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Near-term carbon dioxide removal deployment can minimize disruptive pace of decarbonization and economic risks towards United States' net-zero goal

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Deep decarbonization is essential for achieving the Paris Agreement goals, and carbon dioxide removal is required to address residual emissions and achieve net-zero targets. However, the implications of delaying the deployment of removal technologies remain unclear. We quantify how different carbon removal methods and their deployment timing affect achieving net zero emissions by 2050 in the United States. Our findings show that postponing novel technologies until mid-century forces accelerated decarbonization of energy-intensive sectors, reducing residual emissions by at least 12% compared with near-term deployment of carbon dioxide removal. This delay increases transition costs, requiring carbon prices 59–79% higher than with near-term deployment. It also heightens the risk of premature fossil fuel retirement in the electricity sector, leading to 128–220 billion USD losses compared to gradual scale up starting now. A balanced, near-term co-deployment of novel removal methods mitigates risks associated with relying on a single approach and addresses sustainability and scalability concerns.

A central feature of geophysical climate research is the quasi-linear relationship between cumulative net emissions and temperature increase, implying a threshold on allowable emissions for any short- or long-term temperature stabilization target[1]. This finite emission limit, known as the 'remaining carbon budget (RCB)', is rapidly diminishing. The RCB is estimated to be 250 $GtCO_2$ from 2023 onwards, with a 50% likelihood of limiting global warming to 1.5 °C by 2100[2], which will be exhausted at the current carbon dioxide (CO_2) emission rate in about 6 years[3]. This shrinking RCB necessitates deep, rapid and sustained near-term economy-wide decarbonization strategies such as electrification of end-use sectors[4], renewable energy penetration[5], energy efficiency[6], efficient material use[7], carbon-neutral/negative fuels[8], demand-side reduction approaches[4], improved livestock management[9], and other sustainable agricultural practices[10].

While these strategies can substantially cut emissions, their contribution may be limited in practice. For example, hydropower and biomass productivity may decrease due to the impacts of climate change[11]. Additionally, electrifying energy-intensive sectors (such as steel, aluminum, and cement) presents challenges due to current technological limitations in achieving the necessary high temperatures, and the high costs associated with developing and deploying alternative technologies[8]. These technological challenges, combined with inadequate emission reduction efforts in countries' nationally determined contributions (NDCs)[12], have made carbon dioxide removal (CDR) a prominent feature of recent climate strategies and policies.

CDR contributes to net emission reduction in the near term, counterbalances residual emissions (often from the "hard-to-abate" or "difficult to decarbonize" sources) at net-zero year, and achieves and sustains net-negative emissions post-mid-century if deployed at levels exceeding residual emissions to return temperature to safer limits after temporal overshoots[13]. Furthermore, the Intergovernmental Panel for Climate Change (IPCC) report states that "*the deployment of CDR to counterbalance hard-to-abate residual emissions is unavoidable if net-zero emissions are to be achieved.*"[14]

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CDR features prominently in low-carbon scenarios in the IPCC reports, with estimates of global CDR reaching over 10 $GtCO_2$/yr by mid-century for a net-zero objective[15]. Several integrated assessment models (IAMs) that achieve a 1.5 °C goal deploy novel CDR methods like direct air carbon capture and storage (DACCS) and bioenergy carbon capture and storage (BECCS) to compensate for slow near-term emission reductions[14].

While the role of novel CDR in meeting regional and global climate goals has gained increasing recognition in climate science, its integration into national climate policies remains limited and inconsistent. Most regions primarily plan to use conventional CDR methods, such as afforestation and reforestation (A/R), which currently account for 99.9% of global CDR deployment[16]. These methods are well-established and widely reported by countries as part of land use, land-use change, and forestry (LULUCF) activities. However, they are not durable due to limitations such as their susceptibility to climate change impacts, the vulnerability of land carbon to disturbances, and the potential reversibility of carbon storage[17]. No country explicitly includes novel CDR in their pledged 2030 mitigation efforts, though some quantify it in their long-term strategies (LTS)[18]. As a result, the importance of preparing for large-scale novel CDR is not currently reflected in policy frameworks. This 'CDR gap'[18] is shaped by several concerns, including the low technology readiness levels of CDR methods[19], sustainability implications of large-scale deployment[20], the risk of mitigation deterrence[21], challenges in corporate accounting for scope 3 emissions[22], and a lack of clarity on 'what constitutes residual emissions[1]. These concerns pose a risk of CDR underperforming relative to future expectations and may delay necessary investments in the near term, thereby shortening the time available to scale to the gigatonne level that may be needed by mid-century[23].

In light of the Paris Agreement goal, this study contrasts the portfolio of CDR methods in the near term and their deployment timing. We explore to what extent delaying CDR deployment affects key net emission reduction metrics such as cumulative residual emissions, carbon lock-in, the size and scale-up of CDR required, and other sustainability impacts.

The CDR concerns highlight the need for supporting a diverse range of approaches[24]. Considering this, we model a diverse suite of CDR approaches, building on the work by Fuhrman et al.[24]. This approach shows that through complementarity, diversifying CDR methods can balance out the limitations of individual technologies, reducing the overall strain on the energy-land-water nexus and emphasizing the importance of varied strategies for maximizing carbon removal.

In 2022, the United States (US) was responsible for 11% of global greenhouse gas (GHG) emissions[25]. If the allocation of CDR burden is made under the equity sharing principles of either responsibility or capability, the US will likely hold the largest share of the global cumulative CDR quota by 2100[26]. This study, therefore, focuses on the US, modeling its pathway to net-zero GHG emissions by mid-century to meet its domestic climate goal and contribute to the global 1.5 °C target (See Methods). To better capture the synergies and trade-offs of CDR with the earth system and quantify the poorly understood implications of delayed CDR deployment, we go beyond BECCS[27] and DACCS[28] methods typically modeled in IAM. Only a few studies[24,29,30] have integrated a broader suite of CDR methods into their models. Adopting a wider range of CDR approaches could help address sustainability challenges[24]. Considering a country's energy-land-water nexus, the open question remains 'How does the variety of CDR methods and their deployment timing impact a region's energy structure, the pace of economy-wide and sectoral transitions, and other sustainability concerns? Additionally, the absence of clear long-term policies and regulatory framework for mitigation options regarding emission reductions and the scale of novel CDR deployment exacerbates the risk of fossil assets becoming stranded. Therefore, the question of 'how to balance energy transition strategies and economic stability' becomes critical.

In this study, we explore four scenarios. In the first scenario, referred to as 'B-EARLY', BECCS is deployed in the near term, while other novel CDR methods are delayed until mid-century. In the second scenario, labeled as 'D-EARLY', DACCS is deployed early in the first half of the century, with other novel CDR methods postponed until the mid-century. In the third scenario, labeled as 'CO-EARLY', both DACCS and BECCS are deployed in the near term, while other novel CDR methods are delayed. In the final scenario, represented as 'DELAYED', novel CDR is not prioritized in the US near-term climate actions, delaying deployment until mid-century. The 'DELAYED' stylized scenario shows a sudden, rapid growth in novel CDR volumes by mid-century to reach the net-zero target. Given the gap between this stylized pathway and current trends, the scenario assumes that novel CDR methods are being funded, and actively researched throughout the near term. This ongoing investment allows them to be deployed at scale by mid-century once they reach full commercialization and become more cost-effective.

A sensitivity analysis of the CO-EARLY scenario is modeled where land-based CDR methods, biochar and BECCS are deployed in the near term. This modelling approach of gradual scale-up of biochar in the near-term reflects its development in terms of global deployment and funding[31] (Supplementary Note 2). The diverse suite of novel CDR methods in this study includes BECCS, DACCS, Enhanced Weathering (EW), Biochar, and Direct Ocean Carbon Capture and Storage (DOCCS) (See Methods and Supplementary Note 3 for more details on CDR parametrization). The conventional CDR method of Afforestation/Reforestation (A/R) is available in all scenarios and contributes towards net-emission reductions and net-zero targets. Across our scenarios, the near-term deployment of novel CDR begins in 2025, which is consistent with the earliest deployment of novel CDR in the pathways compiled by the IPCC in its Sixth Assessment Report (AR6)[15].

