

Indirect electrification enables the 2°C goal without reliance on carbon dioxide removal

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Abstract

Achieving the Paris Agreement's 2°C goal has generally been considered to require carbon dioxide removal (CDR); however, large-scale CDR deployment faces technical and societal challenges. Strategies to reduce reliance on CDR have mainly focused on lower energy demand and direct electrification. However, it remains unclear whether the 2°C goal can be achieved by maximizing indirect electrification without reliance on CDR. Here, we used an energy system model to assess the feasibility of such pathways. Indirect electrification is a potential enabler, but rapidly expanding renewables and electrolyzers, as well as widespread electrification and hydrogen use on the demand side, present substantial technical challenges. Furthermore, constraining CDR increases total mitigation costs by approximately 20% over the twenty-first century. These results indicate that CDR is not necessarily indispensable to achieving the 2°C goal, provided that the technical challenges of scaling up indirect electrification across the energy system can be addressed.

Introduction

To achieve the Paris Agreement's temperature goals of limiting global warming to 1.5°C and 2°C, the deployment of carbon dioxide removal (CDR) has been widely regarded as necessary¹. CDR encompasses a range of technologies that remove CO₂ from the atmosphere and permanently sequester it in geological, terrestrial, or ocean reservoirs, thereby delivering negative emissions. The role of CDR can be broadly categorized into three functions². First, as an additional mitigation option that complements conventional emission reduction efforts, CDR moderates the pace of the rapid transformation of energy systems required in the first half of this century, thereby contributing to reductions in net emissions. Second, CDR can offset emissions from sectors where emission reductions are difficult to achieve (hereafter referred to as residual emissions), supporting the attainment of mitigation targets such as net-zero emissions. Third, following an exceedance of the target temperature level (overshoot), CDR can remove amounts of CO₂ that exceed residual emissions, resulting in net-negative emissions and enabling global temperatures to be reduced. Representative CDR options include bioenergy with carbon capture and storage (BECCS), direct air capture combined with carbon capture and storage (DACCS), afforestation and reforestation, enhanced weathering (EW), and biochar. While the deployment of CDR has been shown to reduce mitigation costs^{3,4}, it is also associated with substantial trade-offs, resource constraints, and social risks^{5–10}. For example, carbon capture and storage (CCS) are met with challenges related to social acceptance, including safety concerns among local communities, while land-based CDR options, including BECCS, raise sustainability concerns such as biodiversity conservation and food security due to competition over land use. Additionally, the deployment of CDR to date has been slower than previously anticipated¹¹, and future national deployment plans remain far below the levels assumed in decarbonization scenarios consistent with temperature targets¹².

Against the backdrop of these challenges, previous studies have suggested that measures such as reducing energy demand, accelerating electrification, and mitigating non-CO₂ greenhouse gas (GHG) emissions can contribute to lower reliance on CDR^{11,13–16}. In particular, the Low Energy Demand (LD) scenario achieves the 1.5°C and 2°C goals without deploying CCS-related CDR¹³, but assumes mitigation-enabling conditions, namely substantial reductions in energy demand, that facilitate mitigation compared with cases without emissions constraints. Another study demonstrates that some models yield solutions consistent with the 2°C goal when

the use of CDR is constrained across multiple models, without relying on such mitigation-enabling conditions¹⁷. Nevertheless, the factors determining whether the 2°C goal can be achieved when the use of CDR is completely restricted remain unclear, and evidence on the concrete measures required under such conditions is still limited.

In recent years, the costs of renewable energy technologies, including solar photovoltaics, wind power, and battery storage, have declined substantially¹⁸. Alongside these developments, mitigation strategies have increasingly highlighted the effectiveness of indirect electrification, i.e., using green hydrogen and green hydrogen-derived synthetic fuels, in addition to direct electrification based on the use of electricity in end-use sectors^{19–24}. Indirect electrification contributes to decarbonizing sectors that are difficult to electrify directly, such as aviation, shipping, and industry^{25,26}, and can thereby reduce reliance on CDR²⁷. However, energy system models that explicitly represent options for fully substituting fossil fuels in final energy demand through indirect electrification technologies, such as synthetic fuels, remain limited.

