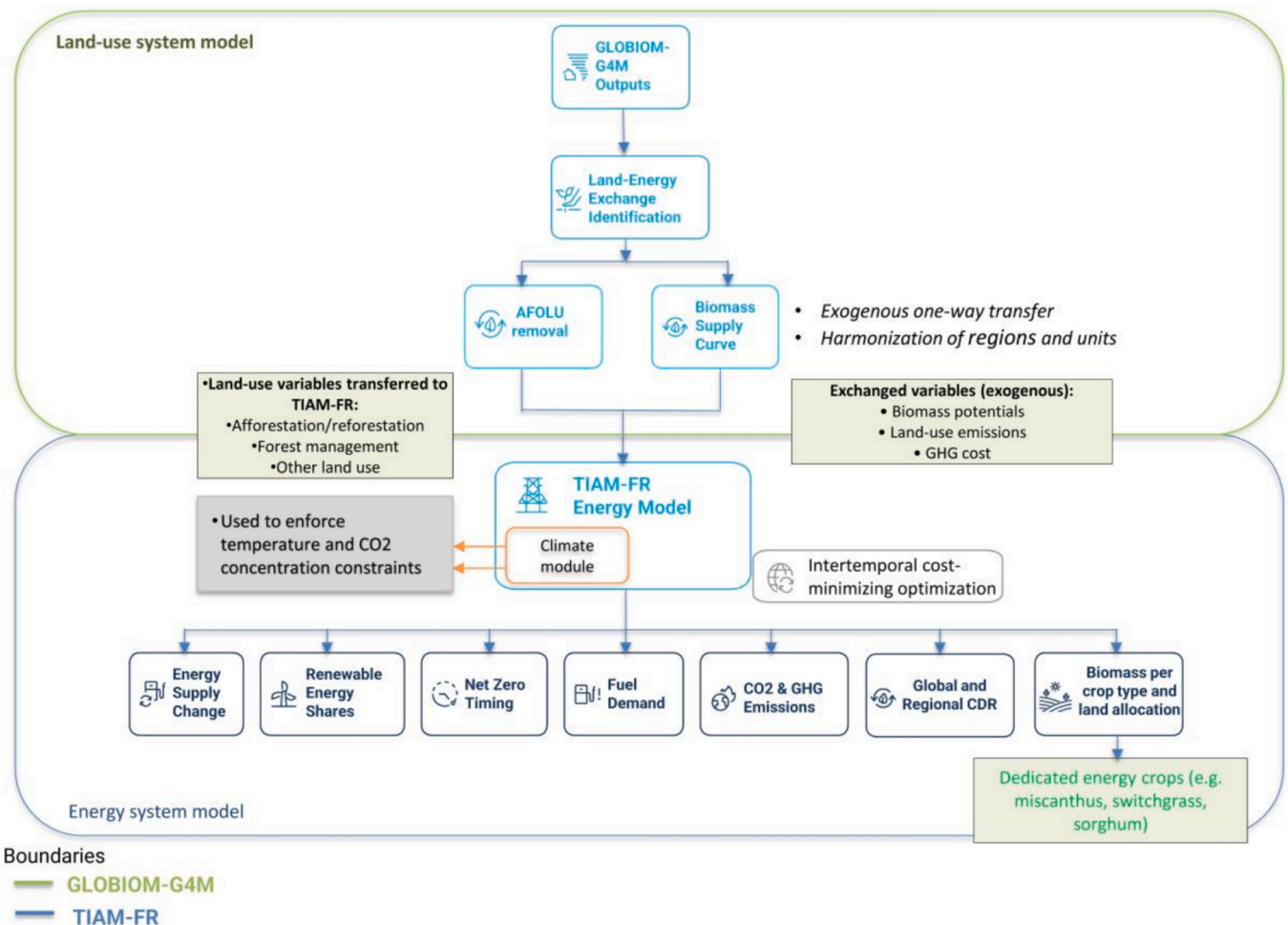


Fig. 3. Soft-linking structure between TIAM-FR and GLOBIOM-G4M emulation.

3.3.2. Modeling of AFOLU carbon dioxide abatement

For the CO₂ abatement from AFOLU, emissions and removals based on the trajectory corresponding to the highest biomass price (13 USD/GJ in 2100) are utilized. These are incorporated as new technologies. Data processing shows that the choice of biomass supply curves significantly influences the mitigation potential of the AFOLU sector, especially regarding GHG abatement. Increasing biomass supply for bioenergy can shift the AFOLU Marginal Abatement Cost Curve (MACC) downward, impacting GHG emissions and enhancing the sector's abatement capacity [3]. For instance, GLOBIOM data show that lower biomass prices lead to higher emission removals from afforestation at a fixed GHG price. This occurs because these prices remunerate forestry harvest residues, thereby promoting afforestation. Furthermore, the analysis of abatement options across different GHG trajectories reveals that the 200 USD/tCO₂eq trajectory shows a sharp and rapid decline in land-use emissions. In fact, at a fixed biomass price, land-use emissions become negative earlier, with higher potential along the 200 USD/tCO₂eq trajectory. For all GHG pathways above this level, land-use emissions become negative starting in 2030, with potential converging to a maximum value of approximately 4 Gt CO₂ by 2100.

To summarize the methodological framework described above, Fig. 3 presents a schematic of the proposed soft-link structure, explicitly illustrating the modeling boundaries, exchanged variables, and direction of information flows between the energy and land-use systems.

4. Results and discussion

This section presents and elaborates the results of the optimization outcomes of soft-linking TIAM-FR and GLOBIOM-G4M from global (Section 4.1) and regional (Section 4.2) perspectives. First global pathways are examined, focusing on the evolution of the energy mix, the role of bioenergy and its feedstocks, and the contribution of CDR in achieving stringent climate targets. Then, these dynamics are analyzed across world regions, highlighting differences in resource endowments, technology deployment, and policy timing. Together, these elements provide an integrated view of how bioenergy and CDR shape decarbonization trajectories in mitigation pathways following the Paris Agreement. In the long-term assessment, different reference years are used throughout the analysis to highlight complementary aspects of system evolution. While results are presented across all modeled periods, selected years are emphasized for interpretation: 2050 is used as a mid-century benchmark to capture structural transitions in energy and land systems, 2060 corresponds to the net-zero year and is used to assess the composition of carbon dioxide removal, while 2030 and 2100 are used to illustrate near-term policy-relevant developments and long-term system outcomes. This selection of reference years ensures consistency between transition dynamics, policy milestones, and end-of-century system outcomes.

4.1. Exploring global pathways for the land–energy nexus

The energy system dynamics such as primary energy, biomass consumption and feedstock utilization are compared for the 2 °C and 1.5 °C scenarios explained in Section 2.1. The place of CDR for a net-zero pathway with NDC and long-term strategies is presented in Section 4.1.4. The outcomes emphasize the dual role of BECCS in the decarbonization of power and industrial sectors. The land occupation by energy crops is determined through TIAM-FR's representation and GLOBIOM's constraints. The production of these crops is dominated by China and the Americas (Section 4.1.3). The CDR amounts are shown in Section 4.1.4 for the 1.5 °C scenario and show that forest management strategies, afforestation and reforestation, etc. are important measures for the timeliness of carbon sequestration before largescale deployments of engineered solutions.

4.1.1. The place of bioenergy in the energy mix

First, the primary energy mix is explored for the 2 °C and 1.5 °C scenarios, with the bioenergy potential obtained from the supply curves of GLOBIOM. The 2 °C trajectory shows an increase in bioenergy production from 64 EJ in 2018 to 103 EJ in 2100, as seen in Fig. 4. Its growth remains steady but is slower than the net-zero scenario (1.5 °C), which increases bioenergy from 64 EJ in 2018 to 127 EJ in 2100. Mid-century trends highlight a growing divergence between the two scenarios. By 2050, bioenergy supply reaches 59 EJ under the 2 °C pathway but is significantly higher at 93 EJ under the 1.5 °C pathway, reflecting an accelerated deployment of biomass-based solutions for carbon removal. The use of coal peaks in 2030, reaching around 100 EJ in 2050 (2 °C) and 109 EJ in 2050 (1.5 °C), indicating a continued dependency on these technologies or lock-in. By 2100, coal declines by around 35% in the 2 °C scenario, but it remains in use due to industrial applications and carbon capture technologies, which is also the case in the 1.5 °C scenario.

Gas follows a decreasing trajectory (−49%), from 131 EJ in 2018 to 72 EJ in 2050 (2 °C) (Fig. 4, left) and 70 EJ in 2050 (1.5 °C) (Fig. 4, right), playing a transitional role before being replaced by renewables. By 2100, gas declines to 67 EJ (2 °C) and 66 EJ (1.5 °C), underscoring a long-term reduction trend.

The energy supply mix shifts significantly by mid-century, driven by decarbonization efforts and the increasing GHG price. Renewables experience the most significant growth: solar expands from 4 EJ in 2018 to 54 EJ (2 °C) and 61 EJ (1.5 °C) in 2050, reaching 75 EJ (2 °C) and 78 EJ (1.5 °C) by 2100. Wind grows from 5 EJ in 2018 to 32 EJ (2 °C) and 32 EJ (1.5 °C) in 2050, further increasing to 51 EJ (2 °C) and 101 EJ (1.5 °C) by 2100. Other renewables, which include hydro, geothermal, wave, and tidal, remain steady at 36 EJ (2 °C) and 37 EJ (1.5 °C) in 2050, expanding to 78 EJ and 92 EJ in 2100, respectively. These trends underscore the growing dominance of low-carbon technologies, with fossil fuels declining but not fully phased out.

4.1.2. Biomass in final energy consumption

In this part of the results, we focus on the role of biomass in sectoral energy consumption. Biomass demand for electricity generation starts increasing post-2030, with a notable rise in both scenarios (Fig. 5). The 1.5 °C scenario sees a faster initial growth in electricity (17% by 2030) but stabilizes post-2060. The 2 °C scenario shows slower growth initially but reaches a higher share, with 46% compared to 42% for the 1.5 °C, reflecting sustained bioenergy use for electricity production. Bioenergy for electricity is part of the long-term decarbonization solution for both scenarios, although increasingly pronounced in the 2 °C scenario, reflecting continued reliance on biomass. Within the transport sector, biomass use transitions from a balanced mix of biodiesel, biogasoline, and ethanol in 2020 to a strong dominance of ethanol by mid-century (≈70–80%), before shifting toward biodiesel by 2100 (≈60–65%), particularly in the 1.5 °C scenario. Solid biomass, biogas, pellets, and torrefied biomass are utilized both in power production and in the process of industries for their decarbonization. For example, they can be used to replace natural gas and coal. In this scenario, biomass types are diversified with a notable rise in biochar and other process biomass carriers in the long-term. The cement, iron and steel industries are also decarbonized through investments in carbon capture. The use of biomass by other industries such as pulp and paper, chemical, etc. is mainly with solid biomass, noting that BECCS for these industries is not yet implemented in this version of the model. By 2050, biomass use in industry, including solid biomass, biofuels, and biogas, reaches 34% of final energy consumption in the 1.5 °C scenario, compared to 31% in the 2 °C scenario. This reflects the stronger decarbonization policies and higher displacement of fossil fuels in the 1.5 °C pathway. However, industry biomass plateaus post-2060 in the 1.5 °C scenario, indicating alternative decarbonization strategies such as carbon removal. In addition, biomass-derived hydrogen and fuel gases i.e., biogas and synthetic biogas represent a consistent share of biomass use starting as early as