Results

GHG emission reduction by sector and species

Figure 1a shows the GHG emission reduction by sector and species across our scenarios. There is a substantial reduction of 57.5–61.5%, in gross CO_2 emissions (excluding biogenic CO_2) across all sectors between 2020 and 2050. The extent of overall GHG emissions is ~9–10% lower in the same period. A high-priority mitigation action in the scenarios is the rapid transition from fossil-fueled electricity generation to low-carbon fuels and renewable energy sources. The magnitude of sectoral decarbonization between 2020 and 2050 in the scenarios follows this order: Electricity (84–87%) > Industry (44–47%) > Transportation (41–47%) > Buildings (38–41%). More details on sectoral emissions are provided in the Supplementary Discussion. A net-zero GHG emission trajectory also drives a comprehensive approach to reducing non-CO_2 emissions, including those from agricultural practices, fugitive sources, waste management, industrial processes, and forestry activities. Methane (CH_4) and fluorinated gases (F-gases) decrease by an annual average of 20% and 56%, respectively, between 2020 and 2050 across the scenarios. Nitrous oxide (N_2O) is a major contributor to GHG emissions in the US, accounting for an average of 44% of total non-CO_2 emissions between 2020 and 2050. We see an increase in N_2O emissions by 18–21% over this period across all modeled scenarios, primarily due to slow progress in mitigation emissions from agricultural processes. Therefore, tailored policies are required to reduce non-CO_2 GHG emissions, particularly in the agricultural sector[32].

The extent of emissions reductions across sectors also depends on the CDR portfolio and its deployment timing. This is evident in the D-EARLY scenario, where the early deployment of DACCS reduces the stringency of decarbonization in energy-intensive sectors due to the promise of later removals. This results in a 57.5% reduction in CO_2 and a 48.1% reduction in GHG emissions between 2020 and 2050, about 4% and 3% lesser than CO_2 and GHG reduction efforts by all other scenarios, respectively. The relaxation of mitigation efforts arises from treating DACCS as a backstop technology, which caps the rise in carbon prices, making it a long-term mitigation measure[33]. Conversely, the largest CO_2 emission reduction occurs when BECCS is deployed as the sole CDR method in the near term, achieving a 61.5% reduction in CO_2 emissions by 2050 compared to 2020 levels. The deployment of BECCS increases the use of bioenergy as both a primary and secondary energy source, replacing fossil fuels in decarbonizing energy systems (Fig. S3, Table S14).

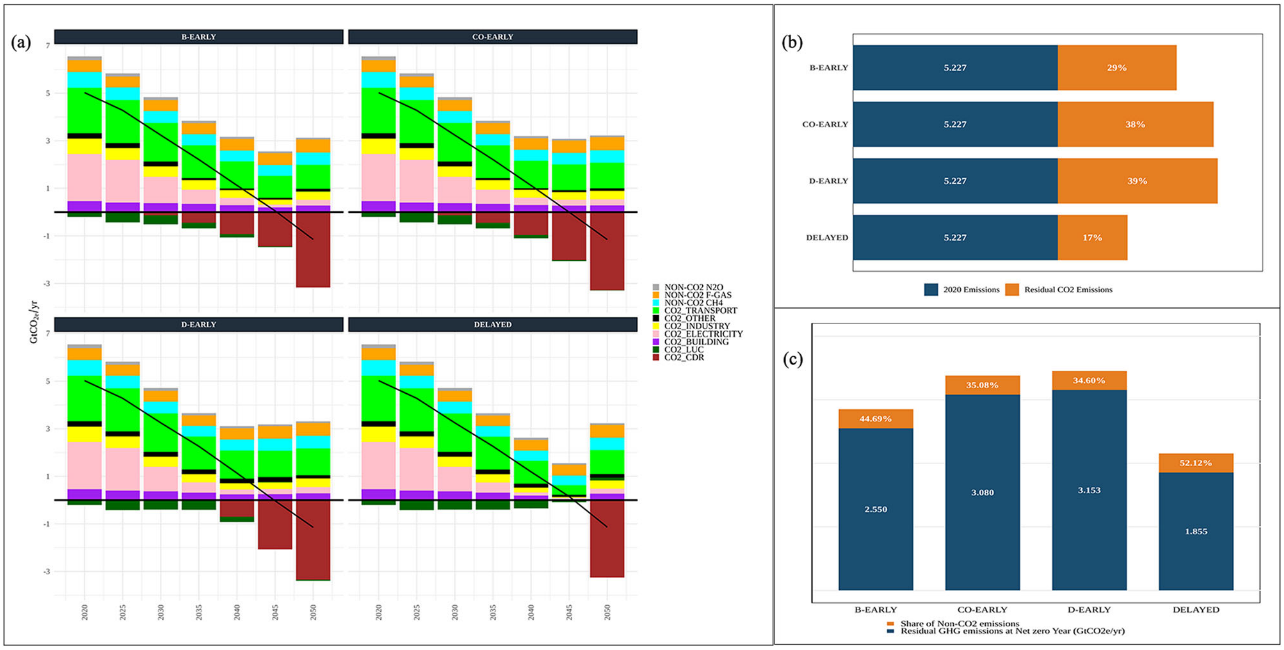


Fig. 1 | GHG and residual emission. a Gross positive and negative GHG emissions by sector and species. Positive emissions come from Fossil fuels and Industry. The black line shows net CO_2 emissions. CO2_LUC represents net emissions from Afforestation/Reforestation and deforestation. The negative values on the y-axis indicate CO_2 removal from the atmosphere. **b** residual emissions relative to 2020 emissions, which is 5.2 $GtCO_2$/yr; and **c** residual GHG emissions in the year when net-zero CO_2 is achieved versus share of non-CO_2 GHG emissions.

In the DELAYED scenario, GHG emissions experience a deeper reduction compared to other scenarios, achieving a 51.3% reduction by 2050 compared to 2020 levels. This outcome is primarily by a more stringent shift away from carbon-intensive fuels, incentivized by a comparatively higher carbon price. Additionally, when the full suite of CDR is delayed, the substitutionary relationship between emission reductions and CO_2 removal leads to accelerated decarbonization across sectors. This occurs as sectors must rely more heavily on immediate emissions reductions to compensate for the delayed CDR deployment. Relative to 2020, the largest economy-wide CO_2 emission reduction by 2050 occurs in the following order: B-EARLY > DELAYED > CO-EARLY > D-EARLY. The order of GHG emission reductions over the same period is DELAYED > B-EARLY > CO-EARLY > D-EARLY.

Our results suggest that delaying CDR deployment in the near term hinders the US from achieving its 2035 NDC[34]. In contrast, the co-deployment of CDR methods (CO-EARLY) achieves a closer net GHG reduction to the NDC goal by 2030, relative to 2005 levels (excluding LULUCF).

Deploying DACCS as the sole CDR in the near-term results in higher average annual net emissions (2.78 $GtCO_2$/yr) between 2020 and the net-zero year. Conversely, the lowest net emission occurs when BECCS is prioritized in the near-term (2.65 $GtCO_2$/yr). Net-zero CO_2 emissions are achieved by 2045, in D-EARLY and CO-EARLY, 2046 in B-EARLY and DELAYED scenario. The earliest net-zero year is driven by the co-deployment of CDR methods in the near-term. Notably, net removals from LULUCF allow net zero to be reached before mid-century in scenario where technological removals are absent during this period.

The DELAYED scenario records the highest share of non-CO_2 emissions in the net-zero year, despite having the lowest absolute non-CO_2 emissions and the largest reduction between 2020 and 2050. In this scenario, the reduction in non-CO_2 emissions is ~19–78% higher than in the other scenarios, primarily due to lower fertilizer use from reduced biomass production and a decline in fugitive emissions from energy production processes. Conversely, deploying BECCS in the near-term results in a relatively high share of non-CO_2 emissions, contributing to residual GHG emissions (Fig. 1b).