The IPCC AR6 indicates that pathways limiting warming to 2°C (with greater than 67% likelihood) or 1.5°C (greater than 50% likelihood) generally require some amount of CDR to offset residual GHG emissions¹. For the 1.5°C goal, the cumulative CO₂ emissions allowable until the end of this century are highly constrained. Approximately 1.5°C of warming has already been observed relative to pre-industrial levels²⁸, rendering the deployment of CDR effectively unavoidable^{14,17,29–31}. In contrast, for the 2°C goal, the possibility remains that the goal could be achieved without deploying CDR, particularly when indirect electrification (especially the use of synthetic fuels) is assumed; however, this possibility has not yet been sufficiently explored.

Here we examine whether CDR is indispensable for achieving the 2°C goal when accounting for indirect electrification and assess the feasibility of meeting the goal under constraints on CDR use. To address this question, we use a global energy system model to develop a mitigation scenario without CDR (CDRoff) and compare it with a Default scenario based on the model's standard settings without additional constraints or parameter modifications. The model employed a high temporal resolution in electricity demand and supply, enabling appropriate representation of indirect electrification, which allowed us to infer implications under climate mitigation constraints^{20,32,33}. We quantified multiple long-term global scenarios by differentiating the assumption of CDR availability. For comparison with CDRoff, we used C3 scenarios from the AR6 scenario database that were consistent with the 2°C goal³⁴. We additionally tested 13 scenarios by varying a wide range of assumptions, including fundamental socioeconomic drivers such as population and GDP, as well as technological assumptions, to identify the robustness and uncertainty of our main findings (Supplementary Note 2). We also assessed the scenarios by using the existing feasibility assessment method^{35,36} to clarify the potential challenges (Table 2).

For clarity, this study focused on CO₂ emissions from fossil fuel combustion and industrial processes (CO₂-FFI). Emission pathways consistent with the 2°C goal were defined to satisfy the following conditions. First, cumulative CO₂-FFI until the end of this century, when combined with CO₂ emissions from the land-use sector, fell within the range of cumulative CO₂ emissions associated with 2°C-consistent scenarios (C3) in AR6. Second, CO₂ emissions from the land-use sector were based on an extension of current policies, without assuming additional mitigation measures. Third, nationally determined contributions (NDCs) were followed up to 2030. Fourth, net emissions were not allowed to become negative over the course of the century.

In this study, CDR was defined as activities that remove CO₂ from the atmosphere and store it over long timescales³⁷. Accordingly, the capture of CO₂-FFI, rather than atmospheric CO₂, in combination with CCS or carbon capture and utilization (CCU), was treated as distinct from CDR (Supplementary Fig. 1). The CDR options considered in this study were limited to those directly linked to the energy system, namely BECCS, DACCS, and EW. Although EW is also related to the land system, it requires substantial energy inputs for rock comminution, raising concerns about its impacts on the energy system³⁸. In light of this consideration, EW was treated as part of the energy system in this study.

Results

Emission pathways without CDR

Compared with the Default scenario, enhanced emissions reductions across sectors enabled a 2°C-consistent pathway without reliance on CDR (Figs. 1a, b). In 2030, CO₂-FFI reached 33.5 Gt-CO₂/yr in both the CDRoff and Default scenarios. For reference, the median estimate of fossil fuel-related CO₂ emissions under unconditional NDCs is 31 Gt-CO₂ (range: 27–37 Gt-CO₂), indicating that the exogenously specified emissions pathway remained broadly consistent with NDC levels through 2030. In CDRoff, residual CO₂-FFI emissions amounted to 0.8 Gt-CO₂/yr in 2060. In contrast, in the Default scenario, EW was introduced around 2045, followed by BECCS after 2060, leading to CO₂ removal of 6.5 Gt-CO₂/yr by 2100, while DACCS was not deployed.

Restricting CDR increased mitigation requirements in the industry and transportation sectors (Fig. 1c). In the CDRoff scenario, both sectors had to achieve nearly complete ($\approx 100\%$) emissions reductions relative to 2020 levels after 2040, whereas in the Default scenario, reductions peaked at 62% in industry and 72% in transportation. In contrast, emissions in the buildings, energy supply, and industrial process sectors declined by 97–99%, 97–98%, and 88% by 2060 (relative to 2020), respectively, and subsequently stabilized, with only minor differences between scenarios.

