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Sustainability implications of different carbon dioxide removal technologies in the context of Europe`s climate neutrality goal

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Abstract

The role of carbon dioxide removal (CDR) is undoubtedly crucial in achieving the climate goals and end-of-century global warming target. Given its role as a leader in global climate actions, the European Union (EU) is expected to take a leading role in CDR developments: yet there is a lack of depth in the region`s CDR strategy and deployment. A comprehensive CDR approach based on integrated assessment modelling for the EU is required to give valuable insights into optimal CDR-based mitigation pathways regarding scalability, technology readiness, trade-offs with earth systems, and deployment strategies. Here, we have used the GCAM-CDR v1.0 to model a diverse novel CDR portfolio of bioenergy carbon capture and storage (BECCS), direct air capture and carbon storage (DACCS), terrestrial enhanced weathering (TEW), and ocean-enhanced weathering (OEW) in a mid-century carbon neutrality target. We find that CO_2 removal by BECCS scales quickly to gigatonnes of CO_2 removal by mid-century, and DACCS is a latter-century mitigation technology in the EU's emission mitigation pathway. TEW will play a crucial role in achieving carbon neutrality in the EU if this climate goal is advanced by a decade. Modelled results show that achieving carbon neutrality through diverse CDRs relies heavily on significant emission reductions in the industrial and hard-to-abate sectors. Finally, we observed that nuclear energy will be an important energy resource for these CDR technologies in Europe. This study recommends that the EU carbon removal structure should not be limited to DACCS, but rather allow for innovations in carbon removal technologies.

Keywords: Carbon dioxide removal, Bioenergy carbon capture and storage, ocean-enhanced weathering, Terrestrial-enhanced weathering

Synopsis: The EU needs to develop a more comprehensive CDR strategy; with bioenergy and nuclear energy playing a vital role and DACCS developing later.

Nomenclature

AR6 – Assessment Report 6

BECCS – Bioenergy carbon capture and storage

Capex – Capital expenditure

CDR – Carbon dioxide removal

DACCS – Direct air carbon capture and storage

EU – European Union

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Flh – Full load hours

H2A – Hard to Abate

Hp – Heat pump

IAM – Integrated Assessment Modelling

IPCC - International Panel on Climate Change

Opex – Operational expenditure

TEW – Terrestrial enhanced weathering

UNFCCC - United Nations Framework Convention on Climate Change

OEW – Ocean Enhanced Weathering

GHG – Greenhouse gas

AR – Afforestation

GWP – Global Warming Potential

Variables and Parameters

A_t- Activity level

β - logit exponent that shapes the distribution

$c_{i,j}$ - cost of the technology or subsector i, j

E_t Emission at time t

EF_{t0} Initial emission factor

exp – exponential

g_k - GHG valuation of gas k

i_j – cost of input j

v_l - valuation of secondary output l

$\alpha_{i,j}$ – share weight of each technology i, j

$\frac{s_i}{s_j}$ – share ratio

t – time period

u – capital, operation and maintenance cost

R_{t_1} Marginal abatement curve reduction year at time

p emission price

TC_{t_2} – Technology change per time

pcGDP – per-capita gross domestic product

1. Introduction

A consensus towards holding global temperature increase to below 2 °C and pursuing a 1.5 °C by 2100 relative to the pre-industrial levels during the 2015 United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties in Paris sparked a myriad of regional climate actions in meeting this target(Schellnhuber et al., 2016). Despite global climate mitigation actions, the carbon budget to stabilize global warming at 1.5 °C is becoming increasingly constrained(Hof, 2021). Transitioning to net-zero emissions by 2050 is crucial to staying within the remaining carbon budget, even more especially with increasing global emissions(Welsby et al., 2021). Most scenarios that achieve end-of-century warming temperatures of below 2 °C utilize carbon dioxide removal (CDR) technologies(Pozo et al., 2020). According to the International Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) ((IPCC), 2023a; Lee, 2022), the deployment of CDR is critical to counter-balance Green House Gas (GHG) emissions especially those from hard-to-abate sectors(Climate change, 2023). The AR6 suggests that a 1.5 °C and 2 °C target would require net-zero emissions to be met by 2050 and 2070 respectively, with expected cumulative gross net-negative emissions in the range of 320-1020 Gt (by the end of the century) (Geden et al., 2018).

The European Union (EU) considers itself an international climate policy leader and has been at the forefront of championing actions towards global climate targets (Afionis et al., 2012). Europe aims to be carbon neutral by 2050, and to achieve this objective, the European Commission (EC) presented its `European Green Deal` in 2019 to the EU (Steininger et al., 2022). As one of the largest emitters, coupled with a historical record of accomplishments of its leadership position in climate change discourse, it is expected that the EU will take a leading role in CDR development(Long & Blok, 2021.; Pozo et al., 2020). (Scott & Geden, 2018) commented that for Europe to achieve carbon neutrality by 2050, gross carbon removal in the range of 1 $GtCO_2$ per year by 2050 is required. (Peters & Geden, 2017)also corroborated the potential of CDR in Europe as they estimated that 7.5 $GtCO_2$ would have to be sequestered through bioenergy carbon capture and storage (BECCS) by 2050. CDR via BECCS is considered a promising CDR in Europe due to its degree of commercial activity (Galán-Martín et al., 2021). Past studies(Fuss et al., 2018a; Terlouw et al., 2021) have however raised concerns regarding the biophysical feasibility and socio-environmental effects of large-scale grown biomass plantations for BECCS, including competition for agricultural and natural land, an increase in food crop prices, biodiversity loss, and an intensification of water scarcity. Therefore, it is crucial that BECCS operations reliably sequester CO_2 while minimizing environmental impacts (Workman et al., 2020).

Despite the absence of a robust technological CDR strategy in the EU, integrated assessment modelling (IAM) studies suggest the significant role that CDR is expected to play in Europe's climate success story. (Geden et al., 2019; Geden & Schenuit, 2020). These IAMs predominantly only include AR/BECCS as CDR options for decarbonization pathways. Resorting to other CDR archetypes with low market maturity can alleviate the large impacts of BECCS on biodiversity, land, and water(Galán-Martín et al., 2021). The deployment of direct air capture (DACCS) shows a large CO_2 removal potential (Meckling & Biber, 2021). Timely deployment and scaling of BECCS and DACCS in Europe is also crucial to achieving climate neutrality. (Galán-Martín et al., 2021)showed that delaying DACCS deployment till 2050 will require its CO_2 removal contribution to be 40% of gross emissions, as against 9% if deployment began in 2020. Delaying the deployment of DACCS could put more strain on its scalability. The demands on DACCS to meet higher CO_2 removal targets would require substantial resource and infrastructural developments, which could potentially lead to technical difficulties, delays and cost overruns (Realmonte et al., 2019a). The more DACCS is delayed without decarbonizing the energy, the residual emission increases.

The reluctance in the EU on wider CDR policy stems primarily from its technological feasibility, and potential consequences (Tamme & Beck, 2021). The concerns surrounding CDR deployment in the EU are an impetus towards more robust IAM studies to be made on diverse CDR technologies other than BECCS and DACCS. This study utilizes the Global Change Assessment Model (GCAM-CDR) v1.0 (a variant of the GCAM v5.4) to model a wide portfolio of technological CDRs including terrestrial-enhanced weathering with basalt (TEW), Ocean enhanced weathering (OEW), coupled with DACCS, and AR/BECCS. This additional CDR technology is entirely missing in most IAM studies.

Ratcheting the near-term ambition of the EU carbon neutrality also plays a critical role in the reduction of some non-CO_2 emissions, which have greater global warming potential (GWP)(Nieto, 2022). In our analysis, a net-zero GHG emission target of 2050 is analyzed which is a replicative of the EU climate goal (Soares, 2024). Also, a net-zero emission target by 2040 is adapted to reflect a more ambitious decarbonization target and to explore the complex interplay concerning CDR deployments and environmental sustainability. The goal of our study is to estimate the potential role of a more diversified CDR technology in achieving carbon–neutrality in the EU and to investigate their role in the decarbonization of the major emitting sectors, especially the hard-to-abate ones. A conservative approach to CDR scaling is represented in our work, as a constraint of annual global CDR deployment of 2GtC (which is about 7.4GtCO$_2$/yr.) is imposed (Chen & Tavoni, 2013; Eufrasio et al., 2022). This constraint ensures a cautious and measured implementation approach that reflects a practical scaling process in reality. This in turn helps to minimize false policy. The present global novel CDR deployment (excluding Afforestation) is about 0.002 GtCO$_2$/year(Powis et al., 2023).

Our work provides insight into the role of CDR in the ambitious net-zero emission pathway set for 2050, and also in achieving an even more aggressive carbon neutrality pathway in Europe. A comprehensive IAM analysis on diverse CDR technology mixture, as against conventional methods, BECCS and more recently DACCS technologies will also be crucial to guiding policymakers in the EU on investments in strategic mitigation pathways. This analysis will give valuable insights into the efficacy, viability, and potential trade-offs of various CDR strategies, including afforestation, BECCS, DACCS, and enhanced weathering. By considering the complete spectrum of the CDR portfolios (BECCS, DACCS, TEW, and OEW) and their implications, policymakers can make informed decisions to optimize resource allocation, promote technological innovation, and support sustainable pathways towards achieving the EU's climate objectives. For clarity’s sake, the novelty and contribution of this work are enumerated as:

- Since the implementation of solely DACCS or BECCS poses negative effects on sustainability, an assessment of a diverse portfolio of CDRs could address both the removal of significant carbon and alleviate the strain on energy and land requirements. The feasibility of this approach and the scale required to meet the EU net-zero target will be evaluated in this work.
- A discussion on the nexus of land, energy, water, and food under various CDRs is explored in contrast to the use of singular CDR technologies. This work contributes to the discourse by highlighting the trade-offs associated with the scaling of diverse technological solutions. The focus is on emphasizing the complexities and interdependencies within the structure of land use, energy production, water

resources, and food systems when implementing a range of CDR strategies as opposed to relying solely on one approach

2. Literature review

The Special Report on 1.5°C, released by the IPCC in 2018 (IPCC, 2018), highlighted the significant gap between global climate targets and the current pace of climate action. This gap underscores the urgency and the need for immediate and more ambitious efforts to mitigate climate change and adapt to its impacts. It emphasizes the discrepancy between the current trajectory of global greenhouse gas emissions and the reductions required to limit warming to 1.5°C above pre-industrial levels. The more recent AR6(IPCC), 2023) report also reiterated that the world is not on track to meet the 1.5°C target, stressing that urgent and rapid actions are needed to achieve peak emissions and reach net zero emissions by mid-century (Climate Analytics, 2024). Also, following the talks on the increasing importance of CDRs in global climate goals, the EU has only recently adopted a Carbon Removal Certification Framework (CRCF)(European parliament, 2024). The CRCF suggested by the European Commission is seen as a crucial instrument for achieving climate neutrality by 2050. This approach necessitates enhanced implementation and financial support for carbon removal technologies and projects. The CRCF covers carbon removal, carbon farming sequestration, carbon farming emissions reduction and carbon storage in products. As the EU gears towards finalizing the law, a key component that requires consideration is the definition of the use and role of carbon removals in EU climate targets, so as not to allow for mitigation deterrence and delay in emission reduction actions. Some climate enthusiasts argue that including the core principle of using carbon removals as complementary to emission reduction has been undermined in the CRCF, as the carbon removal goal is deemed not to have been separated from the emission reduction target. A positive in the CRCF however is that under the permanent storage/removals, the technologies included are biochar Carbon Removal (BCR), Enhanced Rock Weathering (ERW), BECCS and DACCS, which is an improvement of the previous EU draft on removals which only included the latter.

In the IAM perspective of the role of CDR in the climate goals of CDRs, (Rosa et al., 2021)investigated the role of a sole BECCS in the EU`s net-zero climate target. From a combined geospatial and process engineering assessment, their work showed that about 200 $MtCO_2$ per year can be sequestered in Europe using BECCS, which is 25% of the EU`s 2023 emissions. Their work also highlighted some geographic and geopolitical challenges that could hinder the actualization of this CDR expectation. Some of these include a lack of biomass resources in some European countries, distance from emission sources and storage sites and inefficient CO_2 transport networks. (Galán-Martín et al., 2021)assessed the risks involved in delaying CDR involvement in the EU`s climate policies and actions. Their work showed that delaying CDRs could cut in half the removal potential due to unused biomass and land resources, as well as slow technological diffusion speed. The economic loss from CDR inaction in the EU was projected in their work to reach 0.12−0.19 trillion EUR per year. Similar to the work by (Rosa et al., 2021), (Lux et al., 2023)investigated the role of DACCS in the carbon neutrality pathway in the EU. In their work, they showed that the cost of DACCS is within 60 €/tCO_2 and 270 €/tCO_2 by 2050 under a progressive and conservative technology framework. Their study also mentioned that the affordability of DACCS has the potential to reduce the expenses associated with addressing climate change, thereby averting the need for costlier mitigation approaches. However, relying on a DACCS-focused approach to climate defence carries several risks, including the possibility of CO_2 storage breaches, and societal resistance to the necessary expansion of renewable energy.

Literature survey around the EU`s CDR expectations shows a gap in integrating a wider suite of CDR options from an IAM perspective. This is even more crucial as the CRCF has gone beyond DACCS and BECCS in their carbon removal frameworks. This work can serve as a policy lens to understand the implications of CDRs in the EU`s net-zero goals regarding sustainability risks. Also, the CRCF frameworks do not separate CDR and emission reduction targets, which has sparked some debates in the climate community, with arguments that this approach may potentially dilute the focus on urgent emissions reductions in favor of carbon dioxide removal (CDR) methods that are still under development or not scalable to the needed extent. Critics argue that by not distinguishing between these two strategies, there's a risk of undermining efforts to reduce emissions at source, which is seen as essential for limiting global warming in line with the Paris Agreement targets. Proponents of an integrated approach, however, suggest that combining CDR with emissions reductions can provide a more flexible and potentially more effective pathway to achieving net-zero emissions, especially in sectors where reducing emissions is particularly challenging. The debate highlights the broader challenge of balancing immediate actions to cut emissions with the longer-term need to remove CO_2 from the atmosphere, a balance that is crucial for achieving the long-term goals of climate policy. Our work however has been designed to separate CDR and emission reduction target, hence, we see this as a key contribution in improving the CRCF, where we call for a separate CDR and decarbonization strategy.

3. Methods and Scenario Development

The GCAM-CDR (Morrow et al., 2023) modelling approach allows all CDRs to compete on a uniform market, distinguishing itself from other Integrated Assessment Models (IAMs) in the literature. In this mechanism, each technology is compensated based on the price of the CDR sector, determined by the weighted average cost of its constituent technologies. This approach eliminates the substantial economic rents implied by the carbon-price-based method, where it is assumed that the CDR industry enjoys significant revenues and profits beyond what is necessary for economic viability in a market system. The CDR policy option in the GCAM-CDR v.1 reflects a real-world scenario, where each technology's viability is the result of specific decisions made during the design of climate policy and the associated cost implications of scaling. This nuanced approach mirrors the complexities of decision-making in climate policy and aligns with the economic realities of scaling diverse CDR technologies.

The GCAM operational dynamics and operations included in the GCAM-CDR are explained in the supplementary file (SI) (section S1). Also, the GCAM dynamic process functionality, and economic choices across diverse energy technologies, land and water use are described in the Supplementary file (Section 2.1 and 2.2)

In this work, we have designed a GHG constraint climate target with carbon neutrality to be achieved by 2050 in the EU, reflective of the climate goal stated in the EU Green deal (Soares, 2024).. This policy reflects the European Green Deal. The EU policymakers are beginning to discuss how to incentivize CDR scale-up; however, there is insufficient science behind the specific strategies. This work addresses the knowledge gap in deploying diverse CDR technologies to meet the EU green goal. Additionally, we propose ratcheting the net-zero emission deadline by a decade. The implications of this aggressive emission mitigation pathway are examined, concerning the role both land-based (AR) and other chemical and geochemical CDRs will play in balancing the source with sink emissions. These scenarios are designed to evaluate the potential pathways and trade-offs associated with various CDR strategies, by examining the emission mitigation pathways and CDR portfolios, we sought to capture the variety of potential impacts on energy transformation, emission reduction levels, carbon prices, and environmental sustainability.

The discourse of this work will provide policymakers with valuable insights into the potential pathways and challenges of achieving carbon neutrality in the EU-27. For a more detailed list of the countries in the context of the EU-27, reference can be made to the supplementary file, Table S2 (PPNL, 2023). This work can be used to enlighten policy discussions, guide decision-making processes, and identify the most effective and viable strategies for scaling up CDR technologies under the European Green Deal objectives. Our exhaustive analysis sheds light on the intricate interactions between policies, CDR technologies, and carbon neutrality goals. It provides a valuable foundation for policymakers to evaluate trade-offs, make informed policy decisions, and devise robust strategies for achieving carbon neutrality in the EU-27, taking into account the region's specific context and challenges.