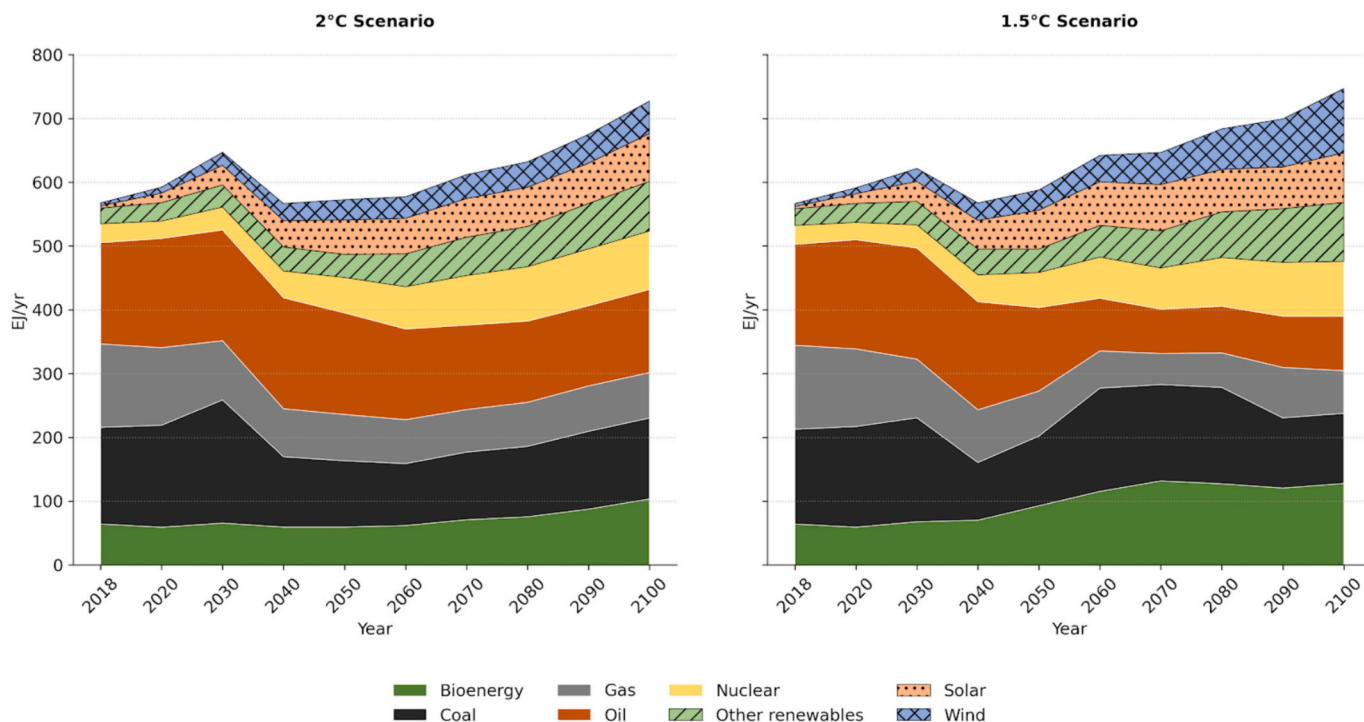


Fig. 4. Primary energy supply for the 2 °C scenario (left) and for the 1.5 °C scenario (right).

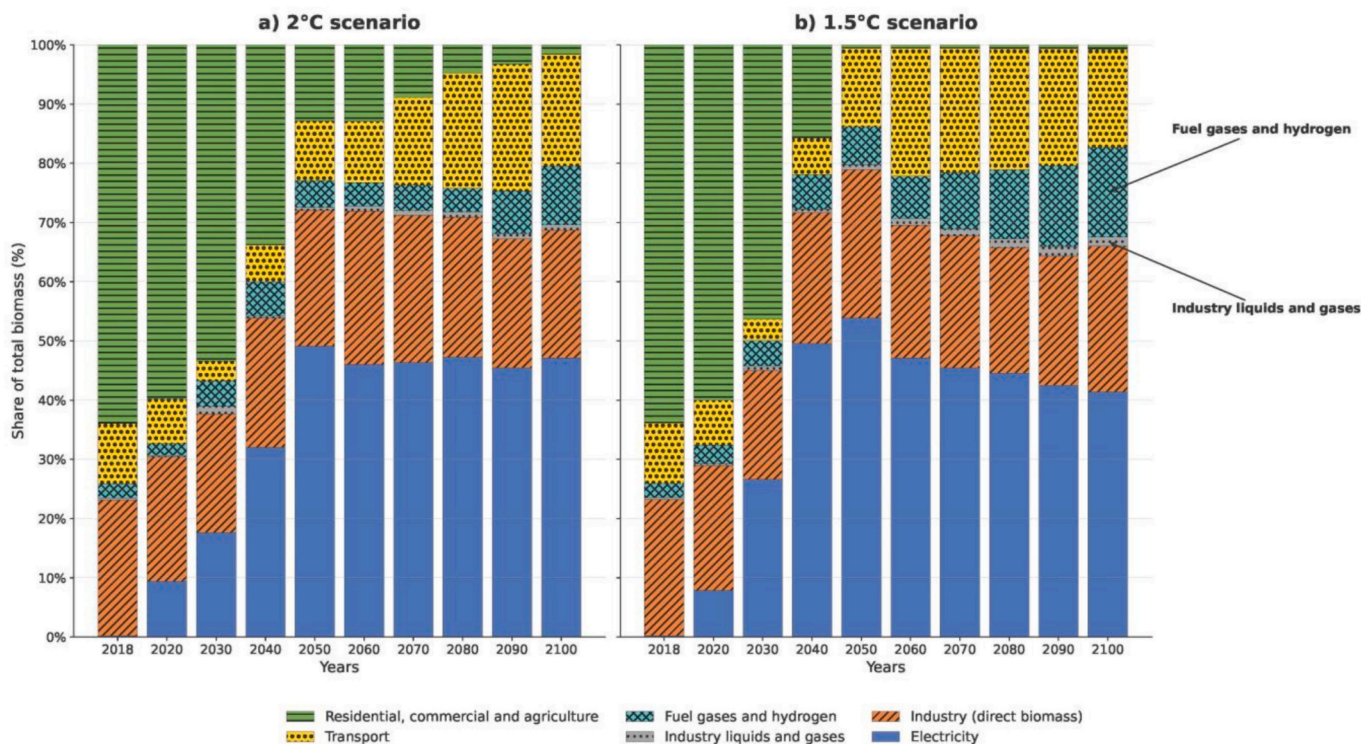


Fig. 5. Biomass utilization across energy services and carriers. Industrial biomass use remains largely dominated by solid biomass throughout the century. In 2050, it represents 75% of biomass use in this sector in the 1.5 °C scenario.

2030, accounting for approximately 7% of total biomass use by 2050 and expanding toward 17% by the end of the century. This aligns with greater reliance on negative emissions technologies (BECCS) and hydrogen-based industrial applications and transport under stringent decarbonization targets. Note that in TIAM-FR, biomass-derived hydrogen can be produced via biomass gasification with or without CCS.

Moreover, hydrogen supply in the model is derived from natural gas reforming, coal gasification, and electrolysis, with distribution across the transport and industrial sectors, or further processing through Carbon Capture and Utilization (CCU) to produce synthetic gases. It is worth noting that the share of biomass-based hydrogen in total hydrogen production reaches 24% by 2050 and 30% by 2100 in the 2 °C pathway,

while in the 1.5 °C scenario, it increases slightly to 26% in 2050 and 41% in 2100. The results of the 2 °C trajectory suggest that biomass is primarily used in direct combustion and biofuels rather than for hydrogen production. This indicates a lower integration of biomass gasification for hydrogen production in moderate climate mitigation scenarios.

Biomass consumption in the residential sector, mainly in the form of biochar, solid biomass, and biofuels, is gradually phased out in the 1.5 °C scenario after 2030. This decline reflects a transition toward electrification and more efficient heating systems, reducing reliance on direct biomass combustion.

4.1.3. Selection of biomass feedstock

The feedstock supply of primary bioenergy shown in Fig. 6 is transformed into solid biomass, lignocellulosic biomass, and pellets. Solid biomass accounts for around 83% and 75% of the biomass supply in 2030 (excluding energy-dedicated crops) in the 2 °C and 1.5 °C scenarios, respectively, produced mainly from agriculture harvests. Its value drops to reach 19% and 11% in 2050, for the 2 °C and 1.5 °C scenarios, respectively. In addition, the transformation of these supplies into lignocellulosic biomass increases until mid-century but then falls to less than 1 EJ post-2070. In both scenarios, harvest residue supplies decrease slowly until the end of the century reflecting a shift toward using wood from forests as feedstock supply. Logging residues are mostly apparent in the 2 °C scenario (Fig. 6) but then completely disappear by the end of the century.

Sawdust, wood and agricultural harvest residues are transformed into pellets or torrefied pellets for heat and electricity generation. Pellets increase significantly with a supply of 7 EJ and 13 EJ in 2030, 41 EJ and 56 EJ in 2050, and 62 EJ and 55 EJ in 2100, for the 2 °C and 1.5 °C scenarios, respectively. Agriculture harvest residues contribute mostly to the production of pellets until mid-century when their inputs reach 36 EJ and 41 EJ for the 2 °C and 1.5 °C scenarios, respectively. Then, in 2100, wood provides 30 EJ and 27 EJ in the 2 °C and 1.5 °C scenarios, respectively. Agriculture harvest residues, which may come from crops cultivated for bioenergy (detailed in the next paragraph), can be transformed into lignocellulosic biomass used for second-generation biodiesel with and without carbon capture.

The model incorporates a diverse range of both edible and energy crops to assess their potential expansion for bioenergy production. However, the integration of GLOBIOM's constraints, which impose stringent limits on the use of first-generation crops, significantly influences their contribution. By 2050, the projected bioenergy supply from the crops reaches around 700 million tons in the 2 °C scenario and around 1700 million tons in the 1.5 °C scenario. In the 2 °C pathway, contributions continue to rise, reaching 1700 million tons by 2100, whereas in the 1.5 °C scenario, they decline to 1300 million tons, reflecting a shift toward advanced biofuels requiring alternative feedstocks (Fig. 6). The crops considered include wheat, ground nuts and sorghum. Agricultural residues from their processing are also available for utilization. By 2050, residue availability reaches 468 million tons in the 2 °C scenario and 1200 million tons in the 1.5 °C pathway.

Next, energy plantations are investigated in terms of quantities and land occupation. First, the constraints from GLOBIOM on first-generation crops limit their utilization for food purposes and promote energy plantations, mainly short rotation crops as shown in Fig. 14 in Appendix G. The increase in biomass quantities at the end of the century for the 1.5 °C scenario indicates a shift from the forestry and agriculture feedstocks noted in Fig. 6 for post-2060.