Role of indirect electrification in final energy demand

In the CDRoff scenario, demand for hydrogen and hydrogen-based energy carriers increased in the industry and transportation sectors (Figs. 2a, b). Compared with the Default scenario, total demand for these energy carriers increased by 65.4 EJ in 2060. As a result, hydrogen and hydrogen-based energy carriers accounted for more than 25% of the final energy demand in the industry and transportation sectors in 2060 under CDRoff. In the industry sector, hydrogen is primarily used for hydrogen-based steel production and high-temperature heat, whereas in the transportation sector, hydrogen and hydrogen-based energy carriers are used in fuel cell vehicles and as fuels for shipping and aviation (Supplementary Fig. 3).

Biofuel consumption remained stable throughout the century and was consistently slightly higher in the CDRoff than in the Default scenario (by up to approximately 20 EJ/yr) (Figs. 2a, b). In the transportation sector, biofuels accounted for up to 19% of the final energy demand and, like synthetic fuels, were used as low-carbon liquid fuels in aviation (Supplementary Fig. 3).

In contrast, the effects of restricting CDR on direct electrification and energy efficiency improvements were limited (Figs. 2a, b). In addition to fuel decarbonization, major demand-side mitigation measures included reductions in energy demand through energy efficiency improvements and electrification³⁰. However, there was little difference between scenarios in total final energy demand or sectoral electrification rates. In the transportation sector, the electrification rate exceeded 62% by 2060, surpassing the 90th percentile of AR6 C3 scenarios. In the buildings sector, electrification reached 45% by 2030 and 88% by 2060 regardless of CDR deployment, indicating rapid electrification that remained within the range of AR6 C3 scenarios.

Energy supply and CO capture, storage, and utilization

In the CDRoff scenario, a greater expansion of renewable electricity generation capacity and electrolyzers was required than in previously presented mitigation pathways consistent with the 2°C goal (Figs. 3a, b and Supplementary Fig. 4). Electricity generation in CDRoff reached 453 EJ/yr in 2060 and 642 EJ/yr in 2100, exceeding the 90th percentile of the AR6 C3 scenarios in both years. In addition, hydrogen production reached 102 EJ/yr in 2060, likewise surpassing the 90th percentile of AR6 C3 scenarios. Compared with the Default scenario, electricity generation in CDRoff was approximately 130 EJ/yr higher in 2100. This additional electricity was primarily allocated to hydrogen production and conversion to synthetic fuels. By 2100, approximately 30% of total electricity generation in CDRoff was used for hydrogen production, and about 36% of the produced hydrogen was further converted into synthetic fuels, resulting in a supply of 30 EJ per year of synthetic fuels (Fig. 3c and Supplementary Fig. 5).

Under both scenarios, fossil fuel supply declined after 2020; however, limiting CDR leads to an additional reduction of up to 120 EJ in fossil fuel supply in the latter half of the century (Fig. 3d). In 2100, the fossil fuel supply in the CDRoff scenario amounted to 39 EJ/yr, approximately 100 EJ/yr lower than in the Default scenario. In addition, the fossil fuel trade was roughly halved after mid-century in CDRoff compared with the Default scenario (Supplementary Fig. 6). Biomass supply was higher in CDRoff than in the Default scenario after 2040, with the inter-scenario difference reaching up to 60 EJ (Fig. 3e). However, after 2060, biomass supply declined in both scenarios, reaching 127 EJ/yr in 2100 under CDRoff.

Regarding CO₂ capture and storage, both were lower in the CDRoff scenario than in the Default scenario (Fig. 3f). In the latter half of the century, CO₂ capture was up to 1.5 Gt-CO₂/yr lower and CO₂ storage up to 3.4 Gt-CO₂/yr lower in CDRoff than in the Default scenario. Nevertheless, both scenarios share the characteristic that CO₂ capture and storage begin in the first half of the century and increase toward 2100. In particular, under CDRoff, all CO₂ from fossil fuel use is directed to geological storage, whereas CO₂ captured from the atmosphere via bioenergy with carbon capture (BEC) and direct air capture (DAC) is entirely utilized for synthetic fuel production. Therefore, even under constraints on CDR deployment, continued development, diffusion, and scaling-up of CO₂ capture and storage technologies remain indispensable.