3.1 Emission initialization, data sources, and emission equations

The total CO_2 emissions in the model are adjusted to the reference year of GCAM, which is 2015, to correspond with the data provided by the Carbon Dioxide Information Analysis Centre database (Boden, 2009). In a similar vein, the fossil fuel consumption for the current year corresponds to the information contained in the Energy Balances Database of the International Energy Agency (International Energy Agency, 2019). The emissions stemming from agricultural activities and modifications in land use are subject to the regional growth patterns, the carbon density intrinsic to the ecosystem, and the degree of changes in land use (Wise, 2014).

GCAM can be said to be a process model for emissions and reductions. The CO_2 emissions change across the model years, as fossil fuel consumption endogenously changes in GCAM based on constraints that have been set. GCAM derives a marginal abatement curve for carbon price applied within the model based on the distinct set policy

GCAM also incorporates the fugitive emissions from fossil fuel resources from the point of point of extraction of natural gas, oil well flares, hard coal etc. The initialization of the fugitive CO_2 emissions is done in GCAM using the CEDS inventory(Hoesly et al., 2018). They are also modelled using the non-CO_2 emissions. A comprehensive database can be found on (JGCRI, 2023b). Table 1 shows the Global Default Emissions Factors.

Parameterized functions are utilised to represent future emissions controls for air pollutants and Marginal Abatement Cost (MAC) curves for greenhouse gases (GHGs). This allows for the dynamic modification of emission factors over time. The purpose of these emission controls is to reduce emission factors in alignment with the trends observed in per-capita GDP for each region and period. This methodology is founded on the premise that there is a tendency to implement contaminant control technologies as incomes rise.

To model non-CO$_2$ GHG emissions, Emission for any technology at a time period t, the equation 1 is used:

$$E_t = A_t * F_{t,0} * \left(1 - MAC\left(E_{price,t}\right)\right) \tag{1}$$

$$\forall \in t \left\{ \begin{matrix} All\ discrete\ time\ periods\ included\ in\ the\ GCAM\ simulation\ from\ the\ base\ year \\ to\ the\ end\ of\ the\ century \end{matrix} \right\}$$

Where the initial emission factor is represented by $F_{t,0}$, activity level at a time period is denoted by A_t, the marginal abatement cost curve is represented by MAC, and emissions price at a time is denoted by $E_{price,t}$

Emission controls are scaled according to per-capita GDP, reflecting the tendency to adopt cleaner technologies as incomes increase. GHG MAC curves, sourced from the EPA's 2019(US EPA, 2019) non-CO$_2$ mitigation report, are integrated with GCAM's technological frameworks. These MAC curves evolve, showing yearly enhancements in reduction potential and phased implementation. Emission reductions under a carbon policy follow the MAC curve's guidance. Non-CO$_2$ GHG MACs representing emissions abatement as a percentage relative to emission prices, prompt technological advancements that shift the MAC curve progressively each year. This shift begins from 2030, following an initial MAC definition in 2025. The MAC related parameters are the annual improvement of reduction potential defined in MAC curve and MAC phase-in periods.

$$R_{t_{2,p}} = R_{t_{1,p}} * (1 + TC_{t_2})^{t_2 - t_1} \text{for all } p \tag{2}$$

The MAC reduction in year t_1 and t_2 are represented by the $R_{t_{1,p}}$ and $R_{t_{2,p}}$ at emission price of p. The technology change in year t_2 is TC_{t_2}. The Emission price is endogenously determined in the model, based on the climate target (or emission constraint) set in the model development.

The modelling of air pollutant emissions is made using:

$$E_t = A_t * EF_{t0} * (1 - EmCtrl(pcGDP_t)) \tag{3}$$

$$\forall \in t \begin{Bmatrix} All\ discrete\ time\ periods\ included\ in\ the\ GCAM\ simulation\ from\ the\ base\ year \\ to\ the\ end\ of\ the\ century \end{Bmatrix}$$

The E_t is the emission at time, t, EF_{t0} is the initial emission factor, A_t is the activity level. The function $EmCtrl$ models a decrease in emissions intensity in correlation with rising per-capita income.

$$EmCtrl_t = 1 - \frac{1}{1 + \frac{pcGDP_t - pcGDP_{t0}}{steepness}} \tag{4}$$

$$\forall \in t \begin{Bmatrix} All\ discrete\ time\ periods\ included\ in\ the\ GCAM\ simulation\ from\ the\ base\ year \\ to\ the\ end\ of\ the\ century \end{Bmatrix}$$

The term pcGDP denotes per-capita GDP, while 'steepness' is a predetermined variable for each technology and pollutant that determines how changes in per-capita GDP influence emissions reductions.

It is also important to mention policy-driven approach in GCAM is built upon placing a price on emissions. This price permeates the entire system and alters production and demand. An example of this is, that a carbon price in a model year (based on an emission constraint) would put a cost on producing electricity from a coal electricity power plant, which then alters their cost relative to other competing electricity technologies. This causes an increase in the price of electricity, which then filters down to the consumption pattern of electricity usage by consumers. This in turn can potentially reduce electricity competitiveness relative to other fuels.

Table 1: Global Default Emissions Factors (JGCRI, 2023a)

Primary Fuel	CO_2 coefficient (kg C per GJ)
regional biomass	23
delivered biomass	23
regional biomass Oil	19.6
regional sugar for ethanol	19.6
regional corn for ethanol	19.6
coal	27.3
regional coal	27.3
delivered coal	27.3
natural gas	14.2
regional natural gas	14.2
gas processing	14.2
gas pipeline	14.2
wholesale gas	14.2
delivered gas	14.2

crude oil	19.6
regional oil	19.6
refining	19.6
refined liquids industrial	19.6
refined liquids end use	19.6
limestone	0.08
unconventional oil upscaling	1.5

*CDIAC inventory IEA energy balance with some GCAM manual adjustments

3.2 CDR parametrization

3.2.1 BECCS

GCAM incorporates a number of BECCS technologies that are utilised in various energy system components, primarily in the electricity and refining industries. Other GCAM also includes BECCS in the hydrogen production, and industrial sectors. In this work, the BECCS competes directly with other forms of CDRs for carbon sequestration. In previous versions of GCAM, the energy demanded from the energy technologies (where BECCS is utilized) determines the quantity of CO_2 that can be sequestered by BECCS. In those cases, the cost of other technologies which competes with BECCS set the limit for the CO_2 sequestration of the latter. The effect of other CDRs like DACCS on BECCS in such model pathway is only through the indirect effect of carbon price from DACCS deployment. However, in more recent versions of GCAM, like the GCAM-CDR, a uniform price can be placed on all CDRs for which they compete directly.

Table 2 shows the fraction of CO_2 captured by transformation technologies for biomass conversion. GCAM also resolves endogenously the resources utilized for the bioenergy supply (Table 3) like land, water, and fertilizers. This is done among the 384 land-use regions which is made up of the 32 geopolitical regions and 235 water basins. The treatment of BECCS includes biomass collection, distribution and pelletization costs.

Table 2: Fraction of CO_2 captured by transformation technologies (JGCRI, 2023c)

Supply sector	**Subsector**	**Technology**	**1971**	**2100**
Refining	Biomass liquids	Cellulosic ethanol ccs level 1	0.26	0.26
Refining	Biomass liquids	Cellulosic ethanol ccs level 2	0.9	0.9
Refining	Biomass liquids	Ft biofuels ccs level 1	0.818	0.818
Refining	Biomass liquids	Ft biofuels ccs level 2	0.9	0.9

Table 3: Biomass liquids production technology (JGCRI, 2023c)

Technology	Inputs

Biodiesel (Soybean)	Oil Crop, Natural gas
Biodiesel (Oil Palm)	Palm Fruit
Biodiesel (Jatropha)	Biomass Oil
Cellulosic ethanol	Biomass
Cellulosic ethanol CCS level 1	Biomass
Cellulosic ethanol CCS level 2	Biomass
Corn ethanol	Corn, natural gas, electricity
Sugar cane ethanol	Sugar crop

3.2.2 TEW

The GCAM-TEW used basalt due to its lesser environmental risk compared to other forms of ERW. The work of (Beerling et al., 2020a) is used in retrieving the annual potential of TEW across different countries and regions. For the regions not included in the work by (Beerling et al., 2020a), the regional explicit potential from the work of (Beerling et al., 2020a) was used in linearly scaling the fully aggregated global TEW supply curve given by (Strefler et al., 2018). In GCAM-CDR, the non-energy costs fall at different rates for different CDR technologies, as shown in Figure 1. The energy-input for TEW in GCAM is within the range of 0.23-10 GJ/tCO_2 of electricity.

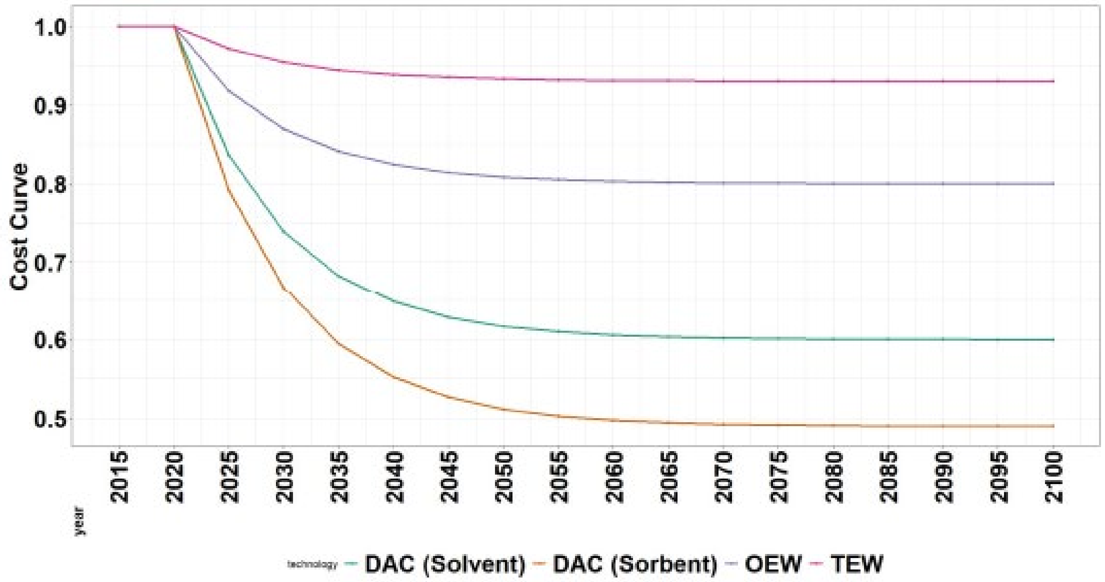

Figure 1: Assumed decline in non-energy costs of various CDR technologies in each future period as a fraction of their non-energy cost in 2020.

3.2.3 DACCS

Table 4 provides comprehensive data on the costs and energy requirements for DACCS processes, operated at high and low temperatures. In the GCAM model inputs, the methodology explained by (Fasihi et al., 2019) with modifications was used. Considering the infancy of DACCS technology, the cost assumptions were adjusted to be more cautious. Also, additional energy is needed for CO_2 compression, based on Keith et al.'s findings. For DACCS methods using solid sorbents, the thermal energy needs were recalculated in terms of electrical energy, considering a specific heat pump efficiency. The costs associated with the electric heat pump facility were also accounted for, referring to the works of both Fasihi et al. and Breyer et al.

$$Capex_{HP}\left(\frac{\$}{tCO_2}\right) = \left(\frac{Capex_{HP+Opex_{HP,fixed}}}{FLh} + Opex_{HP,var}\right) * H \qquad (5)$$

The $Capex_{HP}$ represent the capital expenditure for the heat pump ($\$733/kW_{th}$) (DEA, 2016)

The $Opex_{HP,fixed}$ represent the fixed operating cost of the heat pump ($\$2/kW_{th}$) (DEA, 2016)

The $Opex_{HP,var}$ represent the variable operating cost of the heat pump $(\frac{\$0.001}{kW_{th}.h})$ (DEA, 2016)

The FLh represent the full load hours per year (4000) (Breyer et al., 2020)

H is the scaling factor.

The parameterization of DACCS used in modelling is shown in Table 4

Table 4: Parametrization of DACCS (Morrow et al., 2023)

Technology	Electricity (GJ/tCO$_2$)	Heat (GJ/tCO$_2$)
High-heat DAC (Solvent)	1.32 [1.32-1.8]	5.2 [5.2-8.1]
Low-heat DAC (Sorbent)	0.7 [0.7-1.1]	4.3 [4.3-7.2]

The term "Non-Energy Cost" plays a pivotal role, representing a comprehensive measure of all expenses incurred that are not directly related to energy consumption. This includes capital costs, which cover the initial investment for development, manufacturing, and installation; operation and maintenance (O&M) costs, encompassing regular upkeep, labour, and other operational expenditures; depreciation, accounting for the technology's decrease in value over time due to wear, tear, or obsolescence; and financing costs, which involve interest and other charges related to capital borrowing. Expressed in gigajoules per ton of CO_2 (GJ/tCO_2), Non-Energy Cost quantitatively captures these additional financial obligations on a per-unit-of-output basis

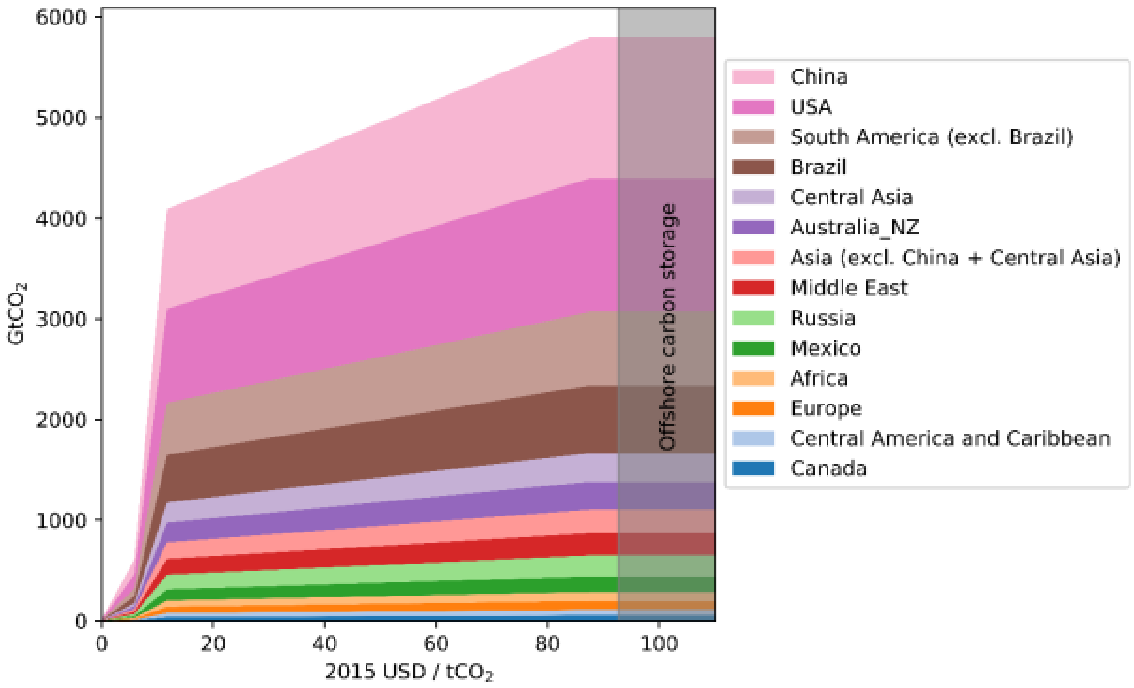

Figure 2: Supply curve parametrization for Geologic carbon storage (JGCRI, 2023)

Figure 2 illustrates cumulative geologic carbon storage supply by region for onshore and offshore storage resources. For this graph, GCAM regions with limited geologic storage capacity are aggregated (e.g., Africa, Europe, and South America excluding Brazil). According to (Dahowski et al., 2011), the onshore geologic storage supply curve for each region is parameterized based on updates (Dooley & Friedman, 2005) and incorporates deep saline sedimentary and basalt formations, depleted oil and gas fields, and unmineable coal seams. Cost is assumed to be a greater barrier to deployment than physical limits on repository availability when it comes to offshore storage. The offshore storage cost estimate of $\$96/tCO_2$ is not intended as an exact point estimate, but rather as a backup reservoir for CCS when regions exhaust their land-based storage. Consequently, a conservative estimation is used (multiple times the $\$32/tCO_2$ estimate from Decarre et al., (2010)) due to the great uncertainty surrounding the costs and availability of offshore and onshore carbon storage.

3.2.4 OEW

GCAM-CDR incorporates ocean liming as a method for increasing ocean alkalinity, akin to ocean alkalinization or enhanced weathering techniques outlined by (Renforth, 2019) and (Caserini et al., 2021). This method entails dispersing lime into the ocean, initiating a series of inorganic chemical reactions that enhance the ocean's capacity to store carbon in the form of bicarbonates. This not only allows the ocean to absorb more CO_2 from the atmosphere but also helps mitigate ocean acidification. However, the positive impacts of ocean liming on ocean alkalinity are not directly represented in the initial version of GCAM-CDR due to the way alkalinity adjustments are integrated within its climate module, Hector. In the framework of GCAM-CDR, the process of OEW is powered by natural gas and limestone, along with electricity, and leverages an unspecified product from international shipping (Figure 3). The approach assumes a specific technique of oxy-flash calcination, as mentioned by (Renforth, 2019), which effectively captures and stores CO_2 emissions produced during the calcination of natural gas and limestone.