These results highlight several key implications. First, they illustrate the difficulty in reducing the contribution of non-CO_2 emissions even under a stringent decarbonization strategy in the fossil fuel and industrial processes. This highlights the need for more aggressive measures to mitigate these gases. Additionally, the expansion of land-based practices, such as biomass cultivation in the B-EARLY scenario and afforestation in the DELAYED scenario, increases the use of inorganic fertilizers, a major source of N_2O emissions (Table S15).

Delaying all CDR until mid-century forces rapid decarbonization, resulting in the lowest residual emissions by the net-zero year, equivalent to 17% of 2020 US CO_2 emissions (Fig. 1c). When novel CDR methods are deployed in the near term, relying solely on BECCS achieves the lowest residual emissions by the net-zero year, at 29% of 2020 emissions. In contrast, using only DACCS results in a more relaxed requirement for emission reduction efforts, leading to the highest residual emissions at the net-zero year, equivalent to 39% of 2020 emissions. Pairing BECCS with DACCS, however, increases emission reduction efforts, lowering residual emissions to 38% of 2020 levels. This highlights the comparative advantage of co-deployment over focusing solely on DACCS in the near term.

The B-EARLY scenario shows that BECCS is a promising CDR strategy in the near term. Deploying BECCS, rather than relaxing emission reduction efforts, increases the scale of the transition away from carbon fuels. The cost-competitiveness of BECCS increases its role in electricity generation and industrial processes. Our results show that by 2030 and relative to 2020 levels, deploying DACCS solely in the near term achieves an economy-wide CO_2 emission reduction of 30.4%, relative to 2020, which is comparable to the DELAYED scenario and greater than the reductions seen in the B-EARLY and CO-EARLY scenarios. This is because, in the near term, the economy-wide transition is directly driven by the cost of emissions on fossil fuel consumption due to the relatively higher levelized cost of DACCS (the cost of removing a tonne of CO_2 using DACCS)[35]. This discourages large-scale DACCS deployment and instead encourages more stringent decarbonization. This focus on near-term decarbonization (2025–2030) is most evident in the DELAYED scenario, highlighting the critical need for a policy focus on strategic non-CDR decarbonization efforts. It also highlights the importance of advancing CDR through continued research and development, alongside the implementation of supportive policy frameworks to promote both immediate mitigation actions and future deployment of CDR technologies

Primary energy, final energy, and electricity generation

The primary energy consumption is illustrated in Figs. 2 and 3. Focusing on DACCS as the only near-term CDR option accelerates fossil CCS consumption compared to other scenarios. This acts as a buffer, allowing for the continued use of high-carbon fuels. The largest consumption of both fossil fuels and fossil CCS occurs in the D-EARLY scenario (Fig. 4), with total fossil fuel CCS rising to reach 31 EJ/yr by 2050 from 2.9 EJ/yr in 2030. In comparison, fossil CCS deployment in the B-EARLY, CO-EARLY, and DELAYED scenarios is approximately 23%, 19%, and 10% lower, respectively. Mitigation actions reduce coal consumption in all scenarios; however, we observe a higher fossil lock-in under the D-EARLY scenario. Coal consumption in the D-EARLY scenario declines from 14.9 EJ/yr in 2020 to

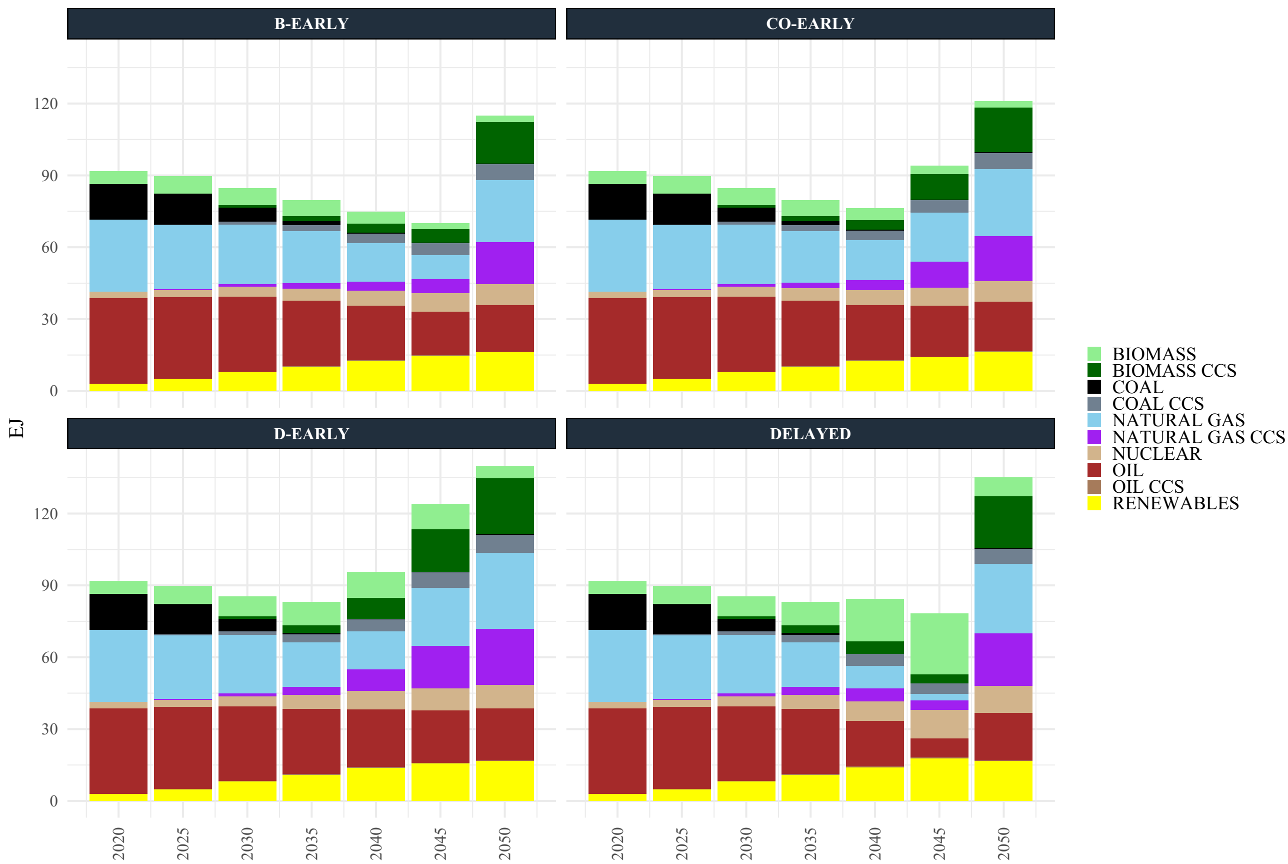
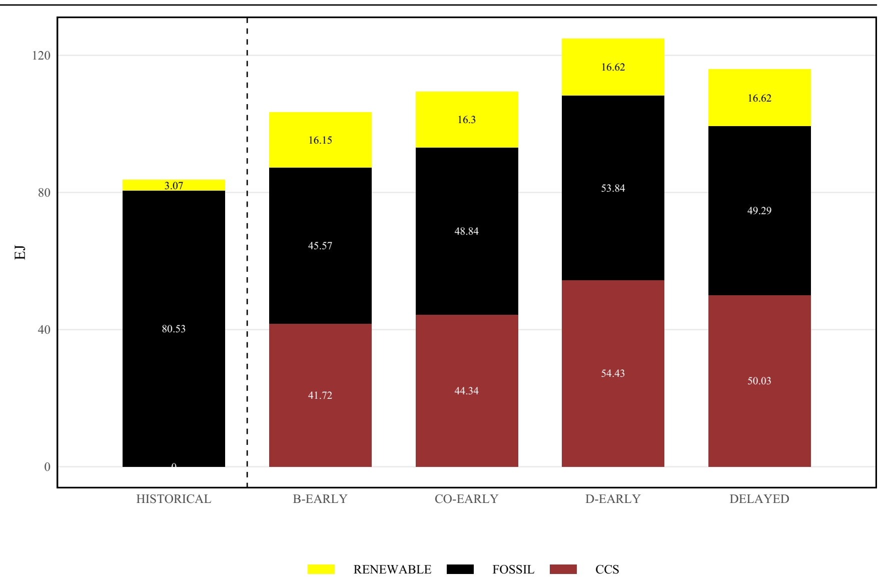


Fig. 2 | Primary energy consumption. Projected primary energy consumption by fuel in a 2050 net-zero GHG scenario for the US. CCS refers to carbon capture and storage. Renewables consist of solar, wind, geothermal, and hydro.