Mitigation cost

Mitigation costs increase when the use of CDR is restricted (Figs. 4a–c). Over the entire century, total energy system costs became 1.2 times higher, and total energy investment increased by up to 1.5 times. In particular,

the investment in electricity and hydrogen supply expanded substantially, increasing to approximately 1.5 and 4.6 times, respectively, due to the expansion of these supply systems. Investment costs in the transportation sector reached 1.4 trillion US\$/yr in the CDRoff scenario. However, the difference between CDRoff and the Default scenario was 140 billion US\$/yr, indicating that achieving the 2°C goal imposed a substantial economic burden on the transportation sector regardless of the reliance on CDR. In CDRoff, the carbon price increased sharply between 2050 and 2060, reaching 720.3 US\$/t-CO₂ in 2060. This level was more than twice that in Default. The surge in the carbon price likely reflected the higher mitigation costs associated with the promotion of direct and indirect electrification in the transportation and industry sectors. Nevertheless, the carbon price in CDRoff remains within the 10–90th percentile range of AR6 C3 scenarios throughout the century.

Feasibility assessment

The feasibility assessment identified challenges across technological, geophysical, economic, and socio-cultural dimensions (Figs. 5). Under both scenarios, with and without CDR, the geophysical feasibility of supplying renewable electricity was assessed as low difficulty (Figs. 5o, p). In contrast, technological feasibility, particularly the expansion of wind and solar power, were assessed as high and medium difficulty, respectively (Figs. 5a, b). Additionally, the economic feasibility associated with stranded assets from the phase-down of coal-fired power generation was assessed as high difficulty, especially in the first half of the century (Fig. 5v). In the CDRoff scenario, the expansion of electrolyzers for hydrogen production was also assessed as high difficulty in terms of technological feasibility by mid-century (Fig. 5m). Given the currently limited scale of green hydrogen production³⁹, substantial deployment and diffusion of the technology are required in the first half of the century. The expansion of DAC as a CO₂ capture technology was assessed as low difficulty in terms of technological feasibility (Fig. 5n). This reflects its relatively limited deployment scale and the comparatively small impact of its associated electricity consumption on the overall energy system.

On the demand side, increasing the share of electricity in the buildings and transportation sectors was evaluated as highly difficult in terms of technological feasibility (Fig. 5h, j). Compared with the Default scenario, increasing the share of hydrogen in the transportation and industry sectors was also assessed as more challenging. In the transportation sector, there was a pronounced shift from internal combustion engine vehicles to battery electric vehicles and fuel cell vehicles in road transportation (Supplementary Fig. 7). In the industry sector, the expansion of hydrogen use was driven not only by high-temperature heat demand but also by the introduction of hydrogen-based steelmaking (Fig. 5g). The increase in the share of biofuels in the transportation sector was evaluated as high difficulty in terms of technological feasibility (Fig. 5k). However, given that the existing supply infrastructure and end-use technologies can continue to be utilized, and that the geophysical feasibility on the supply side remains at a medium level of difficulty, the concerns arising from technological constraints were considered relatively limited (Fig. 5q).

Increases in energy investment and carbon prices were evaluated as high difficulty in terms of economic feasibility both with and without CDR, and the difficulty increased further when reliance on CDR was restricted (Figs. 5s-u). Across socio-cultural feasibility dimensions, the overall concerns were assessed as low (Figs. 5w-z).

Discussion

This study developed the CDRoff scenario, which followed a 2°C-consistent emissions pathway without reliance on CDR. The results indicated that the 2°C goal could potentially be achieved even in the absence of CDR through the promotion of indirect electrification. These findings suggest that, if the technological challenges on both the energy supply and demand sides required to enable indirect electrification were successfully addressed, the deployment of CDR may not be indispensable for achieving the 2°C goal. However, while the scenario yields a model-based feasible solution, this does not necessarily translate into real-world attainment of the 2°C goal. The feasibility assessment identified several challenges that must be addressed to realize this scenario in practice.

Clearly, the CDRoff scenario presents both advantages and disadvantages, and a comprehensive evaluation is necessary, taking into account energy supply and demand, the availability and scalability of low-carbon technologies, system costs, and multiple dimensions of feasibility. Accordingly, to substantiate this, we synthesized the key characteristics of CDRoff and the challenges associated with its implementation from these perspectives. The main features of CDRoff are summarized in Table 1.

Table 1

Characteristics of the CDRoff scenario relative to the Default scenario. Regarding the role of CDR (3), both Default and CDRoff imposed emission pathways without overshoot, so no difference arises; therefore, it is shown in parentheses.