Land use by these non-edible crops reaches around 127 million hectares, which is the maximum allowed value according to the GLOBIOM emulation in 2050 and is the case for both scenarios. In 2100, the land use is 325 million ha and 370 million ha, for the 2 °C and 1.5 °C scenarios respectively, as seen in Fig. 7. Nevertheless, the global land allocation in 2100 for energy crops can reach 530 million hectares under these conditions in GLOBIOM. Energy crops in China (CHI) and Central and South America (CSA) occupy the largest territories for short-rotation crops for both pathways. The most notable difference is the contribution of the United States of America (USA) in the 1.5 °C scenario, which significantly increases post-2070. In 2070, the production of these regions reaches 800 million tons in China, 1200 million tons in CSA, and 540 million tons in the USA for the 1.5 °C scenario. These values represent 11%, 25%, and 11% of the total crops produced for bioenergy, respectively. The region rest of world in Fig. 7 includes Australia, Mexico, Western Europe and Canada which increase from around 4 in

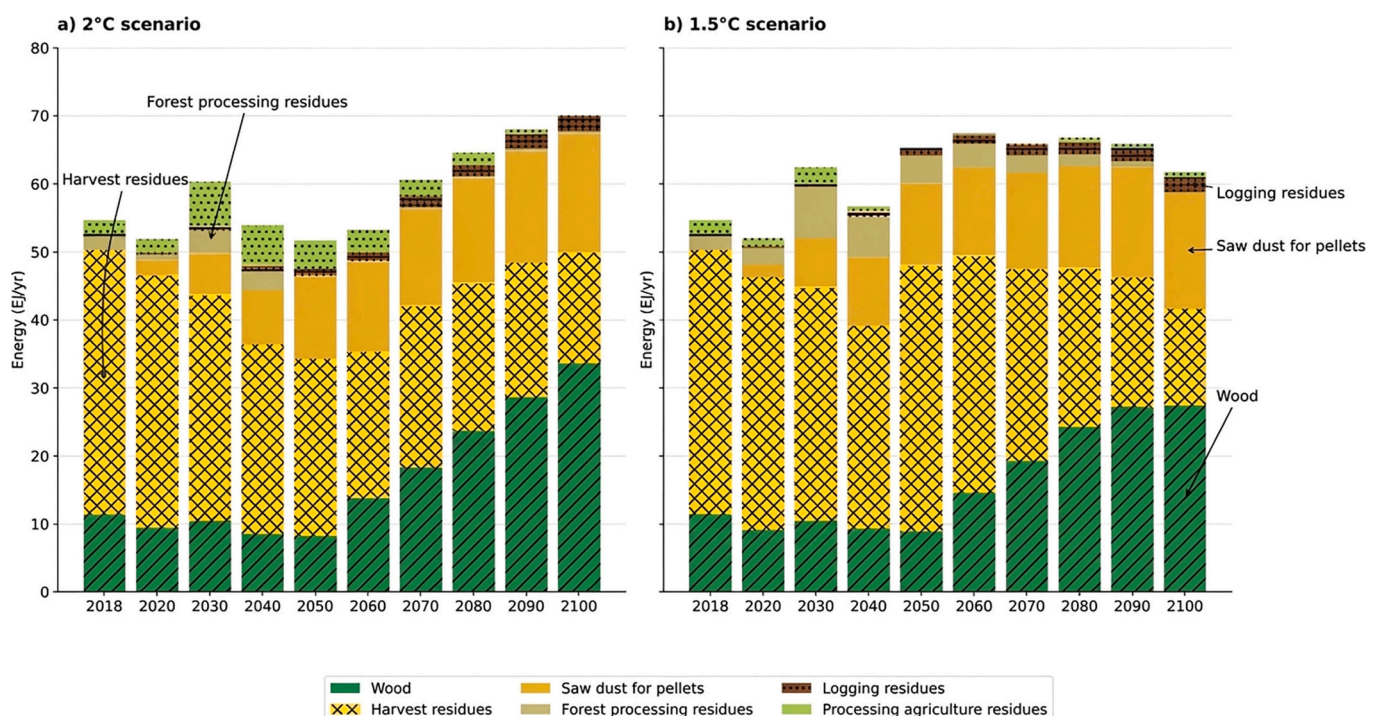


Fig. 6. Evolution of the forestry and agriculture feedstocks in EJ for the 2 °C and 1.5 °C scenarios.

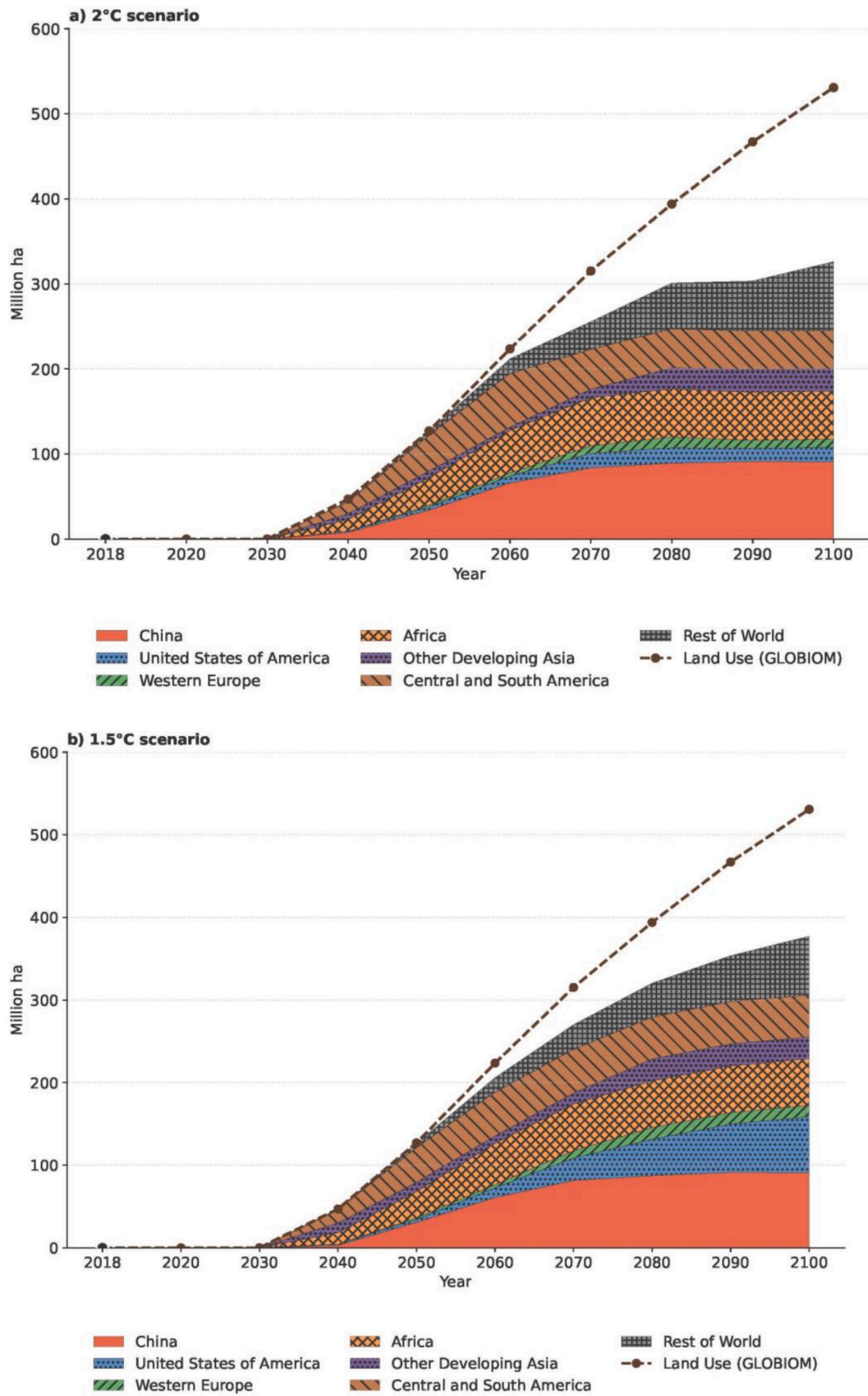


Fig. 7. Regional land use by energy plantations: (a) 2 °C and (b) 1.5 °C pathways. The year 2020 is omitted due to negligible land-use values in early periods.

2050 to 32 million hectares in 2100 in the 1.5 °C scenario. Australia and Western Europe remain the highest contributor in this aggregated region.

4.1.4. Carbon dioxide removal in the 1.5 °C pathway

By 2060, net CO₂ emissions reach zero, indicating the achievement of net-zero CO₂ emissions as shown in Fig. 8. Beyond this point, negative emissions increase, ensuring that cumulative atmospheric CO₂ concentrations remain aligned with the long-term temperature stabilization objective.

Biogenic CO₂ storage through BECCS (light blue bars) emerges as the dominant CDR pathway, driven by its dual role in offsetting residual emissions and providing electricity. Investments in BECCS are concentrated in power plants utilizing direct combustion of pellets and torrefied pellets. Alternative BECCS technologies such as biofuels with CCS are not selected by the optimization. In contrast, land-based mitigation from managed land, including reduced deforestation, afforestation, forest management, and sustainable agricultural practices, plays a more limited role in overall CO₂ removal. However, these solutions contribute to the net-zero timeline earlier compared to other CDR options. This highlights their importance in initiating carbon sequestration efforts before large-scale engineered removals are deployed.

Despite the decline in CO₂ emissions, net GHG emissions (solid brown line) remain slightly positive post-2060, reflecting the continued presence of non-CO₂ GHGs. This highlights two key points. First, there is a need to integrate additional mitigation measures into the model, in sectors such as livestock, fertilizer use, and waste management, where emissions abatement remains challenging. Such mitigation potential is provided by GLOBIOM and is part of future work. Second, the increasing CDR deployment also mitigates these emissions. DACS, which filters carbon from the atmosphere as air flows through a device and reacts with a sorbent, is deployed in this pathway. These solutions are the most expensive forms of CDR (around 600 USD/tCO₂, according to [51]), exceeding the GHG price used in the soft-linking approach. The CO₂ quantities removed using DACS increase late in the century, resulting in 4 GtCO₂ removed by 2100. These technologies are energy-intensive. Further to that, their efficiency in providing negative emissions depends on the decarbonization of the energy system [52]. Thus, it is

essential to discuss their contribution in terms of trade-offs even though they present a low land footprint compared to land-based CDR.

4.2. Regional pathways and the deployment of land-based decarbonization

This section presents the GHG emissions pathways and the regional distribution of CDR deployment associated-energy-land dynamics across Asia, the Americas, Europe, and Africa. The analysis highlights the differences in biomass availability, technological readiness, and policy ambition shape regional CDR portfolios. While China dominates global biogenic CDR through large-scale imports and infrastructure concentration, the Americas rely more on domestic resources and land-based removals, Europe emphasizes BECCS in industry, and Africa emerges as a biomass supplier.

4.2.1. Regional pathways for emissions

Fig. 9 illustrates the regional distribution of the GHG pathways of the 2 °C and 1.5 °C scenarios. Asia, groups China, India, Japan, South Korea and countries in Other Developing Asia (ODA), Oceania includes Australia and New Zealand (AUS). In the 2 °C scenario, emissions decline steadily, but residual emissions persist beyond 2060, with some regions (Africa and the Middle East, and Asia) maintaining positive emissions even in 2100. In the 1.5 °C scenario, emissions drop more rapidly, reaching net-zero before 2060 and transitioning into net-negative emissions post-2060, indicating higher reliance on CDR solutions.