Fig. 3 | Historical vs projected primary energy consumption across scenarios. Historical primary energy consumption by 2020, and projected consumption to 2050 across CDR deployment scenarios for the US. CCS technology is used with biomass, coal, oil, and natural gas.



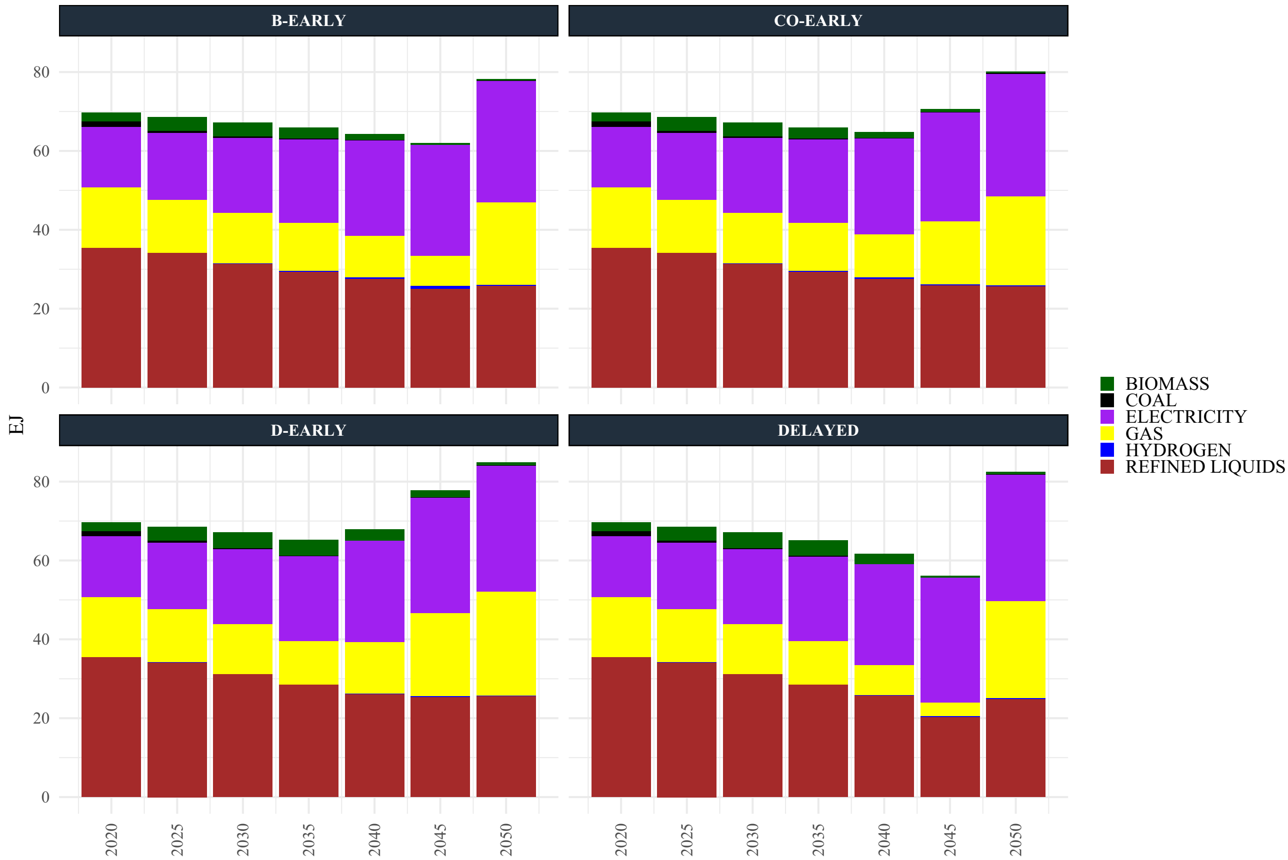


Fig. 4 | Final energy consumption. Projected final energy consumption by fuel for the US in a 2050 net-zero GHG scenario.

0.3 EJ/yr by 2050. In the other scenarios, coal consumption is reduced by a further 5–24% by 2050. Nuclear energy contributes substantially to primary energy consumption, especially when CDR is delayed to mid-century.

The unavailability of novel CDR in the near term accelerates the shift to low-carbon and zero-carbon fuels for energy requirements across sectors. In the DELAYED scenario, we observe higher biomass consumption than in other scenarios, making it a key part of the primary energy mix. The D-EARLY scenario also features substantial biomass consumption, with a higher share of biomass CCS than in the DELAYED scenario. The consumption of renewables as primary energy scales similarly across all scenarios, reaching an average of 16.2 EJ/yr by 2050, an increase of around 80% from 2020. This demonstrates that renewable energy integration is a key element of the net-zero emissions pathway, regardless of the technology choice, scale, or timing of CDR deployment. Renewable energy consistently supports decarbonization efforts, ensuring progress toward climate goals, even as CDR technologies evolve and scale up.

Figure 4 illustrates final energy consumption, which continues to rise through 2050 in all scenarios. The slowest growth is in the B-EARLY scenario, with a 21% increase between 2020 and 2050, compared to 23–30% in the other scenarios.

Final energy consumption decreases by 11% in the B-EARLY and 19% in the DELAYED scenarios between 2020 and 2045. In contrast, it increases by 8% in the CO-EARLY and 22% in the D-EARLY scenarios over the same period. The higher energy demand in the D-EARLY and CO-EARLY scenarios is largely due to the additional energy required for DACCS operations.

Final energy consumption increases sharply between 2045 and 2050 across all scenarios by 10–42%. The most pronounced increase occurs when all CDR methods are deferred until mid-century. In the absence of early CDR deployment, the rate of decarbonization, including energy efficiency measures, increases. However, as CDR scales to gigatonne levels by mid-century, the consumption by energy-intensive methods like DACCS increases substantially. This is particularly notable in the DELAYED scenario due to the higher heat demand needed to support large DACCS operations by mid-century. This highlights the importance of scaling renewable energy generation and developing advanced technologies to improve the energy efficiency of CDR processes in the near term to ensure that CDR projects remain truly net-negative.

The operation of DACCS creates a high demand for gas in final energy consumption due to the need for high temperatures (>1000 °C) in the calciner (in the liquid solvent DACCS process) to adsorb CO_2 from $CaCO_3$[36]. The strategy of deploying DACCS exclusively in the near term increases gas consumption in the US to 26.4 EJ/yr by 2050. This is 7.2%, 17.4%, and 26.2% higher than in the DELAYED, CO-EARLY, and B-EARLY scenarios, respectively.

There is rapid electrification of final energy end uses in the DELAYED scenario, with an average annual share of 34% between 2020 and 2050, which is at least 6% higher than in the other scenarios. The contribution of hydrogen to final energy is larger in the B-EARLY and CO-EARLY scenarios, mainly due to the rapid scale-up of BECCS in the near term.