Role of CDR	CDRoff relative to Default	Key Features
	(1) Mitigation complement to the energy transition: irreplaceable, with higher reduction requirements	Increase in the share of biofuel
	(2) Residual emissions: cannot offset → additional reductions needed	Promotion of indirect electrification
	((3) Recovery from overshoot: no difference with Default)	(Overshoot avoided via pathway adjustment)
Concerns with CDR introduction	(1) Bioenergy supply: increase from mid-century	still effective as low-carbon energy even if CDR is limited
	(2) CO ₂ storage: decrease	storage and capture needed regardless of CDR
	(3) CO ₂ capture: decrease	
Energy System	(1) Renewable capacity (solar, wind): increase	Increase in generation required if CDR is limited.
	(2) Hydrogen production (electrolyzers): increase	Infrastructure expansion also needed
	(3) Energy demand-side transformation: large	System transition scale increases
Mitigation costs	Energy system cost: increase 1.2×; Energy investment: increase up to 1.5×	Investments in the transportation, power generation, and hydrogen supply sectors are substantial.

In the CDRoff scenario, emission reductions in the first half of the century were primarily achieved through an expansion of the bioenergy share, while in the second half of the century, the need for CDR was substantially

reduced by lowering residual emissions themselves through the acceleration of indirect electrification. Furthermore, rather than relying on net-negative emissions after a temperature overshoot, the emissions pathway was adjusted to avoid an overshoot, thereby structurally limiting dependence on CDR. As a result, cumulative residual emissions by the end of the century remained within a range consistent with the 2°C goal, suggesting that under specific conditions, achieving the 2°C goal without deploying CDR remains possible.

However, constraining the use of CDR required a much more ambitious transformation of the energy system from the first half to the middle of the century. The realization of the CDRoff scenario faced multiple technical barriers, including the large-scale deployment of renewable power generation and electrolyzers, which were both assessed as having high technical difficulty, as well as the associated infrastructure expansion in the near future. In addition, extensive capital stock turnover was required in the industrial and transportation sectors to enable electrification and hydrogen-based energy use⁴⁰. Moreover, limiting CDR necessitates the accelerated retirement of coal-fired power plants and internal combustion engine vehicles, which could increase economic burdens and broader social impacts^{41,42}.

Even if the technical challenges required to promote indirect electrification were resolved, additional system costs would remain unavoidable, and the tendency for economic burdens to increase under constrained CDR use would persist. From an economic perspective, this suggests that allowing the deployment of CDR remains an effective mitigation option. Furthermore, current national climate policies, including the existing NDCs, have been shown to be insufficient to achieve either the 1.5°C or 2°C targets⁴³. If policy strengthening is delayed, the deployment of CDR may become indispensable.

Some of the challenges that have been debated within the context of large-scale CDR deployment would not be fundamentally resolved by eliminating CDR. For example, an increase in the bioenergy supply was observed in the second half of the century, even when the amount of CDR is restricted. While the geophysical feasibility of this increase was assessed as medium difficulty, the feasibility assessment did not evaluate normative desirability, such as the sustainability considerations associated with food market and ecosystem conservation^{10,44}. Similarly, the application of CCS declined in the CDRoff scenario but remained necessary to some extent. In particular, CO₂ capture is indispensable for advancing indirect electrification, and achieving the Paris Agreement temperature goals requires continued technological development and market deployment, including applications beyond CDR.

While excessive reliance on CDR has been considered to risk delaying near-term emission reductions^{12,45}, restricting CDR deployment was expected to incentivize stronger mitigation efforts in the industry and transportation sectors. Additionally, a substantial reduction in fossil fuel demand would likely reduce international trade volumes and generate public health co-benefits through reduced air pollutant emissions⁴⁶. At the same time, fossil fuel-exporting countries and related industries may experience economic impacts⁴⁷, highlighting the need for careful policy deliberation that balances these competing interests with the urgency of climate mitigation.