4.2.2. Regional electricity generation

Across regions, renewable energy follows a consistent upward trend for both the 2 °C and 1.5 °C scenarios by 2060 which is the net-zero year for the 1.5 °C scenario. Bioenergy with CCS constitutes a significant part of electricity generation in the USA and Eastern Europe under both scenarios (Fig. 15 Appendix G). Interestingly, the 2 °C scenario exhibits a higher deployment of BECCS than the more stringent 1.5 °C pathway, even though they apply identical land constraints. In 2060, residual emissions reach 9.0 GtCO₂ yr⁻¹ in the 2 °C pathway versus 3.3 GtCO₂ yr⁻¹ in the 1.5 °C pathway, a difference of 5.7 GtCO₂ yr⁻¹. To

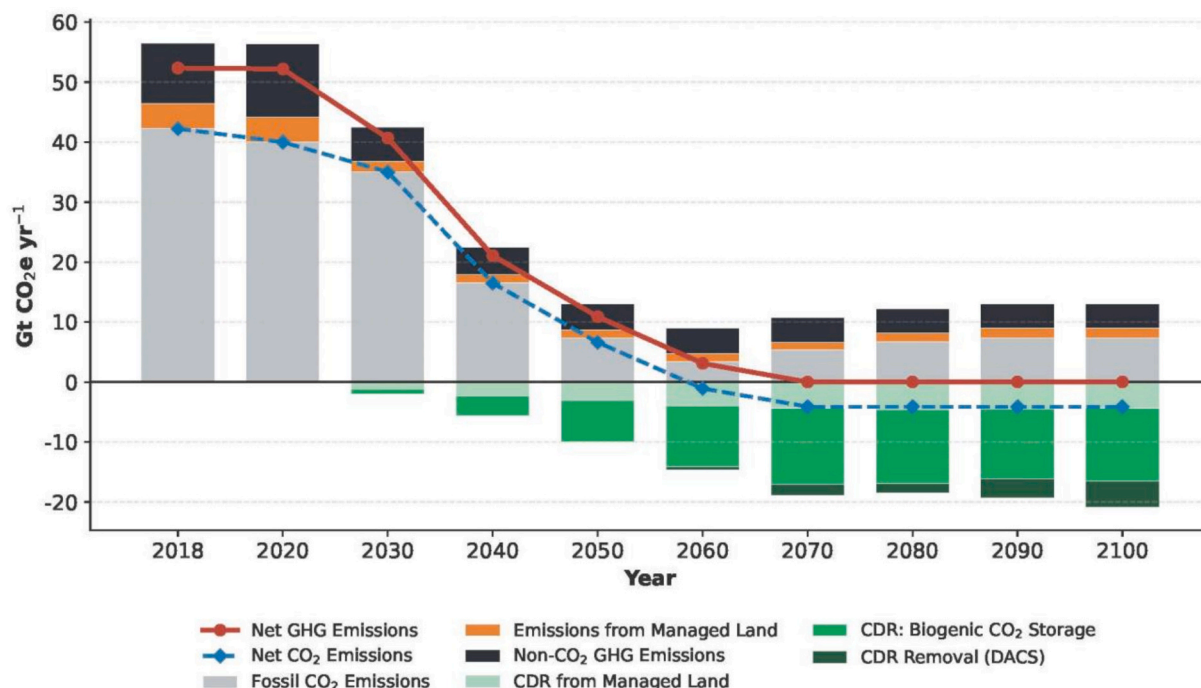


Fig. 8. Role of CO₂ removal in the 1.5 °C scenario.

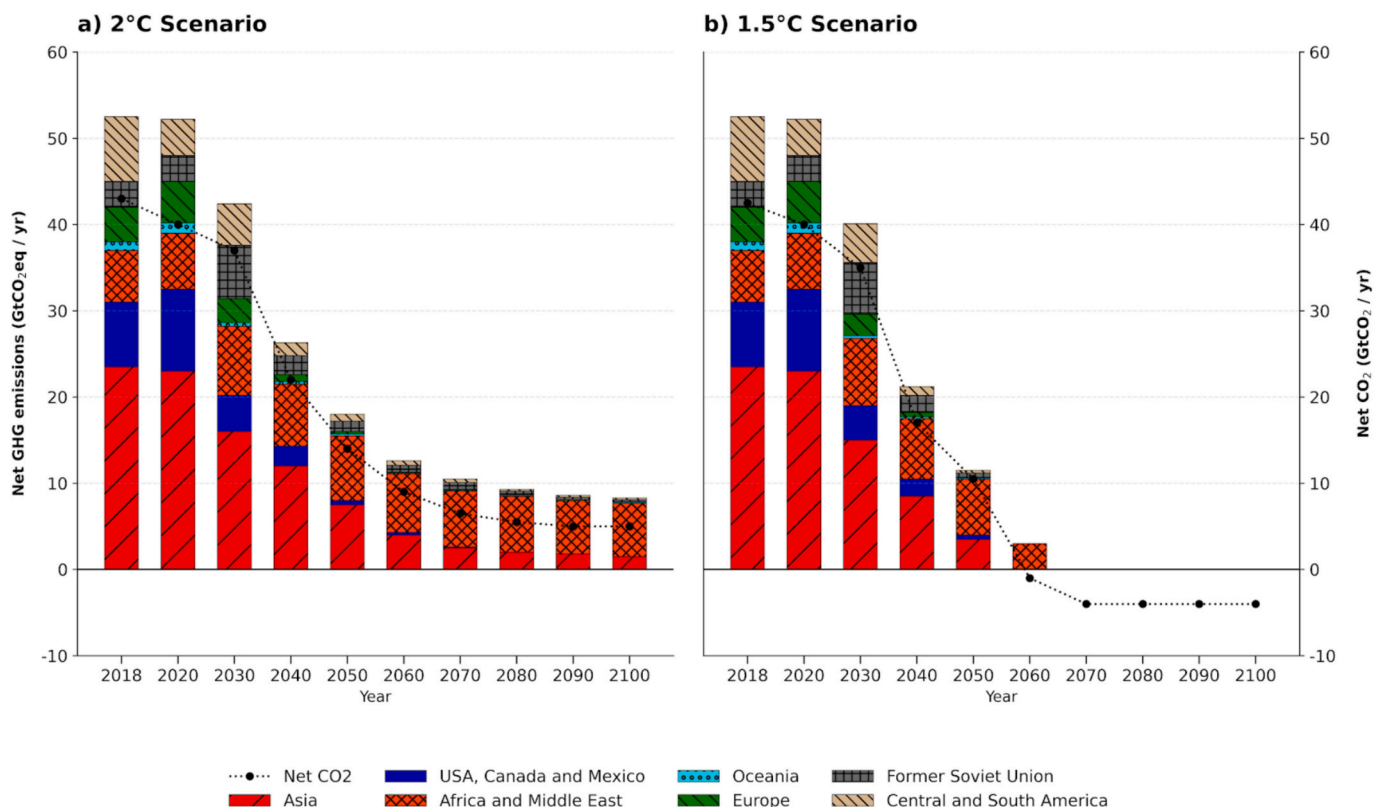


Fig. 9. Evolution of GHG and CO₂ emissions by region for the 2 °C and 1.5 °C scenarios. China, USA, and India remain dominant emitters in both pathways, but their decline to zero is achieved in the 1.5 °C scenario due to stronger policy intervention spurred by the temperature limit and technological shifts, including renewable energy, CDR and CCS, and hydrogen (only for the case of the USA). These regions are the main adopters of negative emissions technologies due to their high biomass availability and industrial production capacities. As for CDR from managed lands, afforestation, which constitutes the greatest potential, is the highest in China, Central and South America, and Africa.

compensate, BECCS provides 3.7 GtCO₂ in the 2 °C case and 3.9 GtCO₂ in the 1.5 °C case, representing 36% and 27% of total biogenic removals, respectively. The 2 °C pathway follows a more gradual decarbonization trajectory, requiring greater carbon dioxide removal later in the century to compensate for earlier emissions, thereby increasing reliance on BECCS. The 1.5 °C scenario accelerates early mitigation through stronger deployment of zero-carbon technologies, including renewables and electrification, reducing the relative role of BECCS. Natural gas with CCS is also prominent in the 2 °C scenario (Fig. 15 in Appendix G), constituting moderate actions toward emission reductions. Despite stringent climate constraints, coal-based power generation persists in both the 2 °C and 1.5 °C scenarios, though its direct combustion declines significantly after 2030. In addition, investment costs play an important role in the regional deployment of co-firing CCS plants. First, coal resources are more expensive in the USA. The country's main source of procuring coal is imports from Central and South America. China's imports are mainly from the Other Developing Asia region (see Appendix A), which presents lower costs. Furthermore, China can rely on the utilization of existing infrastructure. In fact, co-firing can be implemented in existing coal power plants with relatively few modifications, allowing for rapid and cost-effective emissions reduction. Coal-dependent regions rely on co-firing as an interim solution before shifting to BECCS, renewables, and other low-carbon technologies. The 1.5 °C scenario sees co-firing peak earlier (around 2060), then decline in favor of dedicated BECCS and clean power generation. Another reason for the deployment of co-firing with CCS is the use of biomass, which is carbon neutral in the model. Thus, biomass can provide negative emissions and provide flexibility in fuel sourcing. This is not possible with natural gas plants.

4.2.3. Regional role of land-based CDR

The CDR values by type regarding the energy system coupled with GLOBIOM, are shown for different regions in 2060. Some regions are aggregated for visualization. Note that the values from managed land, i. e., afforestation, forest management, and other Land Use Change (LUC) such as agricultural practices, are inputs from GLOBIOM that were fed into TIAM-FR. They are aggregated as land-based CDR in Fig. 10. Recall that Asia, groups China, India, Japan, South Korea and countries in Other Developing Asia (ODA) while Oceania includes Australia and New Zealand (AUS). In both scenarios, Asia leads in CDR, especially in the power and industry sectors. This region also has the highest values of removals by afforestation followed by Central and South America. BECCS CO₂ removal, with respect to total CDR, accounts for 30% in Asia, 14% in the USA, Canada and Mexico, and 12% in Europe for the 2 °C scenario. As for the 1.5 °C scenario, CDR is distributed more across the regions. In this case, BECCS in Asia accounts for 28% of global CDR, while the USA, Canada and Mexico are at 13%, and Central and South America are at 5.8%. DACS deployed along with CDR from managed land provides the possibility of achieving net-zero emissions. In fact, these options have the highest investment costs across all other mitigation solutions. The reliance on engineered CDR highlights the need for high-capacity negative emissions to offset residual emissions from energy and industry.

Furthermore, the results indicate that regions around the world need to exploit their biomass potential to achieve CDR, and switch from using it in sectors such as the residential sector, as shown in Fig. 5, or in some cases in industrial activity, rather than electricity. Within Asia, Japan and South Korea have limited sustainable biomass compared with China and India, while Other Developing Asian countries are heterogeneous. As a result, China becomes a net importer of biomass, sourcing pellets

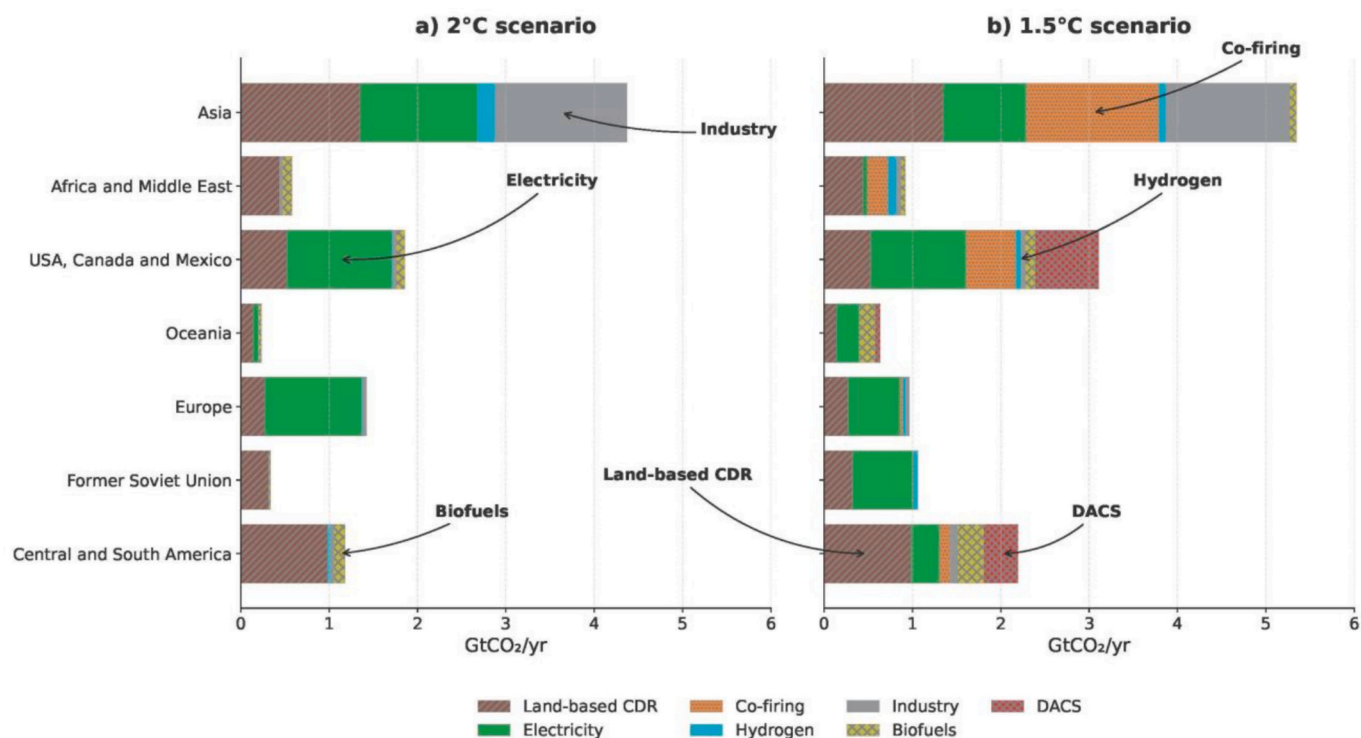


Fig. 10. CO₂ removal by different types of CDR in the TIAM-FR x GLOBIOM linking for the 2 °C (right) and 1.5 °C (left) scenarios in 2060. Land-based CDR includes removals from afforestation, forest management and other land use change. Biofuels includes removals when producing biodiesel and ethanol. Note that Asia includes China, India, Japan, South Korea and Other Developing Asia (ODA), Oceania includes Australia and New Zealand (AUS). The regions and countries overview is provided in Appendix A.