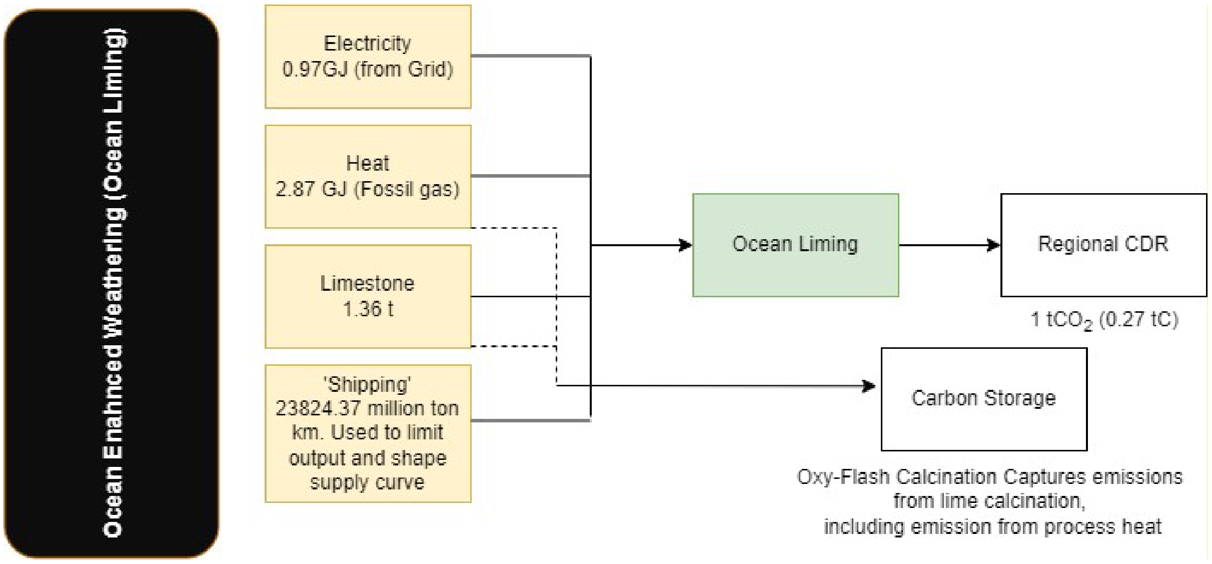

Figure 3: Ocean Enhanced Weathering in GCAM-CDR (Morrow et al., 2023)

3.3 CDR modelling framework and pricing in GCAM-CDR

GCAM-CDR 1.0 offers various methods for defining the overall annual deployment for CDR as a separate target from the emission reduction target. There are three primary methods to determine CDR demand: specifying an exact amount of CO_2 to be removed exogenously, letting CDR demand adjust automatically based on the carbon price, and aligning CDR with a specific proportion or multiple of emissions from certain regions and/or sectors(Morrow et al., 2023b). In our work, we have specified a constraint on the amount of CO_2 to be removed exogenously to be about 7 $GtCO_2$/year globally. Based on the IPCC scenarios (IPCC, 2023), the upper range of annual BECCS and DACCS deployed is 14 $GtCO_2$ and 2 $GtCO_2$/year by mid-century, therefore our CDR assumption is the median scale.

The pricing mechanism for CDR technologies within the GCAM-CDR model operates on a market-based principle, similar to how other goods and services are priced within the GCAM framework. CDR technologies are not allocated a fixed price in GCAM-CDR. Instead of this, they are compensated at market rates. This methodology emulates practical situations in which the costs of goods and services are influenced by the interplay of supply and demand, as opposed to being fixed. The price of the CDR sector as a whole is determined by averaging the costs of the individual CDR technologies that comprise it. Consequently, the proportional contribution of each technology to the sector price is determined by its share of the CDR market. The model takes into account the cost of each CDR technology and its proportional contribution or share to the overall CDR capacity or output to calculate the weighted average cost. As an illustration, the average cost will be significantly impacted by a more expensive technology that is concurrently more prevalent or profitable. Changes in market conditions, policies, or innovations will influence the rate of adoption of various CDR technologies over time; consequently, the weighted average cost of the CDR sector will also fluctuate. This exemplifies the ever-changing cost of services and technologies in a market, where supply, demand, and technological progress all influence the price structure. The implementation of this market-driven pricing mechanism establishes a reciprocal relationship in which the adoption of CDR technologies is impacted by their cost, which subsequently influences the sector's overall price. Increased adoption of technologies that become more affordable or efficient may result in a modification of the weighted average cost of the sector(Morrow et al., 2023b).

3.4 GCAM core and modelling of technologies

The GCAM framework integrates the expense associated with transformation technologies, which encompasses capital, fixed, and variable operation and maintenance costs. These financial metrics are obtained from the NREL Annual Technology Baseline's external database for the year 2019, a source noted for its comprehensive and reliable data, as cited in(NREL., 2019). This data on technology expenses, in conjunction with information on production costs, efficiency of technology, and emission levels, is employed to fine-tune the technology supply within the model to match historical records for various regions and periods. The equilibrium between historical demand and supply that the model uses is based on data from the IEA energy balances.

The fundamental principle underlying the GCAM is market equilibrium (Figure 4). In this model, representative agents utilize price data and other pertinent information to inform their resource allocation decisions. These agents are distributed throughout the model, symbolizing sectors such as regional electricity, refining, and energy demand, as well as land users faced with the task of distributing land among various competing crops in any given land area. The marketplace serves as the platform for interaction among these agents, where they communicate their supply or demand intentions for various goods and services. GCAM then calculates a series of market prices to ensure that supply meets demand across all these sectors within the model, maintaining balance and efficiency. The energy pathway is shown in Figure 5. The land and water pathways are explained in the supplementary document.

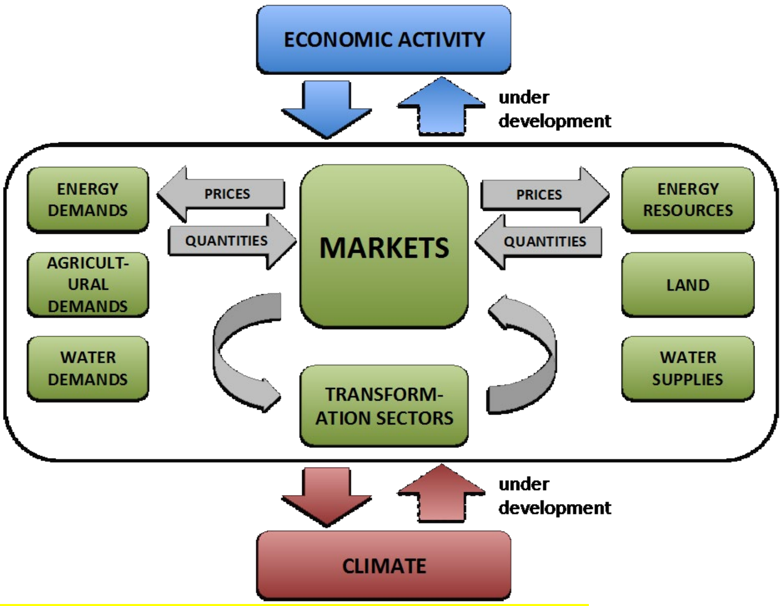

Figure 4: Conceptual operation of GCAM core (JGCRI, 2023b)

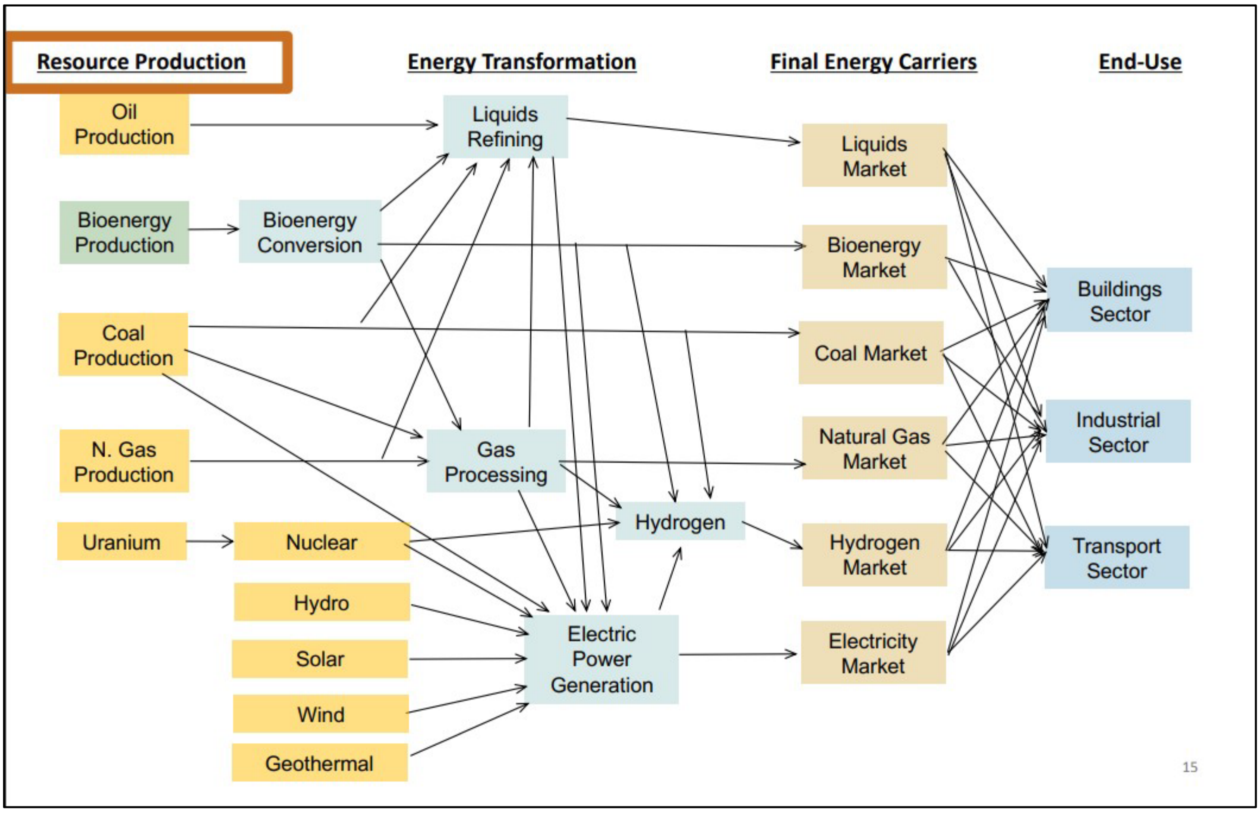

Figure 5: Conceptual energy pathways in GCAM Scenario development (JGCRI, 2023b)

We have modelled three (3) scenarios of diverse CDR archetypes for a 2040 and 2050 net-zero GHG emission target. These scenarios are built upon the central scenario of a GHG emission constraint, where Europe, alongside the rest of the world (ROW), reaches a net-zero GHG emissions constraint by 2050 in a separate market. The modelling construct involves creating an emission constraint market separately for EU-27 and aggregated for the ROW. This emissions peak occurs before 2025 and declines linearly to net-zero emissions by mid-century. The temporal horizon for the GCAM typically extends through the 21st century, concluding the year 2100. This long-term outlook allows for the examination of climate, energy, water, and land-use trends over an extended period, facilitating analyses of long-term environmental and economic impacts of various policy scenarios. However, the specific start and end years can vary based on the version of GCAM and the settings chosen for a particular analysis..

The scenarios of the diverse CDRs are based on the premise that the EU will implement a comprehensive and ambitious set of policy measures, including stringent emission reduction targets, increased investments in renewable energy sources, enhanced carbon capture and storage technologies, and robust support for sustainable land use practices. These scenarios aim to explore the potential pathways for achieving the net-zero goal, considering various technological, economic, and regulatory factors that may influence the deployment and effectiveness of different CDR approaches. Our analysis takes into account uncertainties and challenges associated with each archetype, providing a comprehensive framework for policymakers and stakeholders to make informed decisions towards a sustainable and climate-resilient future. Table 5 shows the scenarios considered in this study.

Table 5: Scenarios used in this study

	Net-Zero Target	
CDR archetype	2040	2050
BECCS	In this scenario, BECCS is deployed from 2025 in a 2040 net zero GHG target	In this scenario, BECCS is deployed from 2025 in a 2050 net zero GHG target
BECCS-DACCS	In this scenario, there is co-deployment of BECCS and DACCS from 2025 in a 2040 net zero GHG target	In this scenario, there is co-deployment of BECCS and DACCS from 2025 in a 2050 net zero GHG target
CDR_Total	In this scenario, there is a wide portfolio of BECCS, DACCS, TEW, OEW from 2025 in a 2040 net zero GHG target	In this scenario, there is a wide portfolio of BECCS, DACCS, TEW, OEW from 2025 in a 2050 net zero GHG target
REFERENCE	No new climate policy. Land use sink from afforestation is the conventional CDR	

NB: Afforestation/Reforestation is included as a traditional CDR option in all scenarios

3.5 Choice Functions and Policy Options in GCAM Modelling.

The economic choice option used in the GCAM modelling is also crucial. Numerous economic activities within GCAM present us with a multitude of options, each offering alternative routes to the desired outcome. These options manifest in a variety of ways, including the selection of various fuels, feedstocks, technologies, and modes of transportation. In addition, the allocation of limited resources, such as land area, necessitates deliberative decision-making to determine the optimal utilisation of these resources across various purposes.

In GCAM, the decision-making procedure revolves around a single numeric value known as the choice indicator (p). This metric functions as a standard by which alternatives are ranked according to their level of preference. Typically, the indicator of choice is quantified by either the cost or profit rate, although other indicators can theoretically be considered. For scenarios involving multiple factors, such as passenger transport where faster modes are deemed preferable, these additional factors are translated into cost penalties, which are then incorporated into the basic cost to create an indicator that encompasses all relevant considerations. This enables GCAM to evaluate and compare alternatives effectively, thereby facilitating informed decision-making in complex economic systems(JGCRI, 2020).

Two discrete choice functions are used: The Logit and the Modified Logit functions. The logit function (absolute-cost-function) is expressed as:

$$s_i = \frac{\alpha_i exp(\beta c_i)}{\sum_{j=1}^{N} \alpha_j exp(\beta c_j)} \quad (6)$$

$\forall i \in \{1,2 \ldots .N\}$, where N is all set of all choices of technologies

s_i is calculated for each choice i in the set of all choices

Here, α_i stands for the share weight for each technology or subsector, exp represents the exponential function, β is the logit exponent that shapes the distribution, and c_i is the cost of the technology or subsector i. This formula determines how the market share of different energy technologies or subsectors is distributed based on their costs and predefined share weights within the model. Initially, they are used to calibrate the model so that it corresponds to the observed historical values. This process of calibration allows the model to account for region-specific preferences regarding particular alternative options. These preferences may be the result of societal preferences, extant infrastructure, market entry barriers, and other factors. In addition, share weights play an essential role in facilitating the progressive incorporation of new technologies within GCAM. To accomplish this, share weights for new technologies begin with low values in their first year of availability and increase progressively until they reach a neutral value. The parameter, also known as the logit coefficient, influences the magnitude of cost differences necessary to generate a given market share disparity. In other terms, it measures the sensitivity of market share changes to cost differences. By examining the expression that represents the ratio of market shares between two options (i and j), we can observe the effect of the logit coefficient on quantifying the relationship between cost differences and proportional changes in market share.

$$\frac{s_i}{s_j} = \frac{\alpha_i}{\alpha_j} exp\left(\beta(c_i - c_j)\right) \quad (7)$$

The ratio $\frac{s_i}{s_j}$ is defined for all pairs of choices i, j where $i, j \in \{1,2 \ldots N\}$ and $i \neq j$

The β parameter is called the logit coefficient, $\frac{s_i}{s_j}$ *is the share ratio*

The modified logit function (relative-cost-logit) is the other discrete choice model used by GCAM:

$$s_i = \frac{\alpha_i c_i^{\gamma}}{\sum_{j=1}^{N} \alpha_j c_j^{\gamma}} \tag{8}$$

$\forall i \in \{1,2, \dots N\}$, where N is all set of all choices of technologies.

s_i is calculated for each choice i in the set of all choices.

Where the share weight and logit exponent are expressed mathematically as α_i and γ. The share ratio is expressed as:

$$\frac{s_i}{s_j} = \frac{\alpha_i}{\alpha_j}\left(\frac{c_i}{c_j}\right)^{\gamma} \tag{9}$$

the ratio $\frac{s_i}{s_j}$ is calculated for all distinct pairs of choices i, j within the set of possible choices.