Figure 5 shows electricity generation in the US under a 2050 net-zero GHG target. The most substantial shift away from fossil fuel-based electricity generation occurs in the DELAYED scenario. The stringent requirement to replace carbon-based fuel technologies is driven by carbon pricing, which accelerates the phasing down of fossil fuel power plants. In the DELAYED scenario, electricity generation from fossil fuels by 2050 will reduce by 87.3% compared to 2020, while in the D-EARLY, B-EARLY, and CO-EARLY scenarios, this reduction is 84%, 85%, and 83.5%, respectively. This highlights the transition from fossil fuels to clean fuels to reach the net-zero target. Compared to the US 2023 electricity mix[37], the share of fossil fuels is more than halved to meet net-zero GHG emissions by mid-century. By 2050, the share of renewable energy in all modeled scenarios is projected to be ~46–47%, roughly double the contribution of renewables in the current US electricity mix. The DELAYED scenario also shows the largest

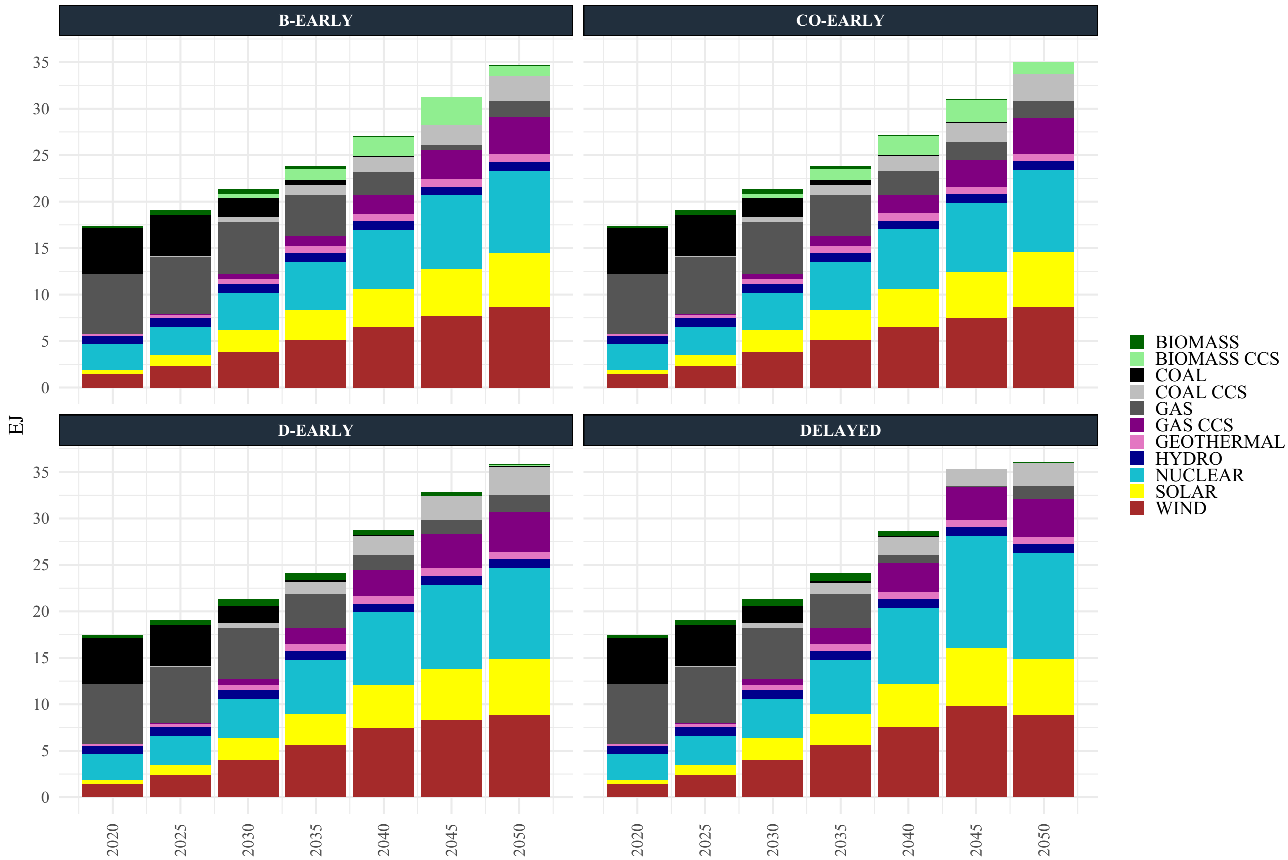


Fig. 5 | Electricity generation mix. Projected electricity generation mix by fuel for the US in a 2050 net-zero GHG scenario.

contribution of nuclear energy to electricity generation, reaching 11.35 EJ/yr by 2050, accounting for 32% of total generation.

Carbon sequestration

Figure 6 shows the scale of CDR in the scenarios. The volume of novel CDR needed to achieve net-zero GHG emissions in the US by mid-century ranges from 3.16 to 3.34 $GtCO_2$/yr by 2050, with each technology scaling at different rates. This CDR requirement scale is higher than the volume projected in IAM scenarios for the US[35], due to the broader range of CDR approaches required to drive a net-zero GHG in this study. The lowest total novel CDR volume before 2045 occurs in the D-EARLY scenario due to the slow scale-up of DACCS in the near term. In contrast, prioritizing BECCS exclusively in the near term results in double the CDR volume between 2020 and 2040. This highlights the longer lead time needed for scaling DACCS, which requires substantial investment and the development of more material-efficient processes.

The contribution of DACCS to total CO_2 removal by 2050 is between 69% and 90% across all scenarios. This implies a minimum of 200 DACCS plants would be required in the US to offset residual emissions (assuming one plant sequesters 1 $MtCO_2$/yr)[38], alongside other CDR approaches to achieve net-zero emissions by 2050. We also see that natural gas-powered DACCS is deployed in preference to electricity-powered DACCS in all scenarios. This relatively modest contribution of electricity-power DACCS is due to the higher cost of scaling renewable energy to meet the large energy demands of DACCS operations. This limitation is less prominent in low-temperature DACCS, where energy demands can be met using heat pumps.

The heat requirement presents a challenge for DACCS, which could be mitigated through strategic siting and infrastructure development, such as locating DACCS plants near industrial facilities to use waste heat[39]. Pairing DACCS with renewable energy may not be cost-effective in the near-term, unless sourced from high-capacity factor technologies like offshore wind. Young et al.[40] found that pairing DACCS with nuclear energy could be a feasible option in terms of both energy requirements and cost. It is important to note that captured CO_2 could be a valuable raw material for various industries, such as enhanced hydrocarbon recovery, synthetic fuel production, and carbonation. These uses could offset some of the additional costs of energy generation.

The co-deployment of BECCS and DACCS allows for a higher CDR volume than deploying individual CDR methods. This demonstrates that diversifying CDR options in terms of investments, funding, grants, research and development, and policy focus reduces the risk of CDR failing to reach necessary levels, even in the near term. We find that BECCS make up ~20% of CO_2 removal in the US by 2050 under the CO-EARLY scenario. Additionally, the co-deployment of CDR methods in the near term results in a greater average sequestration rate through to mid-century compared to relying on a single method. Our results show that novel CDR methods in the CO-EARLY scenario achieve 10–12% higher annual average sequestration between 2020 and 2050 compared to the B-EARLY and D-EARLY scenarios, respectively.

The DELAYED scenario shows a large and rapid increase in CDR deployment by mid-century based on the stylized scenario. This stylized approach fundamentally assumes that technological developments and investments in CDR methods will occur before they are commercially deployed by mid-century. However, this may be unrealistic for some industries in practice. In scenarios with near-term deployment, cumulative CDR between 2025 and mid-century is about twice the volume seen in the DELAYED scenario. The DELAYED scenario also highlights competition between biomass feedstock for biochar and BECCS, with biochar volumes exceeding those of BECCS. Operational details show that slow pyrolysis biochar requires less processing and energy (in the combustion chamber) compared to biomass combustion (gasification). Sawyer[41] also noted that large-scale biochar deployment (via pyrolysis) as a CDR method appeared more feasible than BECCS, based on techno-economic-environmental assessment.

Fig. 6 | Carbon sequestration. Carbon sequestration by technology across the scenarios for near-term CDR deployment and postponement of novel CDR technologies. ELE, NG, and HP represent electricity, natural gas, and heat pumps, respectively, as energy sources for DAC operations.

Negative emissions from bioenergy in the DELAYED scenario come primarily from bioliquids and hydrogen production, rather than electricity generation (Table 2). EW contributes 4–8% to CO_2 removal by 2050, with its largest contribution occurring when all CDR technologies are delayed until mid-century. EW has the advantage of not competing for land used in food production or with other CDR methods, such as BECCS, for feedstock[42]. It can be scaled substantially without putting additional strain on the environment or encroaching on land use practices. However, a challenge with EW in the US could be the unsustainable extraction practices and energy required for the mining, crushing, and distribution of these minerals. There is increasing recognition of the potential of finely crushed basalt, a by-product of mining and aggregate industries, and its CDR potential has been the subject of ongoing research. Utilizing these accumulated crushed basalts, including from the steel industry, would reduce the need for new mines and lower energy demands. Beerling[43] suggested that a national inventory of such accumulated basalt be developed to quantify its CDR potential.