and torrefied biomass from regional suppliers, notably ODA countries, Africa and the former Soviet Union. In our 1.5 °C case, biomass imports to China reach ~11 EJ in 2060 and ~8 EJ in 2100. This enables large-scale biogenic CDR deployment where possibility for CCS in power and industrial clusters and storage sites already exist. Furthermore, Asia's CDR portfolio skews toward BECCS in power and hydrogen, plus biofuels with CCS (biodiesel in ODA; bioethanol in South Korea and ODA) and industrial BECCS (steel, metals, cement in China, Japan, South Korea, ODA).

By contrast, the Americas, despite higher domestic biomass potential, allocate a significant share to exports (driven by price advantages) and to land-based removals and DACS. This is indicated by the result that their in-region biogenic CDR is comparatively smaller to the Asian region. Its bioenergy potential for GHG mitigation is evaluated in [53] where the integration of bioenergy in the energy mix for the Asian region is found to be dependent on the policy setting. The strengthened commitment of updated NDCs shown in Appendix C include net-zero emissions targets for China (in 2060), India (in 2070), Japan and South Korea (both in 2050), and promotes the integration of bioenergy and CCS technologies in addition to other mitigation solutions.

5. Conclusion

This study contributes to understanding the interactions between land and energy systems when considering climate change mitigation pathways with a focus on Carbon Dioxide Removal. By linking two Integrated Assessment Models, TIAM-FR and GLOBIOM-G4M, through a SSP2 emulation, it investigates the potential and hurdles of land-based mitigation. First, this study offers a method for integrating land-use models into the energy system, emphasizing the role of biomass and greenhouse gas pricing, which affect the contribution of both bioenergy supply and the AFOLU sector in providing carbon removal. Second, the results investigate the transformation of the energy system with CDR on

global and regional scales. The scenario analysis conducts a discussion of the land–energy nexus while replying to key questions regarding CDR deployment elucidated in this section including the implications of large-scale CDR (Section 5.1) and the identified bottlenecks of the land and energy sectors (Section 5.2). Section 5.3 outlines the methodological improvements introduced in this work, notably the enhanced consistency with biophysical and economic constraints provided by GLOBIOM-G4M. The conclusion also outlines the remaining modeling challenges and provides main policy insights in Section 5.4.

5.1. Implications of scaling up CDR

Assessing the land–energy nexus in the context of energy system decarbonization and climate mitigation reveals several challenges. By 2060, cropland use for bioenergy, based on TIAM-FR optimization incorporating detailed crop configurations and GLOBIOM-G4M bioenergy supply, reaches 22% and 30% of the global 2020 cropland area [54] in the 2 °C and 1.5 °C scenarios, respectively. These results highlight that the expansion of bioenergy, in particular in the case of CDR, could incur sustainability concerns. Ultimately, mitigation strategies require striking a balance between land use choices for bioenergy purposes, carbon removal, and agriculture, discussed in the following paragraph. However, the choices made with respect to choosing between BECCS and other land-based mitigation could have a similar effect on land-use change and crop displacement. For example, in the context of CDR, land-use efficiency measured in tCO₂ per hectares per year can be used to make comparisons between BECCS and afforestation. The results are higher for BECCS with values around 17 tCO₂/ha in 2060 for the 2 °C scenario and 19 tCO₂/ha for 2060 in the 1.5C scenario. As for afforestation and reforestation, this metric is based on GLOBIOM's output and reaches 5.6 tCO₂/ha. The removal intensity in the case of BECCS is dependent on the feedstock type, where residues from forestry and agriculture can reduce land requirements. Nevertheless, weighing

up and deciding on the deployment of a type of CDR can have further implications regarding biodiversity and ecosystem restoration [55] and the consideration of locations [56].

5.2. Land–energy bottlenecks in Paris agreement-compliant scenarios

Across the CDR methods studied in this work, some bottlenecks arise due to the land and energy required for their scalability. First, land is subjected to pressure due to the vast areas required for planting trees and biocrops. From a bioenergy perspective, it was found that these scenarios include considerable amounts of bioenergy, either for electricity generation or industrial decarbonization. The optimization of GLOBIOM for the choice of land and resources clearly mitigates the potential risks of favoring edible crops to produce bioenergy. In addition, it makes it possible to move from a grid-level assessment to a regional view, while considering land productivity, opportunity costs for farmers, and GHG marginal abatement cost curves. Nevertheless, cropland expansion has already been observed between 2001 and 2023, with a global increase of about 5% [54]. Our results for cropland allocated to bioenergy with CCS fall within the expected range of 25–46% of global arable land used for energy crops across other IAM studies [57]. In our case, food crops are restricted from bioenergy use, yet overall land occupation remains a concern. Projections for cropland expansion dedicated to food production vary between 69 and 593 million hectares by 2050, equivalent to a 5–37% increase relative to the current cropland area of ~1600 million hectares [54]. These ranges depend strongly on factors such as yield growth, dietary shifts, and particularly on rising demand for animal-based food, reductions in food loss and waste, and the impacts of climate change on yields and prices. The study by [58] highlights that global cropland expansion has already replaced nearly half of natural vegetation, including forests, raising critical concerns about the trade-offs between agricultural production and ecosystem services.

The report [22] further emphasizes the risks of large-scale bioenergy expansion, noting that low-income consumers are particularly vulnerable, with 1–183 million additional people projected to face hunger depending on the socio-economic pathway considered. Extending our framework with an explicit SDG module from GLOBIOM's emulation [3] and implementing SDG relevant hypothesis in TIAM-FR would therefore be a valuable next step to capture these sustainability trade-offs, linking bioenergy expansion with food security, biodiversity, and ecosystem services.

Some bottlenecks were identified on the level of the forestry sector, which gains importance in terms of feedstock supply. Forest management policies need to be enforced to protect sustainable practices and align with the assumptions made regarding this sector in this study. Moreover, forest loss can be due to indirect effects on land competition in the bioenergy, food demand, and socio-economic scenarios [55]. According to the SSP2 assumptions, forest loss is reduced to 1% by 2050 and food consumption grows moderately, with the dietary share of livestock increasing [14]. These assumptions are critical to determine the level of CDR from land-based mitigation solutions, and uncertainties around them would impact the achievement of net-zero targets.

Mitigation technologies incorporating carbon capture impose an energy penalty, particularly for BECCS, fossil-based CCS, and DACS. This penalty arises from the energy required for CO₂ capture technologies. Bioenergy power plants with CCS, specifically those using direct combustion of pellets and torrefied pellets, exhibit lower efficiency compared to conventional bioenergy plants—30% versus 39% in 2040 for BECCS. Co-firing power plants with CCS achieve a moderate efficiency of approximately 36%, while natural gas with CCS reaches 57% in 2050. DACS in the model requires 1275 kWh per ton of CO₂ captured. In the case of BECCS, the efficiency loss due to CCS integration translates into an additional energy consumption of approximately 300 kWh per ton of CO₂ captured. These efficiency constraints highlight the trade-offs between negative emissions deployment and energy system

performance as well as land use.

5.3. Added value and limitations of the TIAM-FR–GLOBIOM linking

The TIAM-FR and GLOBIOM-G4M linking enables a comprehensive assessment of the land–energy nexus by integrating both energy system dynamics and land-use constraints, addressing key aspects of CDR feasibility. GLOBIOM ensures that land-based mitigation remains consistent with biophysical and economic constraints and accounts for the land-use competition between forestry and agriculture. Compared to earlier work with TIAM-FR without GLOBIOM integration, the present results show lower land use for bioenergy and a more diversified use of biomass including a more moderate reliance on BECCS. While the assumptions here are not directly comparable to previous scenarios in [59], the comparison is made in the context of a 1.5°C scenario. First, the potential of the AFOLU sector in terms of bioenergy is more limited, as can be seen when comparing Tables 2 and 6. Surface occupation by energy crops peaks at 500 million ha without GLOBIOM, whereas our results here show a maximum surface occupation of 370 million ha. Second, we note that BECCS in electricity generation remains the most prominent solution in bioenergy with and without land and potential constraints from GLOBIOM. In the present cases, the power sector invests more in co-firing (biomass and coal power plants); this brings more realism to the transition of this sector, especially with the delayed actions and fossil-fuel lock-in, given the limited aspect of biomass resources when land constraints are considered. Nevertheless, the assumptions and the CO₂ removal options are more diversified as more options become available such as afforestation and forest management.

The soft-linking prevents unrealistic bioenergy expansion by ensuring that land-use feasibility is respected when optimizing CDR strategies, particularly BECCS. By integrating land-based CDR (afforestation, soil carbon sequestration) with energy-based CDR (BECCS, DACS), the linking quantifies trade-offs between land-intensive and non-land-intensive negative emissions pathways. It highlights how land availability constraints might increase reliance on engineered CDR (DACs) and fossil power plants with CCS when bioenergy expansion is limited. The integrated modeling approach reveals important insights for policy: pricing mechanisms on carbon and land-use emissions, support for afforestation in high-efficiency regions, and investment in sustainable bioenergy supply chains can all contribute to aligning decarbonization with resource protection. The linkage between TIAM-FR and GLOBIOM-G4M was applied in a unidirectional mode, with land use and biomass supply constraints from GLOBIOM embedded in TIAM-FR. This design ensures resource feasibility while keeping the framework tractable. Energy demand dynamics remain reflected, as TIAM-FR optimizes bioenergy deployment under carbon and cost constraints within the available land envelope. Future work could introduce iterative soft-linking to capture feedback from energy demand onto land allocation, agricultural activities, markets, and prices.

Some limitations are observed that are common to these types of IAM. For example, climate change (temperature variation, extreme weather events) can affect crop yields and the permanence of afforestation and reforestation. It can also alter the soil temperature, leading to carbon losses and thus varying the potential of land-based mitigation. For such cases, Earth system models can be suitable for providing detailed results to address these uncertainties. In addition, regional representation in IAMs rarely encode distance to roads, terrain, or infrastructure, despite the fact that spatially explicit BECCS and biomass studies show that transport distance and local logistics strongly shape marginal biomass and BECCS costs [60]. Fine-scale analyses are needed to capture how siting relative to resource clusters or carbon storage affects feasibility [61]. High spatial datasets assist in analyzing competing land uses and suitability. They often include biomass resource layers at 300–1 km where biophysical, environmental and social constraints are combined [62], showing a finer consideration of these factors than IAMs. While using high-resolution input maps of biomass resources can

Table 4
Main characterization of SSP1, SSP2 and SSP3 focusing on the land–energy nexus.