Where c_i and c_j represent the cost of technology or subsector i or j

The total cost for a technology is the sum of the cost of the technology, the cost of its inputs, and any GHG value:

$$C = u + \sum_{j=1}^{n} i_j + \sum_{k=1}^{m} g_k - \sum_{l=1}^{o} v_l \tag{10}$$

Where C is the total cost, u \$ is the exogenously specified technology cost (capturing capital cost and operating & maintenance costs), i_j is the cost of input j (e.g., a fuel), g_k is the GHG value of gas k, and v_l is the value of secondary output l. Costs vary by region, technology, and year. Table 6 shows the choice of electricity technology and their capture fractions.

Table 6: Electricity technology capture fractions (portion of CO_2 emissions that are captured)

Supply sector	Subsector	Technology	1971	2020	2100
Electricity	Coal	Coal (conventional pulverized CCS)	0.85	0.85	0.95
Electricity	Coal	Coal (Integrated Gasification Combined Cycle CCS)	0.85	0.85	0.95

Electricity	Gas	Gas (Combined Cycle ccs)	0.85	0.85	0.95
Electricity	Refined liquids	Refined liquids (Combined Cycle CCS)	0.85	0.85	0.95
Electricity	Biomass	Biomass (Conventional CCS)	0.85	0.85	0.95
Electricity	Biomass	Biomass (Integrated Gasification Combined Cycle CCS)	0.85	0.85	0.95

Within the GCAM, three principal policy strategies can be employed to mitigate CO_2 and other greenhouse gas emissions: setting a uniform carbon or GHG tax, imposing emission limits, or applying climate targets. Regardless of the strategy chosen, GCAM operationalizes it by applying a cost to emissions. This cost permeates through all sectors within GCAM, influencing both production and consumption patterns. For instance, implementing a carbon tax imposes a financial penalty on the release of emissions from burning fossil fuels. This, in turn, affects the production costs of electricity generated by fossil fuel plants, making them more expensive relative to alternative electricity generation methods and leading to higher electricity prices. Consequently, the rise in electricity prices impacts end-users, potentially diminishing electricity's appeal compared to other energy sources. These policy strategies are outlined as follows: Carbon or GHG prices, Emissions constraints, and Climate constraints. In this work, we have used the emission constraint policies, which drive an economy-wide decarbonization. The rationale behind this is that the scope of climate target coverage in most regions in the world is the economy-wide decarbonization policy.

4. Results and Discussion

4.1 The consequence of CDR on Emission abatement

4.1.1 Gross and Net Emissions

Figure 6 reports the gross positive and negative emissions by sector in a 2040 and 2050 Net-Zero emission deadline. The modelled results for the 2050 net-zero emissions reveal that solely deploying BECCS by 2050 results in the deepest negative emissions, with a 12% and 14% emission reduction, compared to deploying all CDR technologies and co-deploying BECCS and DACCS respectively. This is attributed to more rapid transitioning away from carbon fuels driven by comparatively higher carbon prices in the BECCS scenario. Also, the presence of DACCS relaxes emission abatement, which allows for more residual emissions.

We see that the net emission deepens after the net-zero year, as there are more removals from the atmosphere to meet end-of-century climate goal. Specifically, there is deepest net emissions in the BECCS scenario which reaches -1.6 $GtCO_2$/year. The net emissions reaches -0.66 $GtCO_2$ and -0.76 $GtCO_2$ in the CDR_total and BECCS/DACCS scenario respectively. Additionally, the co-deployment of BECCS and DACCS achieves an average of 8.3% net emissions less than in the CDR_Total scenario. This emphasizes the role of the OEW and TEW as additional CO_2 removals in EU decarbonization pathways. Across various combinations of CDR technologies and different net-zero emission pathways considered, the net emissions range from -0.3 $GtCO_2$/year to -1.6 $GtCO_2$/year. The gross and net emissions for the 2040 net-zero GHG is shown in figure S1 (Supplementary file).

In a reference scenario, the estimated average annual gross emissions in the EU-27 between 2030 and 2100 amount to 3.6 $GtCO_2$/year. Notably, in the BECCS scenario within the 2050 net-zero emission pathway, the lowest gross positive emissions are observed, reflecting an impressive 82% reduction compared to the reference scenario. The inclusion of DACCS in the CDR_Total portfolio plays a pivotal role in reducing the overall stringency towards emissions, which it will later offset (Realmonte et al., 2019a), hence the higher emission level as compared to the BECCS scenario. The mid-century gross emissions when deploying all CDR archetypes are 1.58 $GtCO_2$/year (2050 net-zero pathway), and 1.51 $GtCO_2$/year (2040 net-zero pathway) (Figure S2).

The annual CO_2 removal between 2030 and 2100 reaches approximately 2.86 $GtCO_2$/year, 2.73 $GtCO_2$/year, and 2.59 $GtCO_2$/year in the CDR_Total, BECCS/DACCS, and BECCS scenario respectively for the 2050 carbon neutral deadline scenario. When carbon neutrality is moved forward by a decade, the CO_2 removal from BECCS between 2030 and 2100, when deployed as the sole CDR technology is approximately 3.63 $GtCO_2$/year, which is 71% more than when the diverse set of CDR is deployed. Furthermore, the amount of CO_2 removed using BECCS in the BECCS scenario aimed at a 2040 net-zero goal is approximately twice as much as when the net-zero goal is delayed by a decade.. , in the 2040 carbon neutrality scenario. This additional BECCS capacity when solely deployed as against when paired with other CDR options has substantial implications on land use activities and food security.

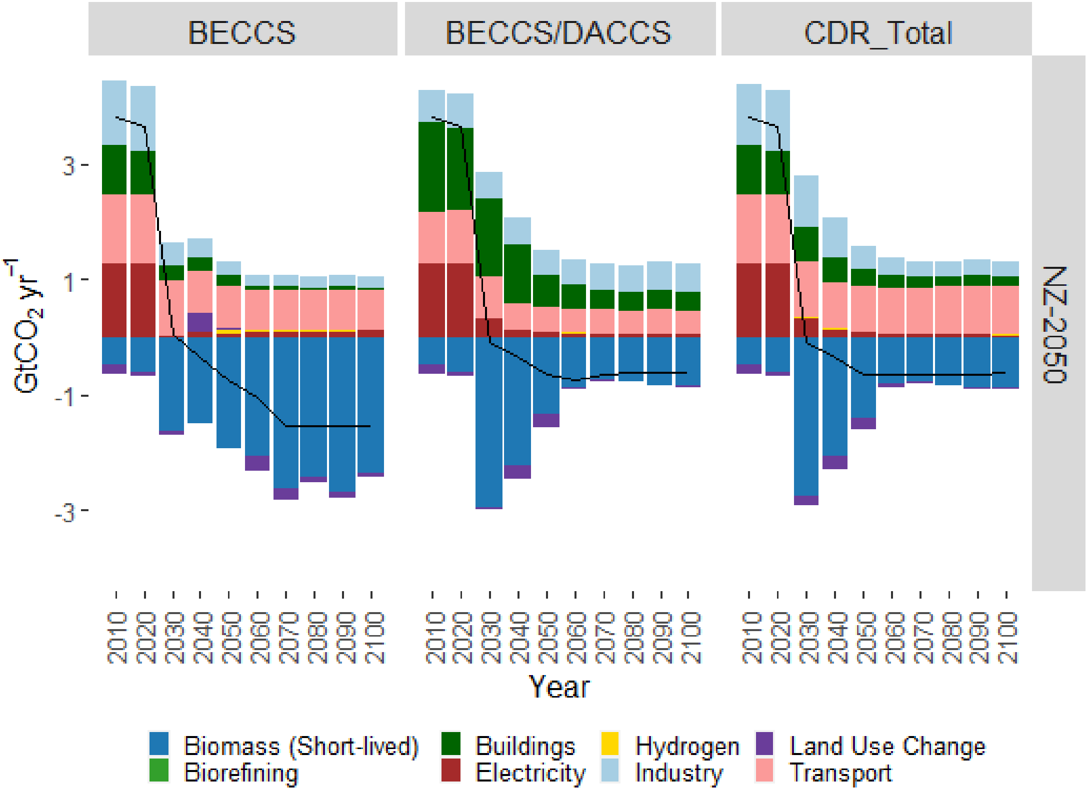

Figure 6: Gross Positive and negative emissions from different sectors across CDR scenarios and 2050 net-zero GHG emissions.CO_2 emission removed by dedicated biomass crops can be used with or without CCS, hence it is referred to as short-lived. The dark line represents the net CO_2 emissions. It is important to note that our scenario sets net-zero GHG for 2040 and 2050, however, net-zero CO_2 is achieved by 2030.

4.1.2 Sectoral Decarbonization and Warming temperature

Figure 6 reports the share of emissions from sectors. The hard-to-abate (H2A) sectors have been one of the strong cases for CDRs in near-term carbon neutrality and long-term negative emission pathways (Hanna et al., 2021). The dependency on hydrogen in hard-to-abate sectors can also be mitigated by other complementary CDR technologies (Fuhrman et al., 2020). Here we show that the share of emissions from the H2A sectors (heavy transportation and heavy industry) increases from 13% in 2010 to 27% and 30% in the CDR_Total scenario, and BECCS scenarios respectively by 2050 for the 2050 net-zero emissions pathways (It is worth mentioning that despite the increasing share of the H2A sectors, their gross emissions reduce during this period). To put in context, the share of gross emissions from the electricity sectors reduces from 27% in 2010 to 4% and 2.7% by 2050 in the CDR_Total and BECCS scenario respectively. A similar pattern of increasing share in the total emissions from the H2A sector is observed in the 2040 net-zero emission pathway. This shows the difficulty in transitioning away from carbon fuels in these sectors, and hence the requirement for CDRs. One of the solutions currently being pursued by the EU in its decarbonization program is green hydrogen for the H2A sectors, given its status as the largest market globally. However, despite the current annual utilization of approximately 9.7 million tonnes of hydrogen, the green hydrogen market is still in its infancy stage (Hossein et al., 2024a). High reliance on hydrogen in the EU makes it susceptible to several risks, especially in the supply chain (Hossein et al., 2024b). This work further solidifies the requirement for the complementary role of CDRs to the expansion of green hydrogen production in the EU especially for removing residual emissions from the H2A sectors.

The gross emissions of the power sector are observed to decrease significantly in the scenarios. This reduction in power sector emissions is crucial, especially if the deployment of CDRs is to play a substantial role in balancing the carbon sink with emission sources for achieving mid-century carbon neutrality. (El Aima & Onoda, 2020). The share of emissions from the power sector in the total gross emissions reduce from a range of 23%-25% in 2020 to a range of 2-2.3% by 2100 across all scenarios. The result shows that emission reduction levels of 95% (power sector), 43% (Industry), and 30% (Transportation) are reached by 2050 in the 2050 net-zero pathway under the CDR_Total scenario (relative to the 1990 emissions level). For the 2040 net-zero and BECCS scenario, the emission reduction is 97% (Power sector), 74% (Industry), and 36% (Transportation). The higher carbon price in the BECCS scenario drives deep and rapid transitioning away from carbon fuels in the sectors, especially in industrial processes. The emission reduction levels of the Industrial sector reach 72% in the 2040 net-zero under the CDR_Total scenario. Here, the result shows that in ratcheting the net-zero emission to 2040, the EU would need to cut emissions by almost double in the industrial sector. Such a substantial reduction in industrial emissions underscores the imperative for transformative measures within the sector. This may involve the widespread adoption of cleaner technologies, increased energy efficiency, and the implementation of sustainable practices to address the complexities associated with industrial processes. Policymakers and industry stakeholders may need to collaborate closely to develop and implement robust strategies, ensuring a balance between environmental sustainability and the continued growth of the industrial sector.

Moreover, these findings emphasize the importance of targeted policies and incentives that encourage innovation and the adoption of low-carbon technologies within the industrial landscape. Achieving such ambitious emission reduction targets necessitates a holistic approach, considering both technological advancements and regulatory frameworks that promote sustainable industrial practices. This underscores the challenging yet essential nature of decarbonizing the industrial sector on the path to a net-zero future

We illustrate the impact on global warming temperatures resulting from achieving either a 2050 or 2040 net-zero emissions target in the EU and globally, taking into account the deployment of CDRs. Here, we see that if Europe reaches carbon neutrality by 2050, alongside the rest of the world, the end-of-century global mean temperature is held at 1.3 ^{o}C (See Figure S13), on the condition of global deployment of a wider diversification of CDR methods (as reflected in the CDR portfolio in our work). The peak temperature of 1.7 ^{o}C is observed in the mitigation trajectory. Ratcheting the carbon-neutral target to 2040 reduces the global mean temperature to 1.1 ^{o}C by 2100, with a peak temperature of 1.55 ^{o}C recorded in 2045. This emphasizes the principal role of aggressive mitigation actions in reaching global climate mitigation targets (Fuhrman et al., 2023; Luderer et al., 2018).

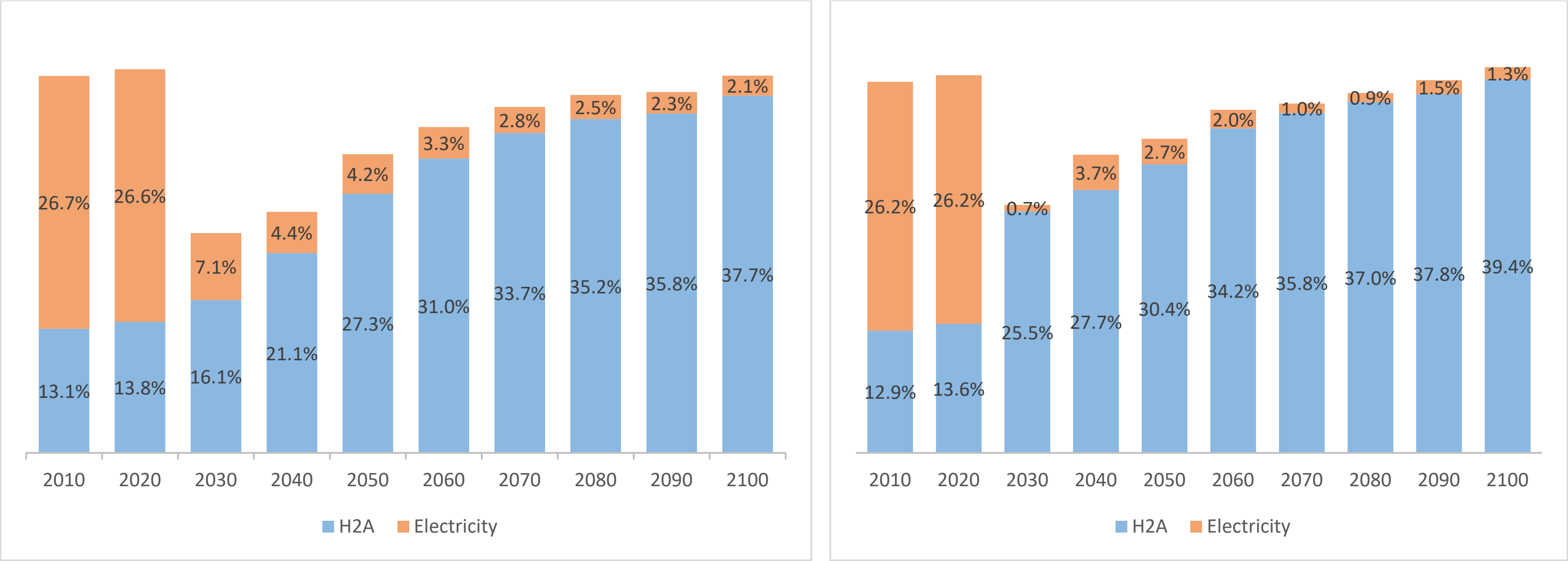

Figure 6: Share of electricity and hard-to-abate industries in total gross emissions in 2050 net-zero emissions (a) With Total CDR technology (b) only BECCS

4.1.3 Sequestration of emissions

Geologic carbon storage supply and CO_2 sequestration are inextricably linked, with the storage supply providing the underlying infrastructure for CO_2 sequestration. As the backbone of the sequestration process, geological formations such as depleted oil and gas reservoirs and deep saline aquifers are essential for storing captured carbon dioxide. Nonetheless, the implementation of this technology entails significant costs, such as site exploration, drilling, monitoring, and maintenance. Estimates range from \$5 to \$120 per tonne of CO_2 stored, although costs can differ based on location and the specific technology employed (Jay Fuhrman etl., 2020). The cost of onshore and offshore geological storage from different GCAM regions is presented in Figure 2. Therefore, the financial aspect of geologic storage is crucial to the viability and expansion of CO_2 sequestration efforts intended to mitigate climate change. A cursory analysis of the annual sequestration of CO_2 in the EU (Figure 7), reveals that when the full portfolio of CDR technologies is deployed (as considered in this work), the scale of DACCS sequestration is larger in the latter part of the century. Between 2030 and 2050, the maximum DACCS sequestration is 0.3 $GtCO_2$/year. After the net-zero deadlines, the average annual sequestration from DACCS is 0.6 $GtCO_2$/year. Ratcheting the net-zero deadline to 2040 reveals a 7 % increase in DACCS sequestration before mid-century (Figure S2). This pattern of accelerated deployment of DACCS towards the latter part of the century is more pronounced in the BECCS/DACCS scenario. For instance, in a 2050 net-zero pathway under the BECCS/DACCS scenario, the deployment of DACCS after mid-century is approximately four times greater than before the net-zero year.