The contribution of DOCCS to CO_2 removal is minimal, with only 0.1 $MtCO_2$/yr removed by 2050 across all scenarios. As explained by Fuhrman et al.[24], extensive DOCCS deployment is more suited to regions with a large projected demand for desalinated water.

Conventional CDR makes a substantial contribution to reducing net emissions, particularly in the near term. However, the contribution of conventional CDR vary in their growth and scale depending on the volume of removals from novel CDR. By 2030, the volume of A/R doubles compared to 2020 across all scenarios. In the DELAYED scenario, pursuing sustainable land-use strategies by halting deforestation and expanding afforestation/reforestation practices becomes more prominent. When all CDR methods are delayed until mid-century, land-use removals account for about 5% of residual emissions in the net-zero year. In comparison, land-use removals contribute only 1.3–2% in the other scenarios, with the lowest share observed in the D-EARLY scenario. This suggests that delaying the deployment of novel CDR methods in the US substantially increases reliance on land-based carbon sinks, potentially leading to increased pressure on ecosystems, and reduced land availability for other critical functions such as food production and biodiversity conservation.

The annual average CO_2 removal from A/R between 2020 and the net-zero year in the DELAYED scenario is 0.27 $GtCO_2$, about 5.7% of current US CO_2 emissions. This average CO_2 removal capacity from land use between 2020 and 2050, when the full suite of CDR is delayed until mid-century, is approximately 15%, 30%, and 32% larger than in the D-EARLY, CO-EARLY, and B-EARLY scenarios, respectively.

Fossil CCS sequestration in the US grows rapidly in the D-EARLY scenario, averaging 0.53 $GtCO_2$/yr between 2020 and 2050, which is 21%, 21.3%, and 9.2% higher than in the B-EARLY, CO-EARLY, and DELAYED scenarios, respectively. This is because retrofitting fossil plants with CCS provides a less stringent alternative to cutting emissions compared to the complete phase-out or shutdown of fossil infrastructure. As discussed in the previous section, reliance on DACCS reduces the pressure for more aggressive, economy-wide mitigation measures, thereby supporting the continued use deployment of CCS as an alternative solution.

Marginal abatement cost of carbon

Table 1 provides a summary of the Marginal Abatement Cost of Carbon (MACC) for various scenarios in the US aimed at achieving the 2050 net-zero GHG target within a global 1.5 °C target. The MACC represents the cost of reducing the last unit of emissions to attain a specific climate target.

In all scenarios, the MACC rises sharply as 2050 approaches, reflecting the increasing challenge of reaching the net-zero target. The CO-EARLY scenario shows the lowest carbon price, while the late deployment of all CDR forces stricter policy on emission reduction, as indicated by the highest carbon price. By 2050, carbon prices in the D-EARLY, B-EARLY, CO-EARLY, and DELAYED are \$281/tCO_2, \$ 293/tCO_2, \$ 285/tCO_2, and

$ 303/tCO_2, respectively. Carbon prices increase sharply between 2040 and 2045, mostly notably in the DELAYED scenario. This highlights the increasing difficulty of meeting the net-zero target as mid-century approaches, especially when CDR deployment is delayed. In the DELAYED scenario, the carbon price rises by 58.4% by 2045 compared to 2040. In the B-EARLY and CO-EARLY scenarios, these increases are 41.1% and 12.7% respectively. This indicates that delaying CDR deployment until mid-century comes at a very high economic cost, with an average price of $ 370/tCO_2 between 2025 and 2050, representing an increase of 59%-79% than other scenarios to achieve the climate target.

Land use

Figure 7 illustrates the land allocation across the scenarios. There is competition for land use between biomass and Biochar, which is exacerbated when BECCS is deployed in the near term. The cropland allocated for biochar will decrease by 92% in 2050 when BECCS is deployed by 2025, compared to when both CDR methods are delayed until 2050. In the B-EARLY scenario, 2,500 km^2/yr is allocated to biochar compared to 31,000 km^2/yr in the D-EARLY scenario.

Table 1 | Optimal carbon prices under various scenarios (in 2015 US$/t$CO_2$)

	2025	2030	2035	2040	2045	2050
D-EARLY	71.4	140.7	236.2	332.6	320.6	281.1
B-EARLY	70.1	132.4	187.4	264.3	448.9	293.9
CO-EARLY	70.1	132.4	187.4	261.3	299.5	285.3
DELAYED	71.4	140.7	236.9	431.4	1036.0	303.5

The DELAYED scenario shows the largest allocation for biochar, at 40,300 km^2/yr. This result aligns with Bergero et al.[44], where biochar scales up substantially when there is less competition from BECCS (which is reflected in our work by the earlier deployment of BECCS). Across all scenarios, ~2.2–2.3 Mkm^2/yr. is allocated to negative emissions through forests. The early DACCS scenario leaves more land available for crop cultivation than other scenarios due to less competition for biomass cultivation. Between 2025 and 2050, 34% more land is allocated to growing biomass feedstocks in the B-EARLY scenario than in the D-EARLY scenario.

Stranded asset in the electricity sector

Delaying CDR deployment till mid-century increases the stringency of economy-wide emission reductions in the near term, which in turn accelerates the phase-out of fossil fuels in the electricity sector. In this situation of rapid and disruptive phase-out of fossils, there is a higher risk of premature retirement of fossil power plants leading to huge economic loss. Delaying CDR leads to 19–41% larger cumulative retirement of fossil power plants between 2016 and 2050 in the US. In terms of financial loss incurred by these stranded assets between 2015 and 2050, the US would lose an additional 128–220 billion US dollars when CDR is delayed till mid-century, compared to the gradual scale-up of novel CDR methods in the near term (More in Supplementary Discussion).

Discussion

The role of CDR in achieving net-zero and end-of-century climate goals is becoming more prominent in IAM research and climate discussions. However, there is still a limited understanding of the trade-offs involved in the timing and scaling of these technologies to the climate-relevant levels. Although the regional focus of this work is on the US, the analysis has broad