Scenario	Bioenergy deployment	Land use change	Renewables adoption	Land-use pressure
SSP1	Sustainable, moderate–high	Decreased deforestation; afforestation and reforestation; sustainable agriculture	High (wind/solar, etc.)	Low due to sustainable practices and dietary shifts reducing cropland demand
	Moderate bioenergy deployment with balanced land competition	Moderate, balancing expansion and conservation	Moderate	Moderate pressure with ongoing but managed land competition
SSP2	Dominance of traditional biomass use; Low deployment of modern bioenergy technologies, regionally focused	Significant expansion of agricultural land; increased deforestation; weak conservation efforts	Low	High pressure due to agricultural expansion, food security concerns

Source: [14,25,71].

enhance spatial patterns in IAMs and give a more realistic accounting of vegetation carbon stocks and yields, their variability remains only partially represented due to the fact that information is collapsed into coarse regions [63,64]. Another specific limitation of this study is that the work does not yet capture water consumption constraints from CDR. Emerging empirical syntheses indicate that large-scale CDR interacts materially with water systems, reinforcing the need to treat water as a binding system constraint alongside land in scenario design [65]. In [66], the study used a GCAM model to determine water use by a diverse CDR portfolio. Regarding water use by bio-crops used in BECCS, it could reach 10% of the total water consumption in some regions in 2050. Moreover, bioenergy expansion and CCS technologies are found to be water thirsty [67]. Using a life cycle assessment on four types of carbon capture power plant in [68], it was found that primary energy demand increased by 21–46% and water resources depletion by 59–95%. This may lead to overestimation of CDR feasibility in water-stressed regions. This topic was explored for TIAM-FR prior to the GLOBIOM update in [69], and will be part of future work on the TIAM-FR and GLOBIOM framework. Pursuing this approach and adding the SDG module would improve comprehension of issues around the sustainability of net-zero pathways and provide an interesting discussion on the plausibility of mitigation scenarios.

To assess the robustness of the findings, future work could include the link between TIAM-FR and GLOBIOM under the assumptions of SSP1 on sustainability and SSP3 on regional rivalry. In fact, agricultural productivity, diet, demand, and biomass potential vary among SSPs. This could lead to a potential shift in price and constraints. Moreover, the energy-focused multi-model SSP comparison shows how socio-economic pathways drive divergent technology choices and resource use, altering biomass uptake and CCS/BECCS roles [70]. Therefore, to reflect the full range of possible land–energy futures, robust testing using SSP1 and SSP3 could help identify those policies or strategies that are effective regardless of the pathway versus those that are sensitive to energy system transformation and land-use drivers. The main characterization of SSP1, SSP2, and SSP3 focusing on the land–energy nexus is shown in Table 4 and indicates that SSP1 demonstrates resource efficiency and low land-use emissions while SSP3 illustrates risks of high land demand and deforestation. Hence, mitigation solutions (land-based

and others) should be checked for effectiveness according to the SSP to ensure their robustness with plausible socioeconomic change.

5.4. Policy implications

To scale CDR responsibly and cost-effectively, climate policy should combine carbon pricing with minimum efficiency requirements and land safeguards. The outcomes of this study provide several policy-relevant insights into the deployment of CDR within net-zero pathways.

- Differentiate CDR support schemes by land-use efficiency.** The findings show that BECCS achieves higher land-use efficiency ($\approx 17\text{--}19$ tCO₂/ha/yr in 2060) compared to afforestation (≈ 5.6 tCO₂/ha/yr). When designing CDR support schemes, policy frameworks should account for such differences in addition to the technology cost and the social cost of carbon, while also recognizing the biodiversity and ecosystem co-benefits of afforestation.
- Promote the use of linked IAM frameworks in policy assessment.** The integration of TIAM-FR with GLOBIOM-G4M highlights the value of embedding land-use constraints in energy system optimization, which strengthens the credibility of scenario-based policy analysis.
- Align national strategies with regional heterogeneity.** The regional results underline the heterogeneity of CDR deployment. This is also emphasized in the AR6 (IPCC, 2022, chap. 12) discussing qualitatively land use and occupation and the finite nature of land. Asia dominates in biogenic carbon capture in electricity and industry, while afforestation and forest management is more prominent in Central and South America with respect to its total CDR contribution in global temperature limitation. National strategies and NDCs should reflect biomass potential, industrial capacity, and land-use constraints.
- Provide stable investment frameworks for CDR scaling.** BECCS and DACS require significant investment in infrastructure, biomass supply chains, and long-term CO₂ storage monitoring. Stable carbon pricing and certification mechanisms can reduce uncertainty and support private-sector engagement.

CRedit authorship contribution statement

Sophie Chlela: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Nicklas Forsell:** Writing – review & editing, Validation, Supervision, Software, Methodology, Formal analysis. **Sandrine Selosse:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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. TIAM-FR regions

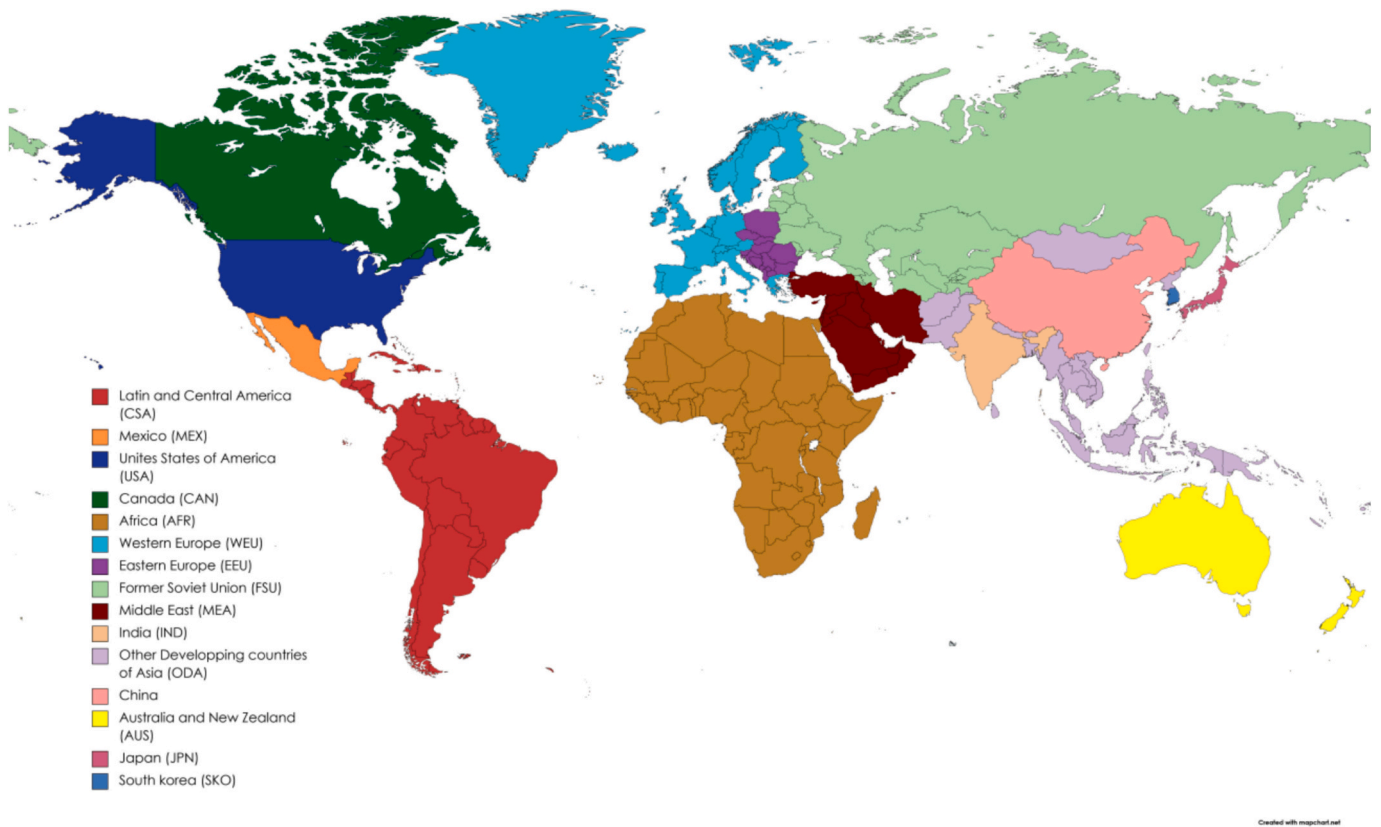


Fig. 11. TIAM-FR region coverage.

Appendix B. Energy crop supply chain in TIAM-FR

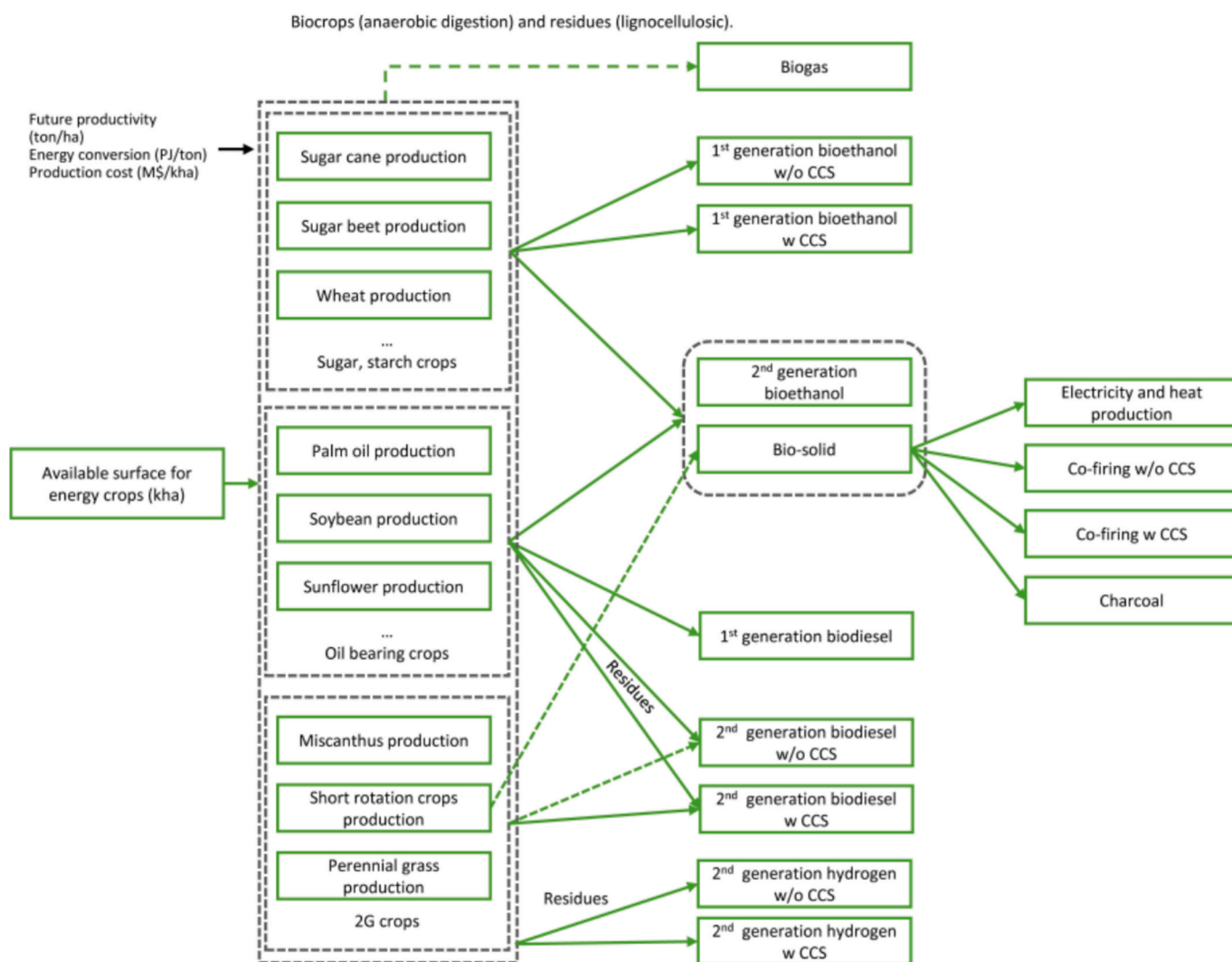


Fig. 12. Crop supply chain in TIAM-FR.