Additionally, our analysis demonstrates that aggressive near-term emission reductions place a greater demand on TEW for sequestering CO_2. A 32 % increase in TEW sequestration is observed between 2030 and 2050 in the 2040 carbon-neutral goal compared to the 2050 carbon-neutral goal. A significant challenge with TEW is the unsustainable extraction practices and energy required for the mining, crushing, and distribution of these minerals. There is an increasing recognition of the potential of finely crushed basalt, which are by-products of years of mining and aggregate industries, and their CDR potential has been a subject of research (Lewis et al., 2021). Utilizing these accumulated crushed basalts, also from the steel industry would reduce the need for new mines, and additional energy requirements. Also, Beerling (Beerling et al., 2020b) suggested that a national inventory of such accumulated basalt be made to quantify the potential of CDRs. A policy statement to incentivize farmers in the direction of changing farming practices to include CO_2 sequestration could be beneficial to the EU.

Also, it is observed from the modelled result that when BECCS is the only CDR technology to meet the carbon-neutral target, a significant portion of sequestration is through hydrogen production through CCS: an annual average of 0.3 $GtCO_2$/year is sequestered to achieve carbon neutrality in the BECCS scenario, in contrast to a meagre 0.03$GtCO_2$/year with diverse CDR deployment. This trend is propelled by the substantial increase in the cultivation of biomass crops in the BECCS scenario, leading to a significant ramp-up in the production of biomass-to-hydrogen fuels. The EU region is a global leader in hydrogen technology development, indicating a high level of technological maturity in the region, although it's important to note that a significant portion of hydrogen production in the EU is still derived from fossil fuels. In 2021, Europe had 55% of the world's new hydrogen projects. Countries like Spain and Germany are investing hugely in green hydrogen, and blue hydrogen via carbon capture, utilisation, and storage (CCUS) systems is the priority for Norway (Stamm, 2023).

In the BECCS/DACCS scenario, under the 2050 net-zero emission trajectory, we observe that DACCS deployment increases threefold by mid-century, relative to the CDR_Total scenario. To put into perspective, if one DACCS plant removes 1 $MtCO_2$/year (International Energy Agency, 2022)(McQueen et al., 2021), a minimum of 850 DACCS plants is required in Europe to counter-balance residual emissions from the atmosphere to achieve net-zero emissions by 2050 under the BECCS/DACCS scenario. This increases the requirement for energy consumption in the near term, given that DACCS is energy-intensive, and this could be mitigated with the deployment of TEW and OEW under the CDR_Total scenario. The OEW sequestration by mid-century is 0.3 $GtCO_2$/year when all CDR portfolios are deployed.

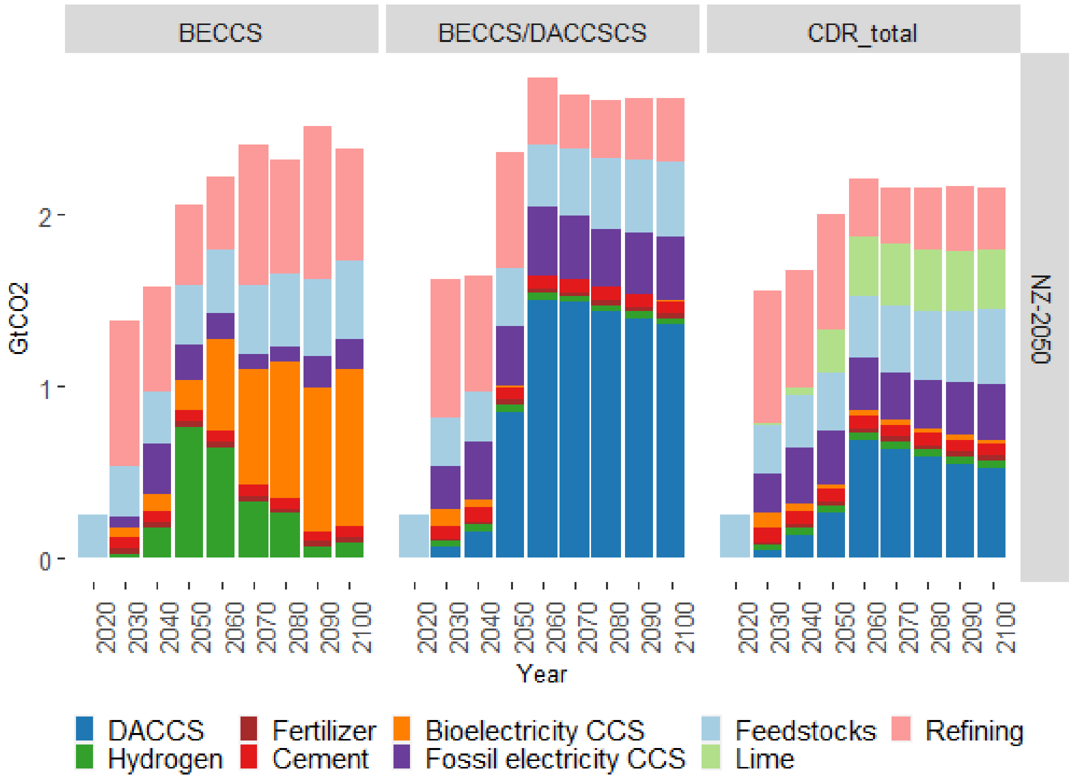

Figure 7: CO_2 sequestration under scenarios. Hydrogen sequestration is from Biomass, Coal and gas to hydrogen CCS. Also, refining includes biofuels CCS and coal to liquids CCS.

The energy and financial parametrization of the DACCS is retrieved from the work of (Morrow et al., 2023) . The data is described in Table 4. The annual average CDR deployment is shown in Figure 8. In the 2050 net-zero emission trajectory, the BECCS scenario necessitates deployment on the scale of 0.9-1.1 $GtCO_2$/year after the net-zero emission deadline until 2100 (Shown in Figure XX in SI). Recent studies have suggested that the scale of BECCS in the EU could approach 1 $GtCO_2$ before 2050 (Geden et al., 2019), a finding that aligns with our study. Here, we go further to show that the annual average BECCS deployment (in the BECCS scenario) between 2030 and 2100 for a 2050 net-zero emission pathway is 0.75 $GtCO_2$/year. To reach the carbon-neutral target of 2050, we show that the estimated BECCS requirement (in the BECCS scenario) is 0.3 $GtCO_2$/year. This estimated annual BECCS capacity before mid-century is within the biogenic CDR availability of the EU. The study by (Rosa et al., 2021) on the CDR potential of the EU estimated approximately 202 $MtCO_2$ per year, distributed across regions with high populations. (e.g Paris, Berlin, Milan) and regions with intensive cropland and livestock populations (e.g. Belgium, Netherlands). Comparing their results with those obtained in this work provides insights into the feasibility of BECCS capacity being within a manageable scale in the EU, facilitating the region's ability to meet the 2050 net-zero emission target. The deployment of only BECCS in the latter part of the century averages 0.9 $GtCO_2$/year annually.

The concern about the viability of BECCS arises from the potential competition with land, agriculture, water, and food resources. This issue is compounded by the possible unavailability of climatically relevant BECCS resources in the EU, emphasizing the need to focus on the integration of other CDRs. Here we show that the share of BECCS is reduced by 97% annually when deployed amongst a more diverse suite of CDRs, relative to the sole deployment of BECCS. The annual average share of BECCS in the comprehensive CDR portfolio across all scenario considered is an average of 3%.

The annual deployment of cumulative CDRs in the CDR_Total scenario is comparatively lesser than in the BECCS scenario before mid-century but higher towards the end of the century. The market maturity of BECCS makes it more viable and scalable in the near term, while DACCS and other CDRs require more research and development to make them a more cost-effective option for CO_2 removal (Morrow et al., 2023). Interestingly, the annual deployment of OEW exceeds that of DACCS for both 2040 and 2050 net-zero emission pathways. Beginning from 2045, in the 2040 net-zero emission pathway, the OEW annual deployment is an average of 7% more than DACCS. OEW is deployed in the scale of 0.2–0.64 $GtCO_2$, while DACCS within that period is 0.2-0.58 $GtCO_2$ (2040 net-zero emission pathway). In the 2050 net-zero emission trajectory, the scale of OEW and DACCS deployment is within the same range as recorded in the 2040 deadline. The higher deployment of OEW can be attributed to several factors. One key factor is the relative efficiency and capacity of OEW in sequestering CO_2. The natural processes involved in OEW, such as the dissolution of minerals in seawater, provide a potentially more substantial and sustainable carbon removal mechanism.

The observed 7% higher deployment average for OEW is also due to its effectiveness, potential for large-scale implementation, and considerations for overall environmental sustainability in achieving net-zero emission goals. Additionally, in principle, OEW might offer advantages in terms of scalability and environmental impact, making it a preferred choice in certain scenarios.

The result also shows 17% less overall CDR capacity when all CDR technologies are harnessed as against the sole and co-deployed CDR scenarios. This is an incentive for policy decisions towards variety in CDR technologies in effectively removing CO_2 from the atmosphere in the EU.

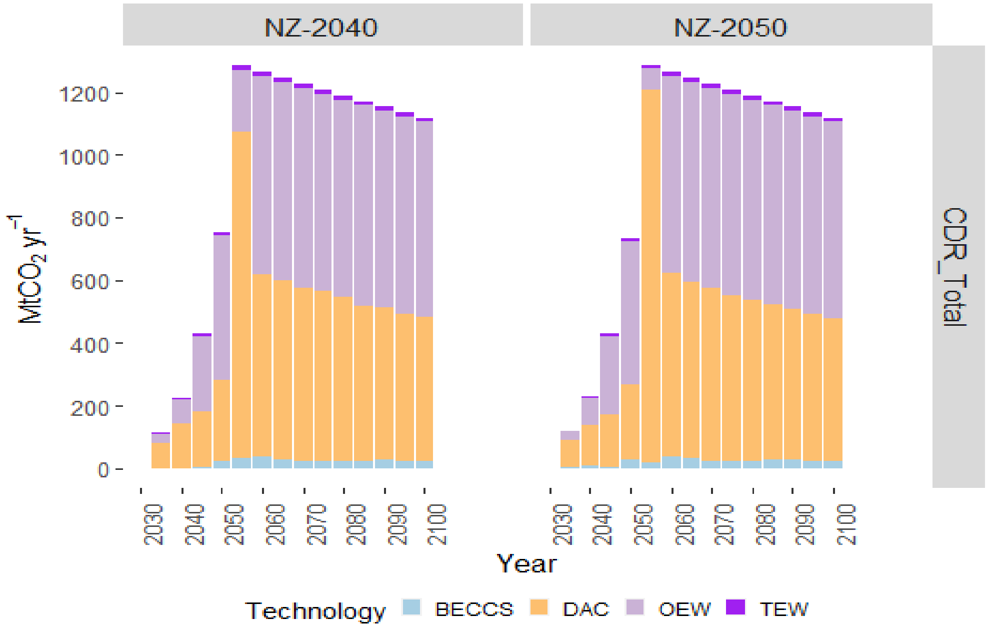

Figure 8: Scale of individual CDR technology deployment when all CDRs are deployed in a 2050 and 2040 net-zero emission pathway in EU-27

4.1.4 CDR Price and Marginal Abatement cost of carbon

The CDR price for the 2050 net-zero emissions is reported in Figure 9. The price of BECCS peaks at 5.15 2019 \$/kg of CO_2 removed in the BECCS scenario. In the scenario of multiple CDR deployment, the price of the BECCS per kg of CO_2 captured drops by about 79%. This is attributed to the less competition for land for biomass cultivation.

The maximum observed BECCS price (in the CDR_Total scenario) at 3.9 \$/kg is on the higher end of the price range reported by (Fuss et al., 2018b), which was between 0.057-0.4 \$/kg. The average price of DAC, OEW, and TEW in the CDR_Total scenario is 2019\$/kg 0.49, 2019\$/kg 0.57, and 2019\$/kg 1.02 respectively. The CDR price of deploying all CDRs falls within the range of 2019 \$/kg 2-7, marking a 41% increase compared to solely utilizing BECCS.

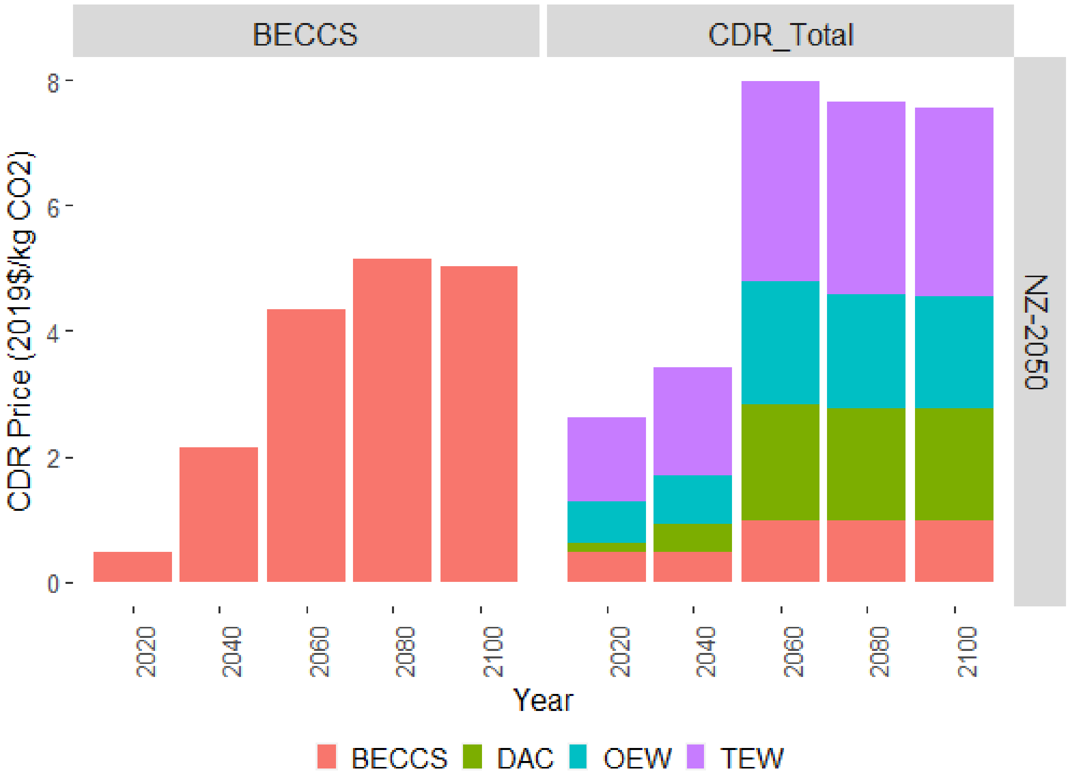

Figure 9: Price of CDR technologies across diverse CDR portfolios

Also, we show that the marginal abatement cost is highest when only BECCS is used for CDR (Figure 10). The marginal abatement cost of carbon (MACC) is the cost of reducing the last unit of emissions to reach a certain climate target (IPCC, 2021). This is also technically referred to as the carbon price. GCAM constructs a MACC for CO_2 by incorporating the effects of fluctuating carbon prices into its computational framework

We see that when BECCS is the only CDR option, the carbon price is significantly higher than in other scenarios with co-deployments. A reason for this is that CDR options like DACCS can serve as a backstop technology, as it can set an upper limit on the carbon price (Fauvel et al., 2023). This means that at a very high carbon price, DACCS can serve as a last resort to meet climate targets rather than deploying more expensive and inefficient technologies.

For the BECCS scenario, the mid-century carbon price is 684 2019$/t$CO_2$ (2050 net zero deadlines). The carbon price required to reach carbon neutrality by 2050 in the CDR_Total and BECCS/DACCS scenario is 2019$/t$CO_2$ 402 and 2019$/t$CO_2$ 407 respectively. This highlights the lower stringency in the scenarios with DACCS availability, hence slowing down near-term decarbonization, and allowing residual emissions, which it will offset in the latter part of the century, driven by lower cost and technological maturity.

The carbon price for the mid-century, concerning the 2040 net-zero emission deadline, is observed to be 8.6% higher than that for the 2050 carbon-neutral trajectory (Figure S3). This is attributed to the more aggressive emission reduction targets and actions associated with ratcheting the net-zero emission deadline. The heightened carbon price reflects the necessity for more aggressive measures and investments in decarbonization technologies and practices to meet the earlier deadline. The disparity in carbon prices indicates the additional economic burden and policy rigour required to accelerate emission reductions and achieve net-zero emissions by 2040.