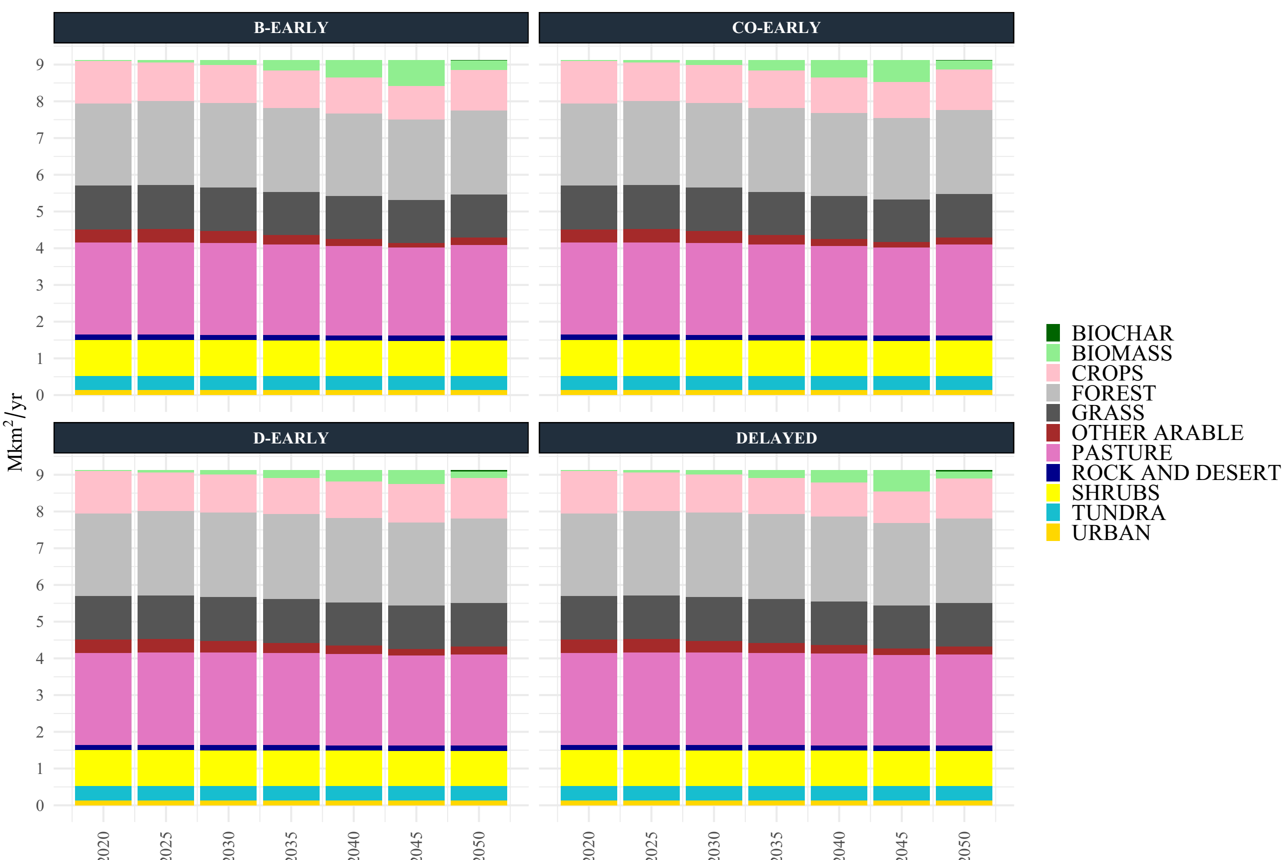


Fig. 7 | Land-use allocation. Total land area used for diverse activities. While land use can change and existing land may be repurposed, the total land area remains constant at 9.124 Mkm^2 across all scenarios and times. "BIOCHAR" refers to bioenergy crops and food/non-food cropland allocated with biochar. "CROP" denotes food and non-food cropland without biochar allocation. "BIOENERGY CROP" specifically refers to bioenergy cropland without biochar allocation.

Table 2 | Summary of results

Indicator	Scenarios			
	D-EARLY	B-EARLY	CO-EARLY	Delayed
Positive GHG emissions/negative CO_2 emissions				
Positive CO_2 emissions ($MtCO_2$/yr)	22,557	22,113	22,727	20,476
Positive non-CO_2 emissions ($MtCO_{2e}$/yr)	7765.80	7762.90	7824.30	7519.50
Gross CDR ($MtCO_2$)	1668.96	1625.9	1846.37	885.4
Primary energy				
Fossil fuels (EJ)	401.96	379.98	397.99	349.72
Biomass (EJ)	111.83	66.49	74.14	117.39
Renewable (EJ)	73.08	69.14	68.90	75.46
Nuclear (EJ)	42.99	38.44	37.96	47.76
Final energy				
Electricity and hydrogen (EJ)	160.38	157.12	156.71	163.09
Carbon-based Fuel (EJ)	340.73	319.04	330.50	307.74
Land Use				
[a]Land allocation for energy and negative emissions (thouskm^2)	1939.54	1939.54	1804.54	1539.78
[b]Stranded assets				
Premature retirement of fossil power plants (GW)	278.60	289.6	244.10	345.00
Cost of retiring fossil power plants (2023 USD billion)	847.00	813.60	754.80	974.70

Implications of different CDR deployment timing in the US pathway to net-zero GHG emissions by 2050. Results are reported in cumulative values from 2020 to 2050 in 5-year intervals.
[a]The land allocation is for forest, bioenergy crops (with and without biochar allocation), and food/non-food croplands with biochar allocation.
[b]Estimated as annual cumulative between 2015 and 2050. Fossil plants include unabated and CCS of coal, oil, and gas sources.

global implications. Several studies have highlighted that based on equitable burden sharing principles of responsibility and capability, the US will bear a substantial share of the global cumulative CDR burden by 2100. Consequently, it is important to consider how these findings can influence and guide international climate policy. As the US adopts ambitious CDR strategies, it can serve as a model for other nations, particularly those with similar economic capacities and environmental responsibilities. This leadership could encourage a more unified and effective global approach to achieving the Paris Agreement goals and mitigating climate change impacts worldwide.

A summary of the results is shown in Table 2. Our work shows that DACCS contributes substantially to CO_2 removal and achieving the net-zero goal in the US. However, this can only be accomplished by developing robust CO_2 transport and sequestration infrastructure coupled with effective regulatory and planning mechanisms. The complexity of overcoming these barriers highlights the importance of early CDR investments to reduce the risk of falling short on future gigatonne-scale CDR targets. A challenge with focusing solely on DACCS early in the century while delaying the deployment of other CDR technologies is the substantial energy demand for its operation, which can only be met in the near term by fossil fuels due to the less cost-competitiveness of renewable energy. We also find that this option relaxes mitigation stringency.

Our result shows that co-deployment of DACCS and BECCS methods in the near-term is a more effective CDR strategy than focusing only on DACCS for driving stronger mitigation. Biochar and EW remove substantial amounts of CO_2 from the atmosphere when deployed by mid-century. It is, therefore, encouraging that current global CDR efforts include a substantial share of grants and research and development for biochar[16]. Delaying all CDR efforts until mid-century would force rapid fuel switching across sectors. While this pathway results in the lowest residual emissions, it also incurs the highest economic costs. It also drives a rapid and disruptive pace of decarbonization rather than a gradual transition, posing major challenges with technology scale-up towards 2050. An argument against focusing on near-term CDR deployment is the risk of deterring mitigation efforts. A key policy recommendation to drive CDR growth in the near term without causing ‘moral hazard’ is to decouple emission reduction from CDR targets, allowing for separate and specific incentives for CDR technologies. Policies should, therefore, aim to eliminate barriers to emissions reductions and make decarbonized alternatives economically viable. A critical component of national policies should be to integrate CDR targets into countries’ national climate goals alongside strengthening monitoring, reporting, and verification (MRV) systems for CDR.

Methods and scenarios

Scenarios

We used a modified version of the Global Change Assessment Model (GCAM-NEU) to model a global 1.5 °C temperature target by 2100. Emissions reduction pathways for the US and the rest of the world (ROW) are placed in two separate markets (Fig. S3). In this stylized setup, GHG emissions in both markets peak by 2025 and then decline linearly to reach net zero by 2050.

Fuhrman et al.[24] updated the CDR portfolio in GCAM to include a comprehensive suite that captures the dynamics of the global climate-energy-land-water nexus. In this study, the delayed deployment of DOCCS, EW, and biochar was modeled to begin by mid-century across all scenarios. This accounts for the time needed for research, development, and scaling to achieve operational effectiveness and economic viability, which are necessary for contributing to the 2050 net-zero emissions goal. The deployment of either BECCS, DACCS, or a combination of both reflects their present current incentivization in the US[45–47]. The primary focus of CDR initiatives in the US is on BECCS and DACCS[31]. This allows for immediate action on carbon removal while the more nascent technologies like DOCCS, EW, and biochar progress toward market readiness and cost-effectiveness. Additionally, it provides a practical framework to evaluate the effectiveness and integration of different CDR approaches within existing energy and industrial systems, aiding informed policy decisions and strategic planning towards the net-zero objective.

We also included a scenario to reflect limited optimism or lack of industrial breakthroughs in the near term, where no CDR is deployed until 2050, while non-CDR mitigation actions continue. All scenarios were developed under the socioeconomic pathway (SSP) 2.

GCAM dynamics of energy, economics, land and water

GCAM models the interaction between human activities and environmental systems. It integrates data from energy, agriculture, land use, water, and the economy to project future trends and impacts. GCAM evaluates how different policies and technologies influence these sectors by simulating various scenarios. It balances demand and supply by considering factors like energy consumption, resource availability, and economic growth.