Appendix C. Formulation of Nationally Determined Contribution (NDC) emission targets

Table 5

Nationally Determined Contributions (NDC) emission targets. (These values are implemented in both scenarios.)

NDC Emission Reduction Type	Description	Affected TIAM-FR regions	Reference year	Target year	Reduction Target	Emission values (GtCO _{2e})*
Relative Emission Reduction	Countries disclose their anticipated emissions under a business-as-usual (BAU) scenario for 2030 and specify reduction goals relative to this scenario which is the NDC target.	MEX	BAU	2030	35%	0.43
		FSU	BAU	2030	Country-based	4.60
		ODA	BAU	2030	Country-based	6.20
		MEA	BAU	2030	Country-based	4.40
		AFR	BAU	2030	Country-based	5.30
		CSA	BAU	2030	Country-based	4.56
		WEU-EEU	1990	2030	55%	2.77
		USA	2005	2030	100%	Net zero
		USA	2005	2030	52%	3.40
		USA	2005	2050	100%	Net zero
Absolute Emission Reduction	Emission reductions are relative to a base year, with countries specifying reduction targets from historical emissions data.	AUS	2005	2030	43%	0.43
		AUS	2005	2050	100%	0
		AUS	2005	2050	100%	0

(continued on next page)

Table 5 (continued)

NDC Emission Reduction Type	Description	Affected TIAM-FR regions	Reference year	Target year	Reduction Target	Emission values (GtCO ₂ e)*
Carbon Intensity Reduction	Countries aim to reduce carbon intensity relative to GDP. Targets are based on a reference year.	CAN	2005	2030	45%	0.80
				2050	100%	Net zero
		JPN	2013	2030	46%	0.76
				2050	100%	Net zero
		SKO	2018	2030	40%	0.50
				2050	100%	Net zero
		CHI	2005	2030	65%	8.52 (GtCO ₂)
				2060	100%	Net zero
		IND	2005	2030	45%	3.92 (GtCO ₂)
				2070	100%	Net zero

Data sources: NDC documents as per the UNFCCC registry, UNFCCC emission inventory, TIAM-FR, OECD GDP data.

Note that there are non-Annex I countries that provide an NDC based on Policies and Actions or Peak of emissions. For Policies and Actions, we rely on *den Elzen, M.G.J., Dafnomilis, Hooijschuur, E., Nascimento, L., Kuramochi, T., Forsell, N., Gutiérrez, Z.A., Gusti (2024), Infographics PBL NDC Tool 2024. Zenodo. <https://doi.org/10.5281/zenodo.10875617>*

* Values are adjusted according to TIAM-FR emissions through interpolation.

Appendix D. Mitigation activities potential from GLOBIOM-G4M emulation

Table 6

Mitigation activities potential from GLOBIOM-G4M emulation according to the GHG price chosen for the linking approach.

Mitigation Activities	Mitigation Potential (million tons (Mt) CO ₂ /year)		GHG Price Range (USD/tCO ₂)	
Afforestation/reforestation/avoided deforestation	2030	856	2030	35
	2050	-541		
	2100	-3215		
	2030	-386		
	2050	-725		
Forest management	2100	859	2050	82
	2030	137		
	2050	-438		
Soil carbon sequestration	2100	-398	2100	200

Appendix E. Reference land system based on the emulation of GLOBIOM

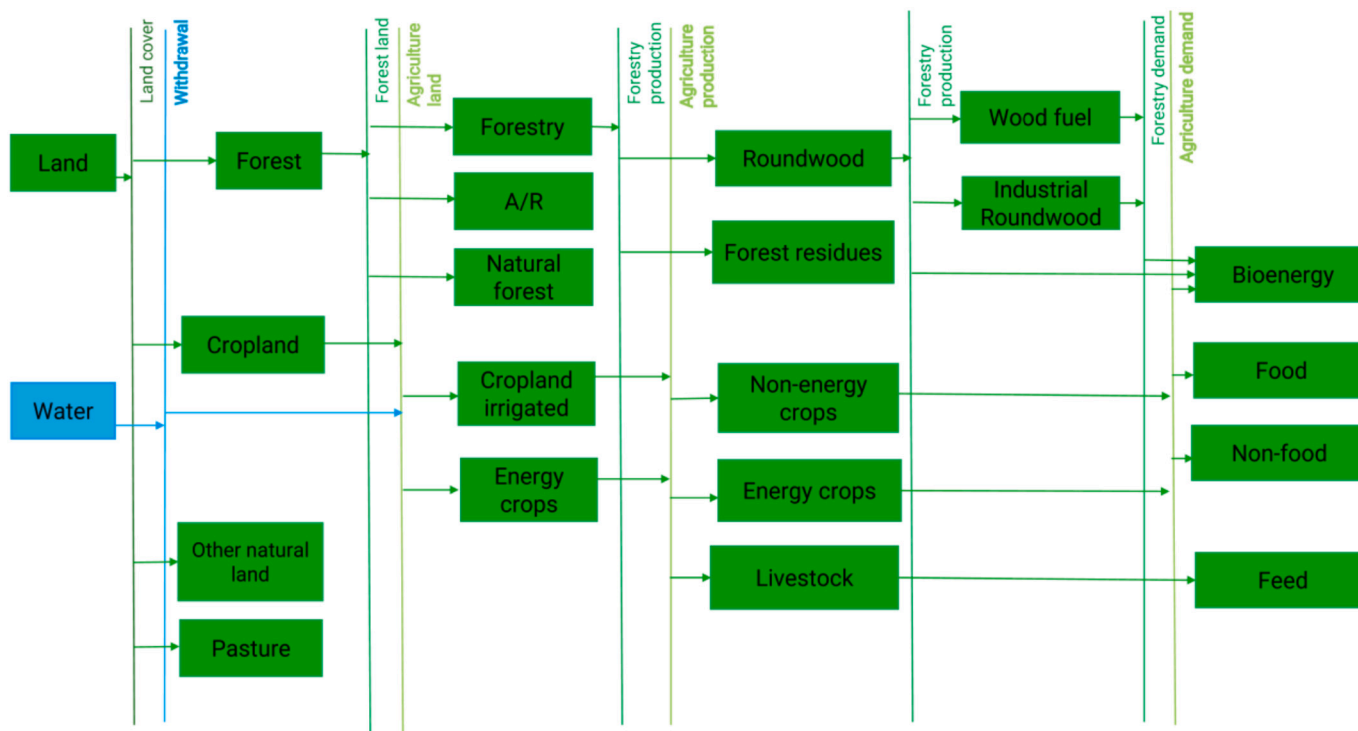


Fig. 13. Reference land system based on the emulation of GLOBIOM.

Appendix F. Key scenario parameters and data sources

Table 7

Key scenario parameters implemented in TIAM-FR.

Parameter	Scenario 2 °C	Scenario 1.5 °C	Notes
Carbon price trajectory	Increasing to 200 USD/tCO ₂ in 2100	Increasing to 200 USD/tCO ₂ in 2100	Source: GLOBIOM emulation
Bioenergy availability	AFOLU biomass supply, including energy plantations, from GLOBIOM	Idem	– Edible (1st generation) crops are constrained according to levels of GLOBIOM, then excluded after 2030. – Residues and waste prioritized.
Land availability constraint	– Exploitable land representation of surface occupation and forestry potential in TIAM-FR. – Land cover by energy plantations according to GLOBIOM.		
CDR option set & performance	BECCS (power, industry, H ₂), land-based CDR from GLOBIOM (afforestation, forest management, other LUC), DACS.		
Technology parameters	– Exogenous input of CAPEX, OPEX and efficiency for BECCS, DACS, renewables, power plants with or without CCS. – Constant/declining with learning; identical across scenarios.		– Coal, Gas and Nuclear [72]. – Bioenergy and BECCS from [73,74]. – Solar and Wind potential and parameters [75]. – Renewable energy projects until 2030 according to [76]. – Hydrogen [77–79]. – CCS equipped power plants [80]. – DACS [51].
Carbon Capture and Storage	– Stated projects till 2030 according to [81]. – Cost of transport and storage according to [82]. – Storage potential by region following a low potential scenario according to [83]		
Emission and climate targets	NDC including net-zero announcements, 2 °C pathway.	NDC including net-zero announcements, 1.5 °C pathway	

Table 8

Bioenergy supply potentials by region and biomass feedstock type, integrated from GLOBIOM (EJ).

Year	Wood (EJ)			Forest Residues (Processing) (EJ)			Agricultural Residues (Harvest) (EJ)			Agricultural Residues (Processing) (EJ)			Logging residues (EJ)		
	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100	2030	2050	2100
AFR	1.65	1.25	3.55	0.51	0.92	2.33	4.22	2.79	0.00	0.38	0.24	0.00	0.04	0.10	0.34
AUS	0.14	0.10	0.27	0.24	0.35	0.59	0.27	0.09	0.00	0.04	0.01	0.00	0.02	0.04	0.10
CAN	1.39	1.13	4.04	0.85	1.17	1.90	0.20	0.09	0.00	0.03	0.01	0.00	0.05	0.11	0.25
CHI	1.24	1.05	4.05	1.08	1.22	1.44	3.54	1.80	0.00	1.74	0.87	0.00	0.02	0.04	0.07
CSA	0.26	0.19	0.92	1.19	1.55	1.98	6.94	4.53	0.00	0.94	0.62	0.00	0.07	0.13	0.23
EEU	0.91	0.77	3.01	0.39	0.44	0.52	1.14	0.60	0.00	0.08	0.05	0.00	0.03	0.04	0.07
FSU	1.59	1.37	5.32	0.79	0.88	1.06	1.64	0.88	0.00	0.16	0.08	0.00	0.05	0.08	0.14
IND	1.23	0.62	1.88	0.34	0.46	0.63	4.04	2.49	0.00	1.35	0.75	0.00	0.02	0.04	0.07
JPN	0.10	0.08	0.34	0.11	0.12	0.13	0.08	0.04	0.00	0.08	0.04	0.00	0.01	0.01	0.01
MEA	0.08	0.06	0.24	0.11	0.15	0.20	0.77	0.40	0.00	0.10	0.04	0.00	0.01	0.01	0.02
MEX	0.01	0.01	0.03	0.03	0.04	0.05	0.33	0.17	0.00	0.05	0.02	0.00	0.00	0.00	0.01
ODA	0.46	0.34	1.27	0.67	0.91	1.25	5.45	2.92	0.00	1.39	0.78	0.00	0.04	0.07	0.15
SKO	0.03	0.03	0.11	0.04	0.05	0.06	0.02	0.01	0.00	0.03	0.01	0.00	0.00	0.00	0.00
USA	2.20	1.77	6.16	1.95	2.67	4.43	3.04	1.54	0.00	0.70	0.36	0.00	0.11	0.21	0.50
WEU	1.12	0.92	3.33	1.24	1.29	1.34	1.70	0.86	0.00	0.52	0.22	0.00	0.09	0.16	0.35
Total	12.41	9.69	34.52	9.54	12.22	17.92	33.36	19.23	0.00	7.57	4.11	0.00	0.55	1.06	2.31

Table 9

First generation biomass availability according to GLOBIOM soft link.