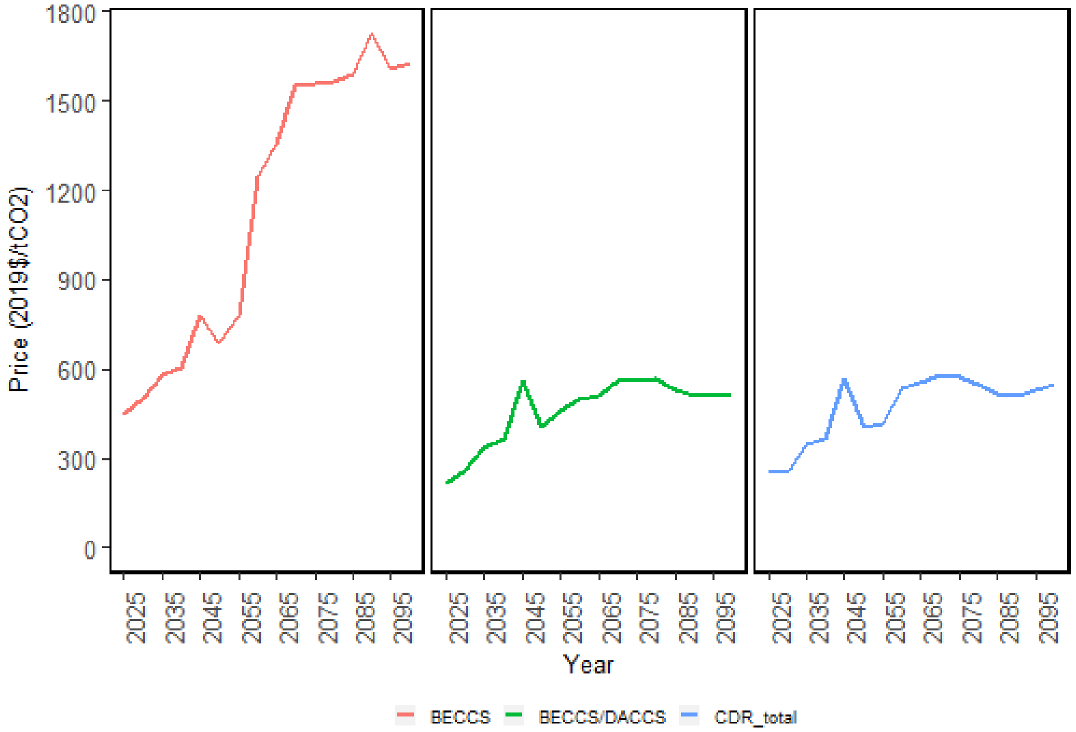

Figure 10: Carbon price for reaching 2050 net-zero year under the considered scenarios

4.1.5 Global Context of emissions sequestration and gross CO_2 removal

Figure 11 shows the global sequestration from CDRs and CO_2 removal by bioenergy cultivation. The parametrization of the geological storage (both onshore and offshore) is included in the supplementary document. The Global CO_2 removal by bioenergy cultivation reaches 24 $GtCO_2$/year by 2050. The United States, China, and the Middle East have the largest deployment of CO_2 removal by bioenergy, reaching the scale of gigatonnes by 2050. To put it in context, the combined land area utilized for bioenergy cultivation in the US, China and Middle East, is equivalent to the total land area of Libya. The share of BECCS in the USA, EU, and China is 56% of the total deployment globally. Likewise, a significant proportion of BECCS sequestration in the mid-century is observed in India and the Middle East. This is due to the specific conditions and characteristics of these regions, such as the availability of suitable biomass resources, favourable climate conditions, and advantageous economic factors, contributing to the prominence of BECCS deployment in their decarbonization pathways. DACCS deployment does not reach the gigatonne scale by 2050 in any country, because of the high energy requirement: a limitation further exacerbated if deployed for near-term climate mitigation. Europe is the front-runner in the deployment of DACCS by 2050, after China and the USA. To accommodate this upscaling in the near term, if one DAC plant is capable of removing 1 $MtCO_2$/year(Chen & Tavoni, 2013), then an unprecedented 240 DAC plants would need to be installed across Europe (reflecting the results from the CDR_Total Scenario). OEW scales up to about 454 $MtCO_2$/year in Europe by 2050, (just behind the USA as a leader in its deployment), to accommodate more CO_2 removal by mid-century. The largest deployment of TEW is in India, scaling to 11 $MtCO_2$ by 2050. Canada, the Middle East, Indonesia, South East Asia, Brazil, and Western Africa contribute significantly to the global share of CO_2 removal by TEW in 2050 (Countries are listed in order of increasing TEW deployment). The practice of planting trees to remove historical emissions scales high in Russia and Canada, reaching 398 $MtCO_2$ and 179 $MtCO_2$ respectively by 2050. A cumulative 1.7 $GtCO_2$ is removed by trees and agriculture globally by 2050. Smaller scales of deployment of CDR are observed in regions like Sub-Saharan Africa, South Asia, and South and Central America.

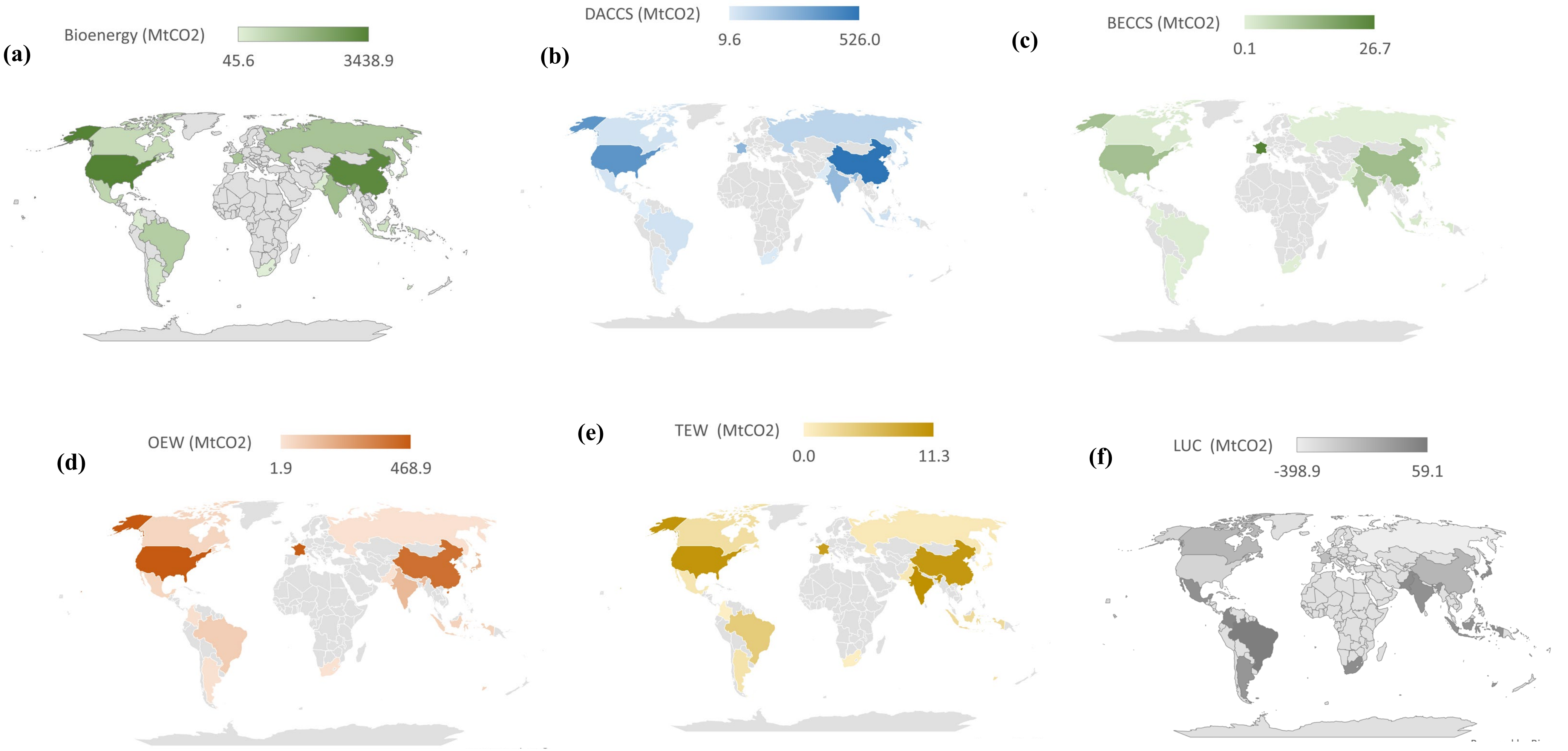

Figure 11: CO_2 removal and Negative emissions by technologies embedded in the 32 GCAM region in 2050. Some regions have positive land emissions. The quantity of emissions could exceed the 7GtCO_2 constraint placed on the CDR: it is essential to note that the restriction does not apply to afforestation, meaning that this specific CDR approach is permitted without restrictions. Afforestation, the establishment of forests in previously unforested areas, has the potential to sequester carbon dioxide naturally through the growth and storage of trees. Likewise, CO_2 removal by Bioenergy cultivation is reflected to show the quantification of land use in global emission removal. (CDR_Total Scenario)

4.2 Energy Transformation

Another important parameter is the dynamics of the energy structure under CDR deployments in climate targets. This affects electricity demand and generation across other sectors, renewable energy generation, and industrial energy use. Past studies (Blanford, 2021; Hanna et al., 2021; Smith et al., 2016) have reported the trade-offs between the use of DACCS and BECCS when deployed in climate-relevant scales. Deploying DACCS frees up the competition with land and water (as explained in the next section), per ton of CO_2 removed from the atmosphere when compared with BECCS. However, there is a significant impact on global energy consumption for DACCS operations, due to substantial heat requirements in the calciner process. Past studies (Realmonte et al., 2019a) have elucidated the unprecedented energy consumption of DACCS when deployed on a ten of gigatonnes scale. However, in this study, we present a more realistic scaling of this technology. Also, to better inform near-term policies leading up to mid-century carbon neutrality in the EU, here we discuss the scale at which energy consumption will be affected based on the CDR approach that is undertaken (Figure 9). The pattern of energy consumption shows that DACCS is not deployed on a large scale to achieve carbon neutrality when all CDR portfolios are deployed: this is evidenced in the higher share of biomass towards mid-century in the CDR_Total scenario, as compared to the BECCS scenario (Figure 12). The results reveal a 34% increase in biomass cultivation in the CDR_Total scenario compared to the BECCS scenario between 2030 and 2050. In contrast, after the net-zero deadline, the consumption of biomass until the end of the century is 60% higher in the BECCS scenario compared to when all CDRs are deployed. This puts DACCS as a “latter-century climate mitigation technology” in the EU drive for the Paris Agreement target. This also reveals the requirement of BECCS (32 EJ/year) (as a sole CDR) in achieving deeper negative emissions to meet end-of-century climate goals (between 2055 and 2100), as against between 2025 and 2050 (16 EJ/year). The annual energy consumption of biomass in the BECCS scenario is between 18-31 EJ/year, while it is in the range of 9-31 EJ/year in the CDR_Total scenario.

The low concentration of CO_2 in the atmosphere makes the process of CO_2 removal from captured air using the mechanism for DACCS process energy-intensive (Fuhrman et al., 2020). Past studies(Wohland et al., 2018) have highlighted the role renewable energy could play in EU decarbonisation plans, both in primary and final energy consumption, however, the magnitude at which it is required in the near term spells more challenges. Here we show that to achieve carbon neutrality in the EU by 2040 or 2050, nuclear energy plays a crucial role. Nuclear energy shows the optimal share of 23.1% and 23.8% in primary energy consumption by 2050 and 2100 respectively. In the 2050 net-zero, renewable energy (hydropower, wind, solar, geothermal) and biomass contribute 44 EJ/year in the total primary energy consumption in the EU in 2050 (representing a 48 % share). This also represents a 64% increase, relative to their consumption in 2020. The study by (Wohland et al., 2018) estimated a renewable energy capacity of 300GW in achieving negative emissions of 0.5 $GtCO_2$/year when DACCS is the only CDR deployed.

We also show that the share of fossil electricity by 2050 in the CDR_Total and BECCS scenario is 29% and 21% respectively. The higher share of fossil electricity in the CDR_Total scenario is attributed to the additional electricity requirement for DACCS operations and the allowance for residual emissions when DACCS is deployed. When the carbon-neutral target is ratcheted to 2040 (Figure S4), the share of wind and solar resources increases from 28% to 30%. Also, the total primary energy consumed by 2050, in the CDR_Total scenario is 15.8% more relative to 2020, while in the BECCS scenario, this value is 19%.

In the BECCS/DACCS scenario, the total primary energy consumption from fossil fuel in 2050 (coal, oil, natural gas) is 28.65 EJ, compared to 20.78 EJ in the BECCS, and 26.84 EJ in the CDR_Total scenarios. This points to the high energy intensity of DACCS operation, especially in the near term. In the BECCS scenario, the share of fossil fuels reduces from 22% in 2050 to 14%, in 2100. In contrast, the share of fossil fuel increased from 31% to 34% in the BECCS/DACCS scenario (for the 2050 net-zero pathway).

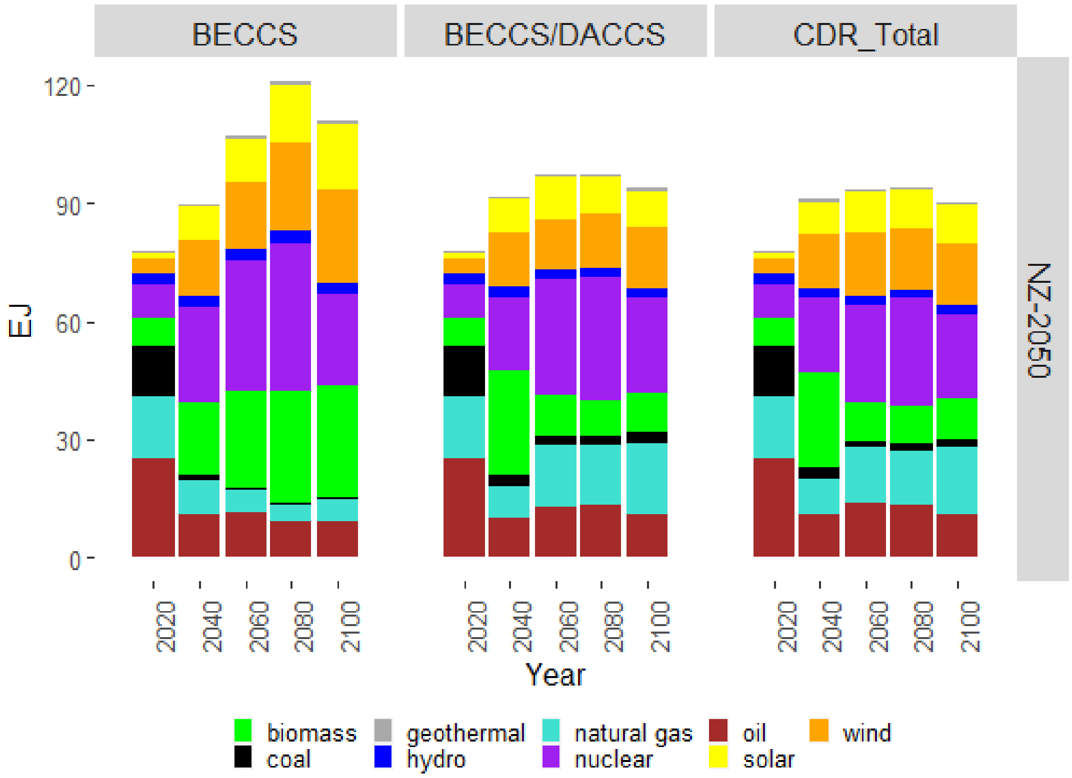

Figure 12: Primary energy consumption across different sectors and species

Figure 13 and Table 7 show the electricity generation in the EU-27 across the scenarios proposed in this work. The highest increase of 62% in the generation of electricity by 2100 is observed when BECCS is deployed. As BECCS is the only CDR technology which is an energy resource (as well as biochar), its deployment as a single CDR would make for an increase in electricity generation through bioelectricity technology. It is observed that the share of biomass in the total electricity generation in the BECCS scenario by 2050 and 2100 is 7% and 12% respectively. In the other scenarios across CDR_Total and BECCS/DACCS and net-zero deadlines, the share of biomass is between 0.1-0.5% in the total electricity generation. As reported in the primary energy consumption, nuclear energy contributes the highest share to electricity generation in the EU. The least amount of fossil fuel electricity is generated from the BECCS scenario. This will be attributed to the higher stringency evidenced by the carbon price in the BECCS scenario. This drives more rapid decarbonization and a transition towards cleaner fuels.

In contrast, a higher share of fossil fuel for electricity is in the CDR_Total scenario. In the BECCS/DACCS scenario, the share of fossil fuel by 2100 is 10%, as compared to 5.4% when only BECCS is used. The share of solar and wind energy in the annual electricity generation by 2050 in the CDR_Total scenario for the 2040 net-zero GHG emission deadline is 42% (Figure S5). According to the IEA (IEA, 2021), there is a promising trend in renewable energy (RE) development for energy consumption in Europe. Recent figures put the Nordic region (Sweden, Denmark, Iceland, and Norway) at the top with about 63% RE share in the total energy generation. The average RE shares in Europe in 2021 was 22%. Our results show that this share has to increase by double, to accommodate for sustainable CDR applications.