For energy, GCAM models depletable resources such as oil, natural gas, coal, and uranium using graded supply curves. Technological advancements can reduce future extraction costs. GCAM's renewable resources include onshore and offshore wind, solar, geothermal, hydropower, and biomass, with some regions also having "traditional biomass" resources. Unlike depletable resources, which track cumulative stocks, renewable resources are measured in annual flows. Wind and solar can generate electricity or hydrogen, while geothermal and hydropower are used only for electricity production. The equilibrium between historical energy demand and supply is based on the IEA World Energy Balances. The costs associated with each technology include input expenses, specific technology costs, and GHG valuation. Costs are quantified as:

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

Where C is the total technology cost, t is the externally determined capital and operation & maintenance (O&M) expenses of the technology, i is the cost of input j (such as coal or fuel), g_k is the GHG valuation of gas k, and v_l is the valuation of secondary output l. This v_l term accounts for any economic value derived from secondary outputs, which can reduce the overall cost of the technology. These are essentially credits or revenues that offset some of the costs, such as the value of electricity generated as a by-product or the value of heat recovered and sold. The n represents the number of input types (j) contributing to the cost, m represents the number of GHG (k) for which a GHG value is applied, and o represents the number of secondary outputs (l) produced by the technology.

The socioeconomic component of GCAM determines economic activity and related demands for simulations. It uses population and per capita GDP growth assumptions for 32 regions to calculate GDP. These assumptions drive various demands in the model. Information on population and economic activity is passed to other GCAM components without feedback. For instance, the model's GDP output is unaffected by energy prices, quantities, or services provided to the economy. Regional GDP is calculated using:

$$GDP_{r,t+1} = POP_{r,t+1} * LF_{r,t+1} * \left(1 + GRO_{r,t+1}\right)^{tStep} \left(\frac{GDP_{r,t}}{POP_{r,t} LF_{r,t}}\right) * \left(\frac{P_{r,t+1}}{P_{r,t}}\right)^{\infty} \tag{2}$$

Where r is the region, t is the period, and $tStep$ is the number of years in the time step. $GDP_{r,t}$ is the gross domestic product, $P_{r,t}$ is the population, $LF_{r,t}$ is the labor force participation and $GRO_{r,t}$ is the labor productivity growth rate, all for region r in period t. The last term is the energy-price feedback, where $P_{r,t}$ is the price of energy services and ∞ represents the feedback elasticity (i.e., the percentage change in GDP due to a percentage change in energy prices).

Decisions in GCAM about land use are made using a model that compares the profitability of different options. Each land use in a region has a potential profit, and land is allocated based on which option is projected to be the most profitable. This means land is shared among different uses according to which is expected to yield the highest profit. The profit rate for all agricultural production technologies is calculated as follows:

$$\begin{aligned} profitRate = & 10^9 * (price + subsidy - \mathrm{var}Cost - inputCosts + secondaryValue) \\ & * yield + impliedSubsidy \end{aligned} \tag{3}$$

where *price* is the commodity price, *subsidy* is any externally specified subsidy, var*Cost* is the non-land variable cost, *inputCosts* are the costs of inputs like fertilizer and water, *yield* is the yield for the technology and *impliedSubsidy* is an implicit subsidy calculated during calibration periods to ensure profits exceed a specified threshold.

GCAM models three types of freshwater: renewable water, non-renewable groundwater, and desalinated water. Renewable water comes from natural sources such as surface runoff and underground infiltration. Non-renewable groundwater includes ancient fossil water or groundwater that's depleted faster than it's replenished. Both renewable and non-renewable sources are tracked separately to meet each basin. Desalinated water is also available as an additional source for various water needs within each basin.

An extensive description of the entire GCAM framework can be retrieved from https://jgcri.github.io/gcam-doc/v5.4/toc.html.

CDR model dynamics in GCAM

The scenarios developed in this work assess and quantify the implication of CDR deployment timing. The CDR capacity deployed in each model year is constrained by technological learning, resource availability (energy, land, water), competition for market share, and sustainability criteria. The parametrization of CDR technologies is detailed in the Supplementary document. The parameterization of DACCS approaches follows Fuhrman et al.[28]. DACCS requires both energy and non-energy inputs. The energy inputs include natural gas (for heat) or electricity, while the non-energy inputs include capital and maintenance costs, which are aggregated into the levelized non-energy cost term. DACCS indirectly competes in GCAM against emission abatement and other CDR options based on its cost and the subsidy provided for CO_2 removal (carbon price). DACCS is deployed only when the carbon price exceeds the levelized cost. It also serves as a backstop technology, meaning it is deployed only when other emission reduction pathways become more expensive, thereby lowering the mitigation or marginal cost to stay on track for a climate target[33]. DACCS also places an upper limit on carbon prices; therefore, at extremely high carbon prices, DACCS becomes economically feasible, acting as a ceiling for the cost of carbon removal[35]. This ensures that if carbon reduction costs in other sectors exceed a certain threshold, DACCS provides a cost-effective alternative to mitigate emissions, thus playing a key role in controlling the overall cost of achieving net-zero targets.

GCAM incorporates several BECCS technologies that are utilized in various energy system components, primarily in the electricity and refining industries. GCAM also includes BECCS in hydrogen production and industrial sectors. GCAM endogenously resolves the resources used for bioenergy supply, such as land, water, and fertilizers. This is performed across 384 land-use regions, which consist of 32 geopolitical regions and 235 water basins.

The treatment of BECCS includes biomass collection, distribution, and palettization costs[24]. The modeling of EW and DOCCS is based on the work of Fuhrman et al.[24]. GCAM-EW uses basalt due to its lower environmental risk compared to other forms of EW. The work of Beerling et al.[43] is used to retrieve the annual potential of EW across different countries and regions. The region-specific potential from the work of Beerling[43] was used to linearly scale the fully aggregated global EW supply curve. DOCCS technology within GCAM can be stand-alone or a co-product of seawater desalination. DOCCS is parametrized based on Digdaya et al.[48]. The modeling of biochar is based on Bergero et al.[44]. Biochar production in GCAM is modeled to be from the lignocellulosic biomass feedstocks, with syngas as the output. Generally, biochar is administered to a particular land area only once. Approximately 70% of the carbon contained within biochar remains within the soil for several centuries.

An application rate of 20 tonnes per hectare is used for croplands, but this is not immediately applied to the proportion of land that GCAM deems economically viable for biochar in the long term; rather, it is applied gradually and equitably throughout the model horizon. The factors influencing yield improvement from biochar include the availability of irrigation and the climate of water basins. Biochar competes with BECCS for biomass feedstocks, and this is modeled endogenously in GCAM. More detailed technical and cost assumptions for CDR technologies are presented in the SI.

Estimating capital stock turnover

To quantify annual capacity additions, stranded assets, and capital investments within the electricity sector, we use the methodology developed by Ou et al.[49], as follows. GCAM monitors power plant capital stock, technology type, and age over each technology's operational lifespan. Power plants may retire in two ways: (1) through natural retirement upon reaching the end of their physical lifespan, or (2) through profit-driven early retirement, where continued operation is less financially viable, leading to stranded assets. Calculations for capacity and capital stock turnover in the electric power sector were conducted with the *Plutus* package in R[50], following a 3-step process. First, each country's scenario output is used to determine electricity generation by technology and vintage. In the second step, the natural retirement fraction for each technology's vintage is estimated for newly added fleets. By comparing our scenario's electricity generation output with the expected natural retirement pathway from step 2, we estimate premature retirements and stranded assets. Finally, we calculate stranded assets by multiplying the capital cost of each technology by the extent of premature retirement.

Data availability

All modeling data for this study are available in a public repository accessible at https://doi.org/10.5281/zenodo.13931692.

Code availability

GCAM is an open-source community model available at https://github.com/JGCRI/gcam-core/releases. The version of GCAM and additional input files associated with this study are available at https://doi.org/10.5281/zenodo.13931692.

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Author contributions

H.A. and J.D.A. conceived and designed the research. H.A. developed the scenarios, conducted the modeling, and wrote the first draft of the paper. H.A. and J.D.A. contributed to the modeling tools. H.A. and J.D.A. co-led parts of the assessment and contributed to data analysis. Y.H., I.S., and H.G. supervised the research. H.A., J.D.A., O.B., Y.H., I.S., and H.G. contributed to the writing of the article.

Competing interests

The authors declare no competing interests.

Additional information

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