	1st generation in million tons dry matter per year (t DM/yr)			
	2020	2030	2050	2100
AFR, MEA	1810	1810	1810	1810
ODA, CHI, IND, JPN, SKO	28,620	28,600	28,620	28,620
CAN, USA, MEX	148,198	147,838	147,297	143,723
CSA	74,235	74,235	74,235	74,235
WEU, EEU	38,810	38,673	38,255	37,118
FSU	538	538	538	538
AUS	494	494	494	494

Table 10
Second generation crop potential according to GLOBIOM's soft link.

Energy crops	World
Year	Energy crops (EJ)
2020	0
2030	0.0
2040	12.9
2050	33.0
2060	55.1
2070	75.5
2080	92.3
2090	105.5
2100	112.8

Sources: [82,83].

Appendix G. Results

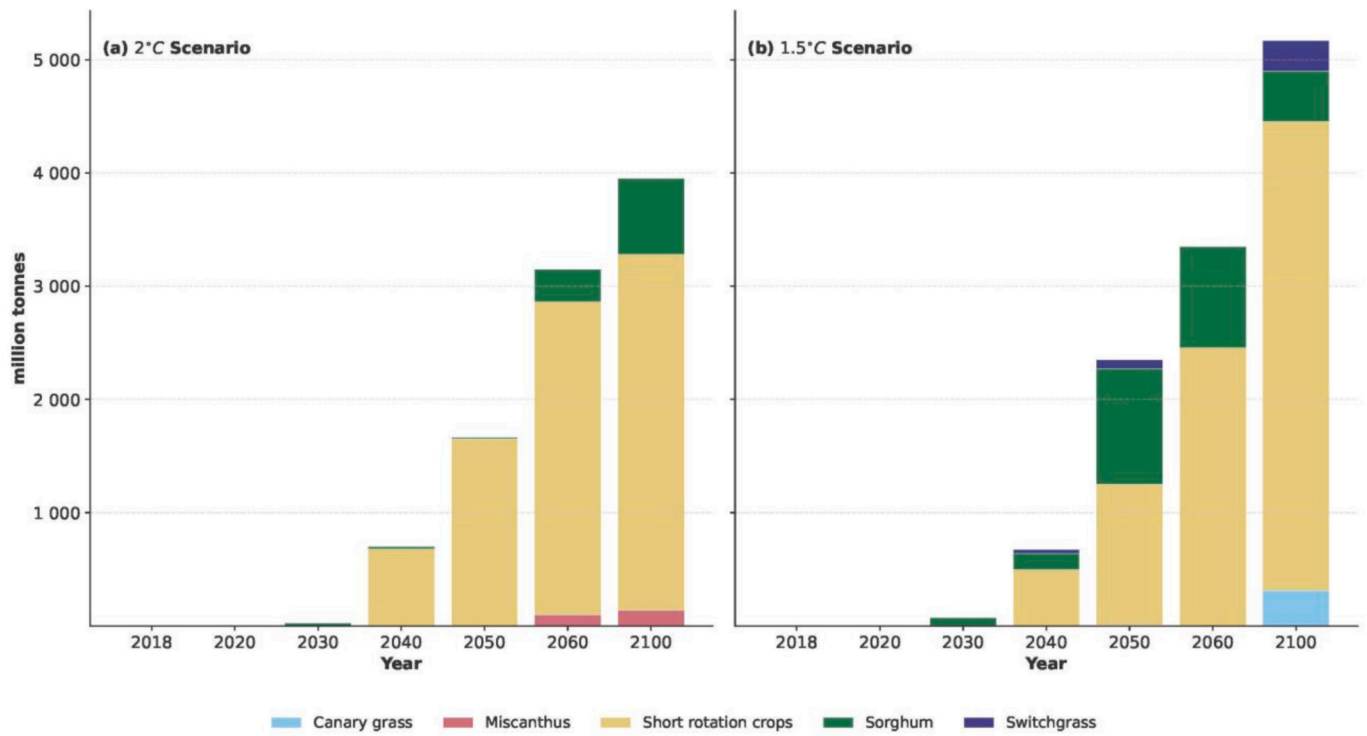


Fig. 14. Energy plantation supply in million tons in the 2°C and 1.5°C scenarios.

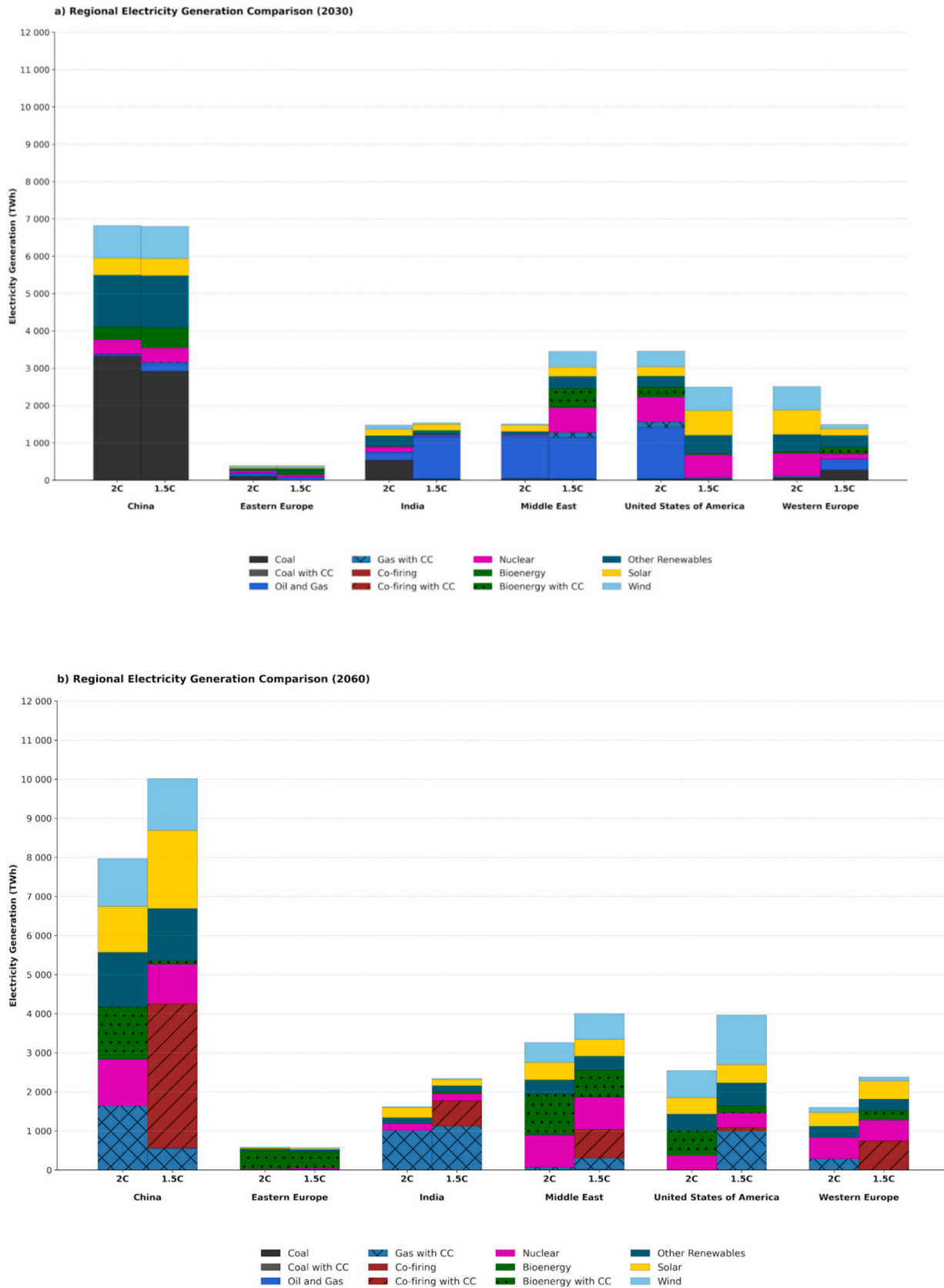


Fig. 15. Electricity generation for selected regions 2 °C and 1.5 °C scenarios for three milestone years.

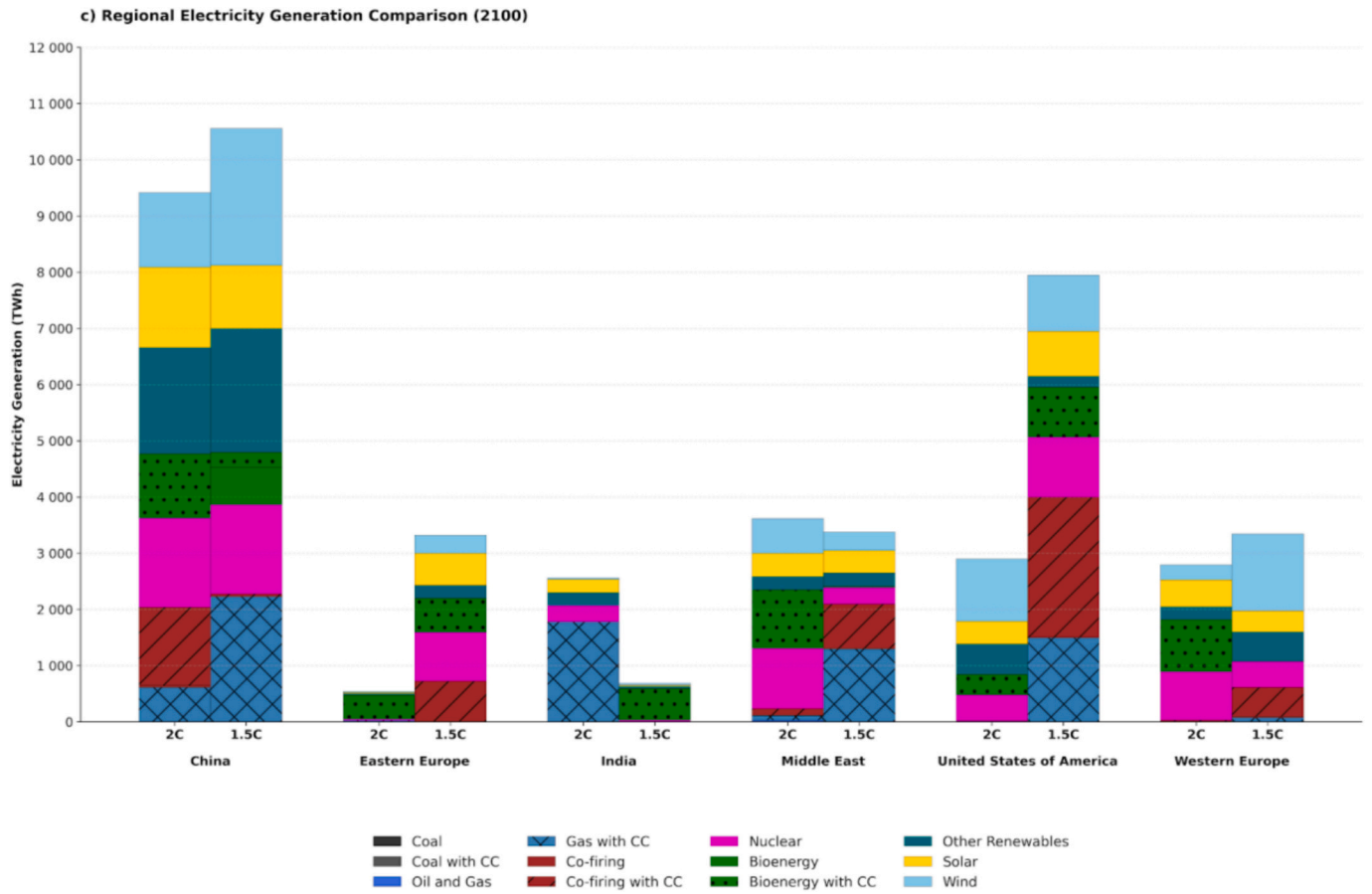


Fig. 15. (continued).

Data availability

Data will be made available on request.

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