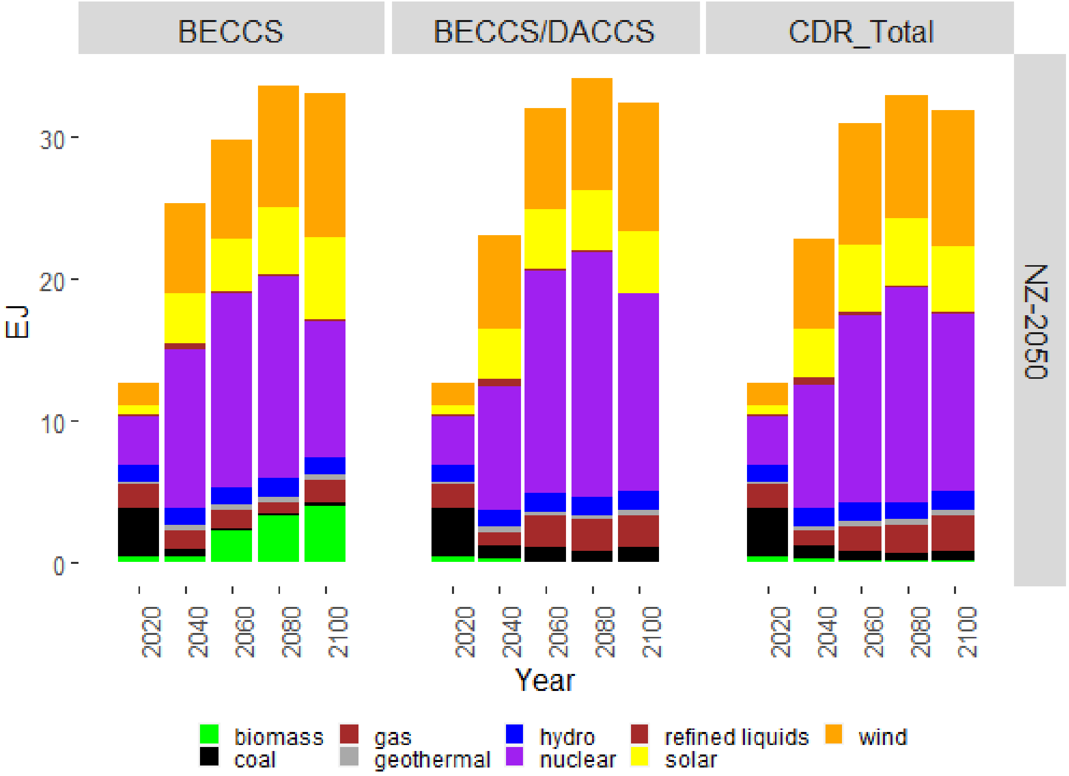

Figure 13: Electricity generation from different resources in the 2050 net-zero GHG emission deadline. The electricity generation from biomass is both from the CCS and non-CCS technologies.

Table 7: Electricity generation from technologies by 2050 in EJ

Scenarios	Bioelectricity without CCS	Bioelectricity CCS	Fossil without CCS	Fossil CCS	Renewables	Nuclear
BECCS	0	0.66	0.02	1.71	11.3	11.5
BECCS/DACCS	0.008	0.02	0.17	2.55	13.2	11.3
CDR_Total	0.005	0.09	0.17	2.09	13.4	8.9

4.3 Land use, water, and Food

We assess the extent of the land requirements that scaling CDR technologies to achieve carbon neutrality will have and the competition with other land demands in Europe. The appropriation and competition for land and water use as endogenously computed in GCAM are detailed in the supplementary document. Also, the discourse on food security presented in the supplementary document (Chen & Tavoni, 2013; Marcucci et al., 2017) have shown that the deployment of BECCS at the gigatonne scale required to offset global emissions will put significant strain on land use. (Fuhrman et al., 2020) also showed that deploying DACCS will soften the sharpest trade-off of land due to its smaller physical footprint relative to BECCS. Land use change will play a role in emission mitigation in Europe, both in the near and long term, depending on the CDR approach taken (Figure 14). In the BECCS scenario, here, we show that 0.8 Mkm^2 of land is dedicated to climate mitigation in the form of biomass, and 1.02 Mkm^3 in the form of forest (managed and unmanaged). The land allocated to crops in 2040 (food and non-food) when only BECCS is deployed, is about 12% and 0.12% lower relative to deployment of all diverse CDRs and when BECCS/DACCS are deployed respectively. A similar pattern is noticed across all the years. It is worth mentioning that more land is allocated for food crops in the CDR_Total scenario (as compared to other CDR portfolios in this work). In principle, this situation also fosters higher food yield due to the nutrient composition of basalt used in TEW on soils. There is more competition for crops in the BECCS scenario: we notice 48% less land available in 2100 for food crops relative to 2020. In comparison, land available for non-food crops only decreases by 11% within the same period. In the situation of CDR_Total and BECCS/DACCS scenario, the unavailable land for food is 36% and 37% respectively, relative to 2020. Likewise, the scale of BECCS development in the form of land resources is unparalleled: about 1784% of land for Biomass is required in 2100 in the BECCS scenario relative to 2020. The land allocation when the carbon-neutral deadline is ratcheted to 2040 is shown in the supplementary file (Figure S6).

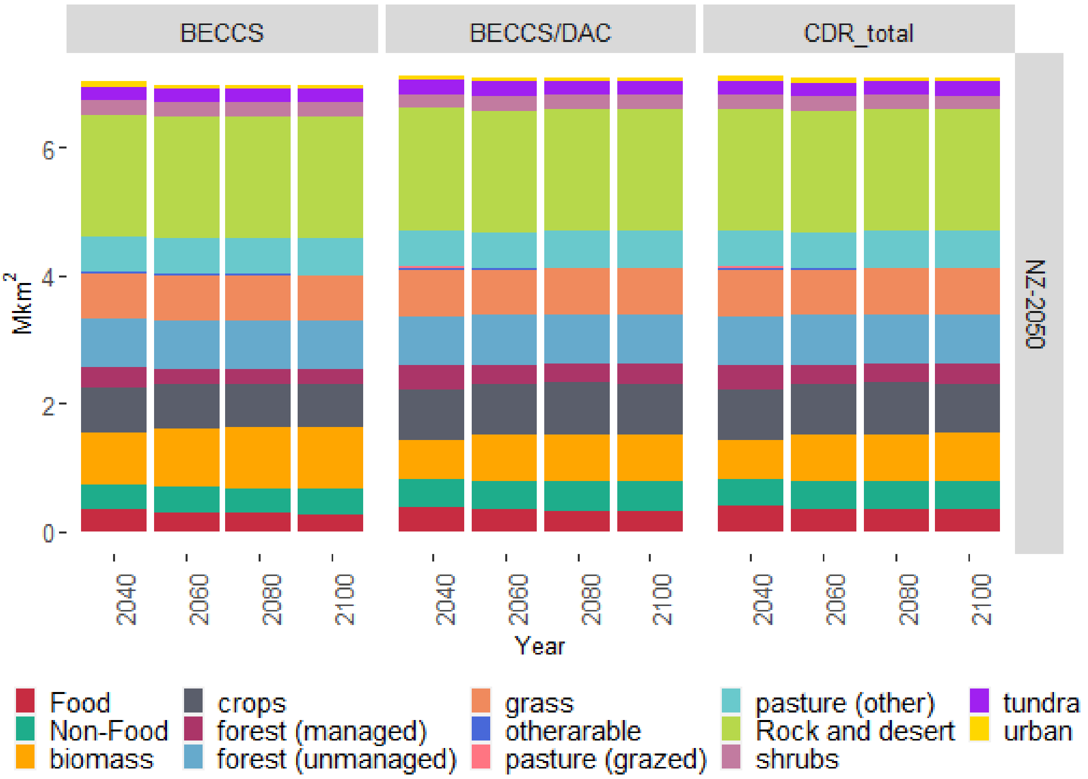

Figure 14: Land use for carbon neutrality deadlines across diverse CDR deployments

The total water consumption for 2050 carbon neutrality in the EU is on the scale of 50-100 km^3, which majorly is utilized for crop cultivation (Figure 15). The variation in water consumption levels across the different CDR deployment portfolios is minimal. A significant amount of water is consumed for bioelectricity in the BECCS scenario: By 2100, its share is 2.3%, as compared to 0.07% in the BECCS/DACCS and CDR_Total scenarios. Another key inference from the result is that the water consumed for crop cultivation in the latter century is higher than in the years approaching the net-zero deadline. The stringency of meeting carbon neutrality in the EU will put more challenges to land availability for crop cultivation than on water consumption (as we had shown that the land available for crop cultivation is higher leading to achieving carbon neutrality (between 2020 and 2050) than in the latter years of the end of the century (between 2055-2100. The water consumption when the carbon neutral deadline is ratcheted to 2040 is shown in the supplementary file (Figure S7).

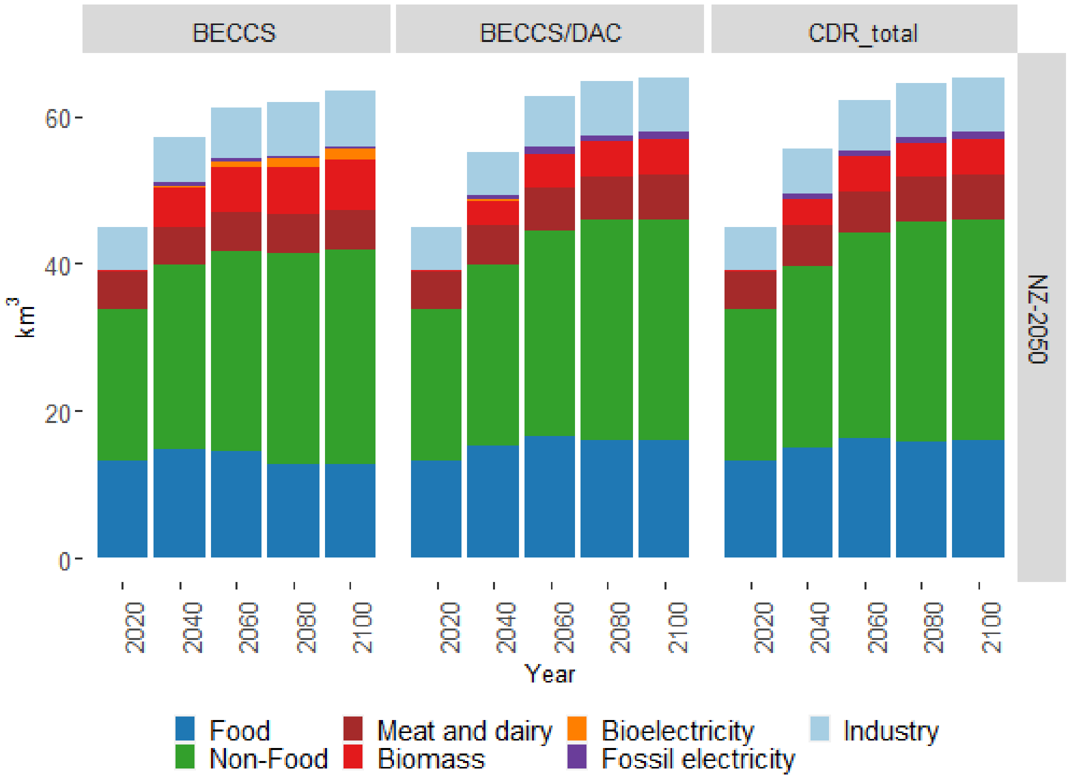

Figure 15: Water consumption for carbon neutrality deadlines across diverse CDR deployments

GCAM calculates agricultural and industrial water consumption, water withdrawals, and crop evapotranspiration endogenously. This treatment of water consumption yields a result that would be counterintuitive if scaled by the water intensity of each CDR (Fuhrman et al., 2020) (Detailed information is available on Ref (JGCRI, 2020). In terms of the total water consumption and withdrawal (Figure S15), here we show that the BECCS/DACCS consumptive water use is higher than when only BECCS is deployed as a CDR technology. Though it has been reported in the literature (Galik, 2020; Rosa et al., 2021) about the large water intensity of BECCS (which is rightly so), however, the larger scale of DACCS deployment which is meant to remove emissions that it had allowed earlier in the century (referred to as the rebound effect)(Realmonte et al., 2019a), causes more water usage.

The need for negative emissions from BECCS is reduced due to DACCS. However, concurrently, DACCS enables the growth of positive emissions to the atmosphere. These increased positive emissions are then removed, or "offset," by DACCS. Consequently, large-scale deployments of DACCS result in an overall increase in water demand for negative emission control, despite the fact that DACCS utilizes significantly less water compared to the irrigation of bioenergy crops. The complementary deployment of TEW and OEW offsets a portion of DACCS, thereby further reducing water consumption when all CDRs are deployed. However, ratcheting the net-zero target to 2040 increases the consumptive water demand of the entire CDR portfolio considered. (Figure S8). The discourse for the implication of food demand is presented in the supplementary document.

5. Conclusion

It is undoubtedly that historically, the EU has taken a leading role in global climate mitigation actions, however, the same case cannot be made in the light of championing CDR development in achieving global climate stabilization. In the same vein, there is global acceptance of the role of CDRs as a requirement for achieving carbon neutrality in the mid-century, yet, policymakers in the EU have not particularly defined clear and robust pathways toward the technical details of transitioning towards scaling these technologies. More recently, the European Green Deal has increased interest towards technological CDR approaches and emphasized the indispensable role of DACCS and BECCS in achieving carbon neutrality in the EU. Making CDR more integral in the EU climate policy would require a more detailed assessment and understanding of the roles of diverse CDR technologies in removing historical emissions across sectors, as it pushes emission reduction across sectors. The sustainability and environmental implications of their scaling, and appropriate CDR deployment timelines concerning meeting climate mitigation targets are therefore important. We suggest a more comprehensive and realistic CDR approach in IAM-based studies to give practical context on effective policies towards EU climate mitigation goals. Some past studies on emission pathways for EU-27 had only considered BECCS, and most recently, DACCS. In this work, we show that a more diverse CDR portfolio can enhance the viability and effectiveness of EU climate mitigation initiatives. By expanding CDR options beyond BECCS and DACCS, the EU can leverage the potential of emerging technologies like TEW, OEW, and others (biochar, and direct ocean carbon capture and storage). This diversified approach not only enhances the efficacy of carbon removal but also addresses potential limitations and obstacles associated with relying solely on a single CDR technique.

Modelling results obtained in this work suggest that relying on BECCS only as a CDR technology places more demand on hydrogen production to sequester emissions in the EU.

Results show that the EU can ratchet their carbon-neutral deadline to 2040, when diverse CDRs are deployed, with TEW playing a crucial role. A 2040 net-zero mitigation pathway in the EU will require emissions from industries to be cut by 72% relative to 2020, as well as 7% more DACCS than a decade later carbon-neutral deadline. Meeting the energy requirement for these CDRs will be heavily reliant on nuclear energy. In the case of land use, deploying a diverse portfolio of CDR increases the land available for crop cultivation significantly as compared to when only BECCS is deployed. We showed that there is more competition for food crops when only BECCS is deployed: as there is 48% less land available in 2100 for food crops relative to 2020, as compared to a diverse CDR portfolio. In terms of CDR deployment and carbon neutrality target on global mean temperature, the modelling result showed that warming temperature is held at 1.3 ^{o}C, when emission stabilization occurred in 2050 with the presence of diverse CDR technologies. In ratcheting the carbon neutral deadline to 2040, with diverse CDR technologies, the warming temperature is limited to 1.09 ^{o}C with a peaking temperature of 1.55 ^{o}C.

References

Afionis, S., Fenton, A., & Paavola, J. (2012). EU climate leadership under test. *Nature Climate Change*, *2*(12), 837–838.

Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrasio, R. M., Renforth, P., Sarkar, B., Andrews, M. G., James, R. H., Pearce, C. R., Mercure, J. F., Pollitt, H., Holden, P. B., Edwards, N. R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N. F., Janssens, I. A., … Banwart, S. A. (2020a). Potential for large-scale CO2 removal via enhanced rock weathering with croplands. *Nature*, *583*(7815), 242–248. https://doi.org/10.1038/s41586-020-2448-9

Beerling, D. J., Kantzas, E. P., Lomas, M. R., Wade, P., Eufrasio, R. M., Renforth, P., Sarkar, B., Andrews, M. G., James, R. H., Pearce, C. R., Mercure, J. F., Pollitt, H., Holden, P. B., Edwards, N. R., Khanna, M., Koh, L., Quegan, S., Pidgeon, N. F., Janssens, I. A., … Banwart, S. A. (2020b). Potential for large-scale CO2 removal via enhanced rock weathering with croplands. *Nature*, *583*(7815), 242–248. https://doi.org/10.1038/s41586-020-2448-9

Bergero Marshall Wise, C., & Lamers Yong Wang Maridee Weber Article, P. (2022). *Biochar as a carbon dioxide removal strategy in integrated long-run climate scenarios*. https://doi.org/10.21203/rs.3.rs-1805544/v1

Blanford, G. J. (2021). Impact of carbon dioxide removal technologies on deep decarbonization of the electric power sector. *Nature Communications*, *2021*, 1–12. https://doi.org/10.1038/s41467-021-23554-6

Boden, T. A. , M. G. , & A. R. J. (2009). Global, regional, and national fossil-fuel CO2 emissions. . *Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tenn., USA Doi, 10.*

Breyer, C., Fasihi, M., & Aghahosseini, A. (2020). Carbon dioxide direct air capture for effective climate change mitigation based on renewable electricity: a new type of energy system sector coupling. *Mitigation and Adaptation Strategies for Global Change*, *25*(1), 43–65. https://doi.org/10.1007/s11027-019-9847-y

Chen, C., & Tavoni, M. (2013). Direct air capture of CO2 and climate stabilization: A model based assessment. *Climatic Change*, *118*(1), 59–72. https://doi.org/10.1007/s10584-013-0714-7

Climate Analytics. (2024). *Europe-Climate target*. https://1p5ndc-pathways.climateanalytics.org/countries/european-union/#fn14

Climate change. (2023). Synthesis report - Summary for Policymakers. *An Assessment of the Intergovernmental Panel on Climate Change*, *335*(7633), 1318.

Dahowski, R. T., Davidson, C. L., & Dooley, J. J. (2011). Comparing large scale CCS deployment potential in the USA and China: A detailed analysis based on country-specific CO2 transport & storage cost curves. *Energy Procedia*, *4*, 2732–2739. https://doi.org/10.1016/j.egypro.2011.02.175

DEA. (2016). *Technology Data for Generation of Electricity and District Heating*.

Dooley, J. J., & Friedman, S. J. (2005). *A Global but Regionally Disaggregated Accounting of CO2 Storage Capacity: Data and Assumptions for Compiling Regional CO2 Storage Capacity Supply Curves for Incorporation within ObjECTS->MiniCAM*.

El Aima, R., & Onoda, M. (2020). World View. *Artnews*, *118*(4), 88–93. https://doi.org/10.2307/j.ctvpj76dk.6

Eufrasio, R. M., Kantzas, E. P., Edwards, N. R., Holden, P. B., Pollitt, H., Mercure, J. F., Koh, S. C. L., & Beerling, D. J. (2022). Environmental and health impacts of atmospheric CO2 removal by enhanced rock weathering depend on nations' energy mix. *Communications Earth and Environment*, *3*(1), 1–13. https://doi.org/10.1038/s43247-022-00436-3

European parliament. (2024). Union certification framework for carbon removals. *Representation*, *12*(47), 13. https://doi.org/10.1080/00344897208656356

Fasihi, M., Efimova, O., & Breyer, C. (2019). Techno-economic assessment of CO 2 direct air capture plants. *Journal of Cleaner Production*, *224*, 957–980. https://doi.org/10.1016/j.jclepro.2019.03.086

Fauvel, C., Fuhrman, J., Ou, Y., Shobe, W., Doney, S., McJeon, H., & Clarens, A. (2023). Regional implications of carbon dioxide removal in meeting net zero targets for the United States. *Environmental Research Letters*, *18*(9). https://doi.org/10.1088/1748-9326/aced18

Fuhrman, J., Bergero, C., Weber, M., Monteith, S., Wang, F. M., Clarens, A. F., Doney, S. C., Shobe, W., & McJeon, H. (2023). Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. *Nature Climate Change*, *13*(April). https://doi.org/10.1038/s41558-023-01604-9

Fuhrman, J., McJeon, H., Patel, P., Doney, S. C., Shobe, W. M., & Clarens, A. F. (2020). Food–energy–water implications of negative emissions technologies in a +1.5 °C future. *Nature Climate Change*, *10*(10), 920–927. https://doi.org/10.1038/s41558-020-0876-z

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., De Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. V., Wilcox, J., Del Mar Zamora Dominguez, M., & Minx, J. C. (2018a). Negative emissions - Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 2016–2050. https://doi.org/10.1088/1748-9326/aabf9f

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., De Oliveira Garcia, W., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. V., Wilcox, J., Del Mar Zamora Dominguez, M., & Minx, J. C. (2018b). Negative emissions - Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 2016–2050. https://doi.org/10.1088/1748-9326/aabf9f

Galán-Martín, Á., Vázquez, D., Cobo, S., Mac Dowell, N., Caballero, J. A., & Guillén-Gosálbez, G. (2021). Delaying carbon dioxide removal in the European Union puts climate targets at risk. *Nature Communications*, *12*(1), 1–12. https://doi.org/10.1038/s41467-021-26680-3

Galik, C. S. (2020). A continuing need to revisit BECCS and its potential. *Nature Climate Change*, *10*(1), 2–3. https://doi.org/10.1038/s41558-019-0650-2

Geden, O., Peters, G. P., & Scott, V. (2019). Targeting carbon dioxide removal in the European Union. *Climate Policy*, *19*(4), 487–494. https://doi.org/10.1080/14693062.2018.1536600

Geden, O., & Schenuit, F. (2020). Unconventional Mitigation: Carbon Dioxide Removal as a New Approach in EU Climate Policy. *SWP Research Paper*, *8*, 1–39.

Geden, O., Scott, V., & Palmer, J. (2018). Integrating carbon dioxide removal into EU climate policy: Prospects for a paradigm shift. *Wiley Interdisciplinary Reviews: Climate Change*, *9*(4), 1–10. https://doi.org/10.1002/wcc.521

Hanna, R., Abdulla, A., Xu, Y., & Victor, D. G. (2021). Emergency deployment of direct air capture as a response to the climate crisis. *Nature Communications*, *12*(1), 1–13. https://doi.org/10.1038/s41467-020-20437-0

Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert, J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N., Kurokawa, J. I., Li, M., Liu, L., Lu, Z., Moura, M. C. P., O'Rourke, P. R., & Zhang, Q. (2018). Historical (1750-2014) anthropogenic emissions of reactive gases and aerosols from the

Community Emissions Data System (CEDS). *Geoscientific Model Development*, *11*(1), 369–408. https://doi.org/10.5194/gmd-11-369-2018

Hof, A. F. (n.d.). On the optimality of 2°C targets and a decomposition of uncertainty. *Nature Communications*, *2021*, 1–11. https://doi.org/10.1038/s41467-021-22826-5

Hossein, A., Mcdaid, C., & Mahmoudzadeh, A. (2024a). Green hydrogen supply chain risk analysis : A european hard-to-abate sectors perspective. *Renewable and Sustainable Energy Reviews*, *182*(May 2022), 113371. https://doi.org/10.1016/j.rser.2023.113371

Hossein, A., Mcdaid, C., & Mahmoudzadeh, A. (2024b). Green hydrogen supply chain risk analysis : A european hard-to-abate sectors perspective. *Renewable and Sustainable Energy Reviews*, *182*(May 2022), 113371. https://doi.org/10.1016/j.rser.2023.113371

IEA. (2021). *Renewables-Energy system overview*. https://www.iea.org/reports/renewables

International Energy Agency. (2019). *World Energy Balances* .

International Energy Agency. (2022). Direct Air Capture: A key technology for net zero. *International Encyclopedia of Geography*, 1–76.

IPCC. (2023). *AR6 Scenario Explorer hosted by IIASA*.

(IPCC), I. panel for climate change. (2023a). *Sixth Assessment Report*. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_LongerReport.pdf

(IPCC), I. panel for climate change. (2023b). *Sixth Assessment Report*.

IPCC, V. M.-D. P. Z. H. O. P. D. R. J. S. P. R. S. A. P. W. M.-O. C. P. R. P. S. C. J. B. R. M. Y. C. X. Z. M. I. G. E. L. T. M. M. T. T. (2018). *Global warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*.

Jeffery, S., Verheijen, F. G. A., van der Velde, M., & Bastos, A. C. (2011). A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. In *Agriculture, Ecosystems and Environment* (Vol. 144, Issue 1, pp. 175–187). Elsevier B.V. https://doi.org/10.1016/j.agee.2011.08.015

JGCRI. (n.d.-a). *GCAM v7 Documentation: Demand for Water*. Retrieved August 31, 2023, from https://jgcri.github.io/gcam-doc/demand_water.html

JGCRI. (n.d.-b). *GCAM v7 Documentation: Economic Choice in GCAM*. http://jgcri.github.io/gcam-doc/choice.html

JGCRI. (2023a, October 26). *GCAM emission factor*.

JGCRI. (2023b, October 31). *Fugitive Emission* .

Lee, H. et al. (2022). IPCC Sixth Assessment Report - Synthesis Report. In *Diriba Korecha Dadi*.

Lewis, A. L., Sarkar, B., Wade, P., Kemp, S. J., Hodson, M. E., Taylor, L. L., Yeong, K. L., Davies, K., Nelson, P. N., Bird, M. I., Kantola, I. B., Masters, M. D., DeLucia, E., Leake, J. R., Banwart, S. A., & Beerling, D. J. (2021). Effects of mineralogy, chemistry and physical properties of basalts on carbon capture potential and plant-nutrient element release via enhanced weathering. *Applied Geochemistry*, *132*(June), 105023. https://doi.org/10.1016/j.apgeochem.2021.105023

Long, T. B., & Blok, V. (n.d.). *Green Deal fi nancing in Europe : lessons from and for the agri-food climate transition*. *2021*. https://doi.org/10.1057/s41599-021-00945-0

Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O. Y., Pietzcker, R. C., Rogelj, J., Boer, H. S. De, Drouet, L., Emmerling, J., Fricko, O., Fujimori, S., Havlík, P., & Iyer, G. (2018). Residual fossil CO 2 emissions in 1 . 5 – 2 ° C pathways. *Nature Climate Change*, *8*(July). https://doi.org/10.1038/s41558-018-0198-6

Lux, B., Schneck, N., Pfluger, B., Männer, W., & Sensfuß, F. (2023). Potentials of direct air capture and storage in a greenhouse gas-neutral European energy system. *Energy Strategy Reviews*, *45*(November 2022). https://doi.org/10.1016/j.esr.2022.101012

Marcucci, A., Kypreos, S., & Panos, E. (2017). The road to achieving the long-term Paris targets: energy transition and the role of direct air capture. *Climatic Change*, *144*(2), 181–193. https://doi.org/10.1007/s10584-017-2051-8

Masson-Delmotte, V. P., Zhai, P., Pirani, S. L., Connors, C., Péan, S., Berger, N., ... & Scheel Monteiro, P. M. (2021). *Summary for policymakers. in: Climate change 2021: The physical science basis. contribution of working group i to the sixth assessment report of the intergovernmental panel on climate change.* (IPCC, Ed.). IPCC.

McQueen, N., Desmond, M. J., Socolow, R. H., Psarras, P., & Wilcox, J. (2021). Natural Gas vs. Electricity for Solvent-Based Direct Air Capture. *Frontiers in Climate*, *2*(January). https://doi.org/10.3389/fclim.2020.618644

Meckling, J., & Biber, E. (2021). A policy roadmap for negative emissions using direct air capture. *Nature Communications*, *12*(1), 1–6. https://doi.org/10.1038/s41467-021-22347-1

Morrow, D. R., Apeaning, R., & Guard, G. (2023a). GCAM-CDR v1.0: Enhancing the representation of carbon dioxide removal technologies and policies in an integrated assessment model. *Geoscientific Model Development*, *16*(3), 1105–1118. https://doi.org/10.5194/gmd-16-1105-2023

Morrow, D. R., Apeaning, R., & Guard, G. (2023b). GCAM-CDR v1.0: Enhancing the representation of carbon dioxide removal technologies and policies in an integrated assessment model. *Geoscientific Model Development*, *16*(3), 1105–1118. https://doi.org/10.5194/gmd-16-1105-2023

Nieto, M. J. (2022). Whatever it Takes to Reach Net Zero Emissions Around 2050 and Limit Global Warming to 1.5c: The Cases of United States, China, European Union and Japan. *SSRN Electronic Journal*, *January*. https://doi.org/10.2139/ssrn.4007974

NREL. (2019). *Annual Technology Baseline ATB Cost and Performance Data for Electricity Generation Technologies.*

Peters, G. P., & Geden, O. (2017). Catalysing a political shift from low to negative carbon. *Nature Climate Change*, *7*(9), 619–621. https://doi.org/10.1038/nclimate3369

Powis, C. M., Smith, S. M., Minx, J. C., & Gasser, T. (2023). Quantifying global carbon dioxide removal deployment. *Environmental Research Letters*, *18*(2). https://doi.org/10.1088/1748-9326/acb450

Pozo, C., Galán-martín, Á., Reiner, D. M., Dowell, N. Mac, & Guillén-gosálbez, G. (2020). Equity in allocating carbon dioxide removal quotas. *Nature Climate Change*, *10*(July). https://doi.org/10.1038/s41558-020-0802-4

PPNL. (2023). *GCAM*. https://gcims.pnnl.gov/modeling/gcam-global-change-analysis-model

Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2019a). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications*, *10*(1), 1–12. https://doi.org/10.1038/s41467-019-10842-5

Realmonte, G., Drouet, L., Gambhir, A., Glynn, J., Hawkes, A., Köberle, A. C., & Tavoni, M. (2019b). An inter-model assessment of the role of direct air capture in deep mitigation pathways. *Nature Communications*, *10*(1), 1–12. https://doi.org/10.1038/s41467-019-10842-5

Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R., & Lehmann, J. (2010). Life cycle assessment of biochar systems: Estimating the energetic, economic, and climate change potential. *Environmental Science and Technology*, *44*(2), 827–833. https://doi.org/10.1021/es902266r

Rosa, L., Sanchez, D. L., & Mazzotti, M. (2021). Assessment of carbon dioxide removal potential: Via BECCS in a carbon-neutral Europe. *Energy and Environmental Science*, *14*(5), 3086–3097. https://doi.org/10.1039/d1ee00642h

Schellnhuber, H. J., Rahmstorf, S., & Winkelmann, R. (n.d.). *Why the right climate target was agreed in Paris*.

Scott, V., & Geden, O. (2018). The challenge of carbon dioxide removal for EU policy-making. *Nature Energy*, *3*(5), 350–352. https://doi.org/10.1038/s41560-018-0124-1

Smith, P., Davis, S. J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R. B., Cowie, A., Kriegler, E., Van Vuuren, D. P., Rogelj, J., Ciais, P., Milne, J., Canadell, J. G., McCollum, D., Peters, G., Andrew, R., Krey, V., … Yongsung, C. (2016). Biophysical and economic limits to negative CO2 emissions. *Nature Climate Change*, *6*(1), 42–50. https://doi.org/10.1038/nclimate2870

Stamm, A. (2023). *Green Hydrogen : Implications for International Cooperation With Special Reference to South Africa Green hydrogen : Implications for international cooperation With special reference to South Africa*.

Steininger, K. W., Williges, K., & Meyer, L. H. (2022). *Sharing the effort of the European Green Deal among countries*. https://doi.org/10.1038/s41467-022-31204-8

Strefler, J., Amann, T., Bauer, N., Kriegler, E., & Hartmann, J. (2018). Potential and costs of carbon dioxide removal by enhanced weathering of rocks. *Environmental Research Letters*, *13*(3). https://doi.org/10.1088/1748-9326/aaa9c4

Tamme, E., & Beck, L. L. (2021). European Carbon Dioxide Removal Policy: Current Status and Future Opportunities. *Frontiers in Climate*, *3*(September), 1–7. https://doi.org/10.3389/fclim.2021.682882

Terlouw, T., Bauer, C., Rosa, L., Mazzotti, M., & Bauer, C. (2021). *Environmental Science Life cycle assessment of carbon dioxide removal technologies : a critical review †*. 1701–1721. https://doi.org/10.1039/d0ee03757e

Wang, J., Xiong, Z., & Kuzyakov, Y. (2016). Biochar stability in soil: Meta-analysis of decomposition and priming effects. In *GCB Bioenergy* (Vol. 8, Issue 3, pp. 512–523). Blackwell Publishing Ltd. https://doi.org/10.1111/gcbb.12266

Welsby, D., Price, J., Pye, S., & Ekins, P. (2021). *Unextractable fossil fuels in a 1 . 5 ° C world*. *597*(July). https://doi.org/10.1038/s41586-021-03821-8

Wise, M. , C. K. , K. P. , L. P. & E. J. A. E. (2014). Economic and physical modeling of land use in Gcam 3.0 and an application to agricultural productivity, land, and terrestrial carbon. . *Clim. Change Econ.*, *05*, 1450003.

Wohland, J., Witthaut, D., & Schleussner, C. F. (2018). Negative Emission Potential of Direct Air Capture Powered by Renewable Excess Electricity in Europe. *Earth's Future*, *6*(10), 1380–1384. https://doi.org/10.1029/2018EF000954

Workman, M., Dooley, K., Lomax, G., & Maltby, J. (2020). *Decision making in contexts of deep uncertainty - An alternative approach for long-term climate policy*. *103*(August 2019), 77–84. https://doi.org/10.1016/j.envsci.2019.10.002

Ye, L. , C.-A. M. , S. Q. , L. J. , S. B. , and S. M. (2020). Biochar Effects on Crop Yields with and without Fertilizer: A Meta-Analysis of Field Studies Using Separate Controls . *Soil Use and Management*, *20*(1), 2–18.