Several caveats should be noted. First, cumulative CO₂ emissions through the end of the century were used as the metric for assessing consistency with the 2°C goal, assuming that non-CO₂ gases were reduced to levels compatible with this goal. The CO₂ emissions from the land-use sector were based on current policies, and no

additional mitigation in that sector was considered. As a result, the emissions constraint imposed on the energy system was relatively stringent. Accounting for additional land-use mitigation would likely relax the constraint on the energy system and improve the feasibility of the CDRoff scenario. Second, previous study indicated that limiting CDR can lead to differences across models in the likelihood of achieving climate goals¹⁷, highlighting the value of multi-model analyses. Finally, the study assumed that emission reductions were undertaken under a uniform marginal abatement cost across regions. Even if mitigation burdens were allocated across countries based on equity considerations^{48–50}, the overall difficulty of emissions reductions would likely remain similar, primarily affecting the distribution of economic burdens. Therefore, the main conclusions of this study would be unlikely to change substantially. It should also be noted that regional CO₂ emissions constraints were determined endogenously in this study, and recently announced national net-zero targets were not explicitly incorporated.

Methods

This study developed a scenario that restricted the use of CDR and, for comparison, a scenario that allowed the use of CDR. Using a global energy system model, we conducted scenario analysis at the global scale. As a 2°C-consistent constraint, we constructed a CO₂-FFI emissions pathway based on the cumulative emissions consistent with the 2°C category in the IPCC AR6 scenarios³⁴. The model simulation period spanned from 2005 to 2100.

AIM-Technology

The AIM-Technology model used in this study is a detailed global energy system model that explicitly represents energy technologies on both the demand and supply sides. Given the exogenous assumptions on service demand (derived from population and GDP), energy efficiency, capital costs, and operation and maintenance costs of various technologies, the model endogenously determines annual technology deployment and operation to minimize total energy system costs. It estimates sectoral emissions as well as the energy supply and demand balances.

On the supply side, the model includes electricity generation, hydrogen conversion, and energy extraction. On the demand side, it represents industry (steel, cement, and other industries), buildings (residential and commercial), and transportation (road, rail, shipping, and aviation). In the power sector, multiple primary energy sources including fossil fuels, renewables, and nuclear, are converted into electricity. To account for the variability of variable renewable energy (VRE) and integration measures, the model balances electricity supply and demand on an hourly basis. Technologies for system flexibility include batteries, seasonal storage, and hydrogen production via electrolysis. Hydrogen can be produced from fossil fuels, biomass, or electricity.

The energy potential and costs of bioenergy crops are based on estimates from AIM/PLUM. Carbon capture from large point sources is modeled for power generation, hydrogen production, oil refining, biofuel production, and the production of steel, cement, and other industrial processes. Captured CO₂ is assumed to be either stored (CCS) or utilized (CCU). In this study, carbon capture facilities were newly introduced for industrial process emissions other than cement. Industrial processes consisted of multiple emission sources with different CO₂ partial pressures, leading to differences in capture cost and energy requirements⁵¹. However,

identical parameter values were assumed for all non-cement industrial processes (Supplementary Table 1). The CO₂ capture rate was set at 95% for cement and 90% for other sectors. Operation and maintenance costs included the costs of liquid solvents and waste treatment⁵². Other parameters were assumed to be the same as those in the cement sector.

We introduced alternative DAC and EW options that were not originally represented in the model. DAC was modeled as two separate processes: CO₂ capture via DAC and geological storage via CCS. The original model represented liquid-solvent DAC (hereafter L-DAC). In this study, we introduced a solid-sorbent DAC (hereafter S-DAC). Two options were considered: (i) solid-sorbent DAC using natural gas, bioenergy, electricity, or hydrogen as a heat source (hereafter S1-DAC), and (ii) solid-sorbent DAC using heat pumps (hereafter S2-DAC). The energy consumption and cost parameters for DAC were based on literature values^{3,38} and are summarized in Supplementary Table 2. Because detailed technical information on solid-sorbent DAC is partly proprietary and technological development lags behind that of L-DAC⁵³, S-DAC is assumed to have a later availability date and a shorter lifetime than L-DAC. Captured CO₂ from DAC and fossil fuel use can be stored via CCS or utilized for synthetic fuel production.

It was assumed that EW involved the application of crushed rock exclusively to cropland. In the model, rock mining, transportation, crushing, and spreading are treated as a single process. The energy consumption and cost parameters for EW were based on literature values^{38,54} and are summarized in Supplementary Table 3. Previous studies focused on cropland in tropical and temperate climates as potential deployment regions^{4,38}. In contrast, in this study, it was assumed that all global cropland was located in temperate climates. Although carbon removal per unit of rock is higher in tropical climates than in temperate climates, we applied the carbon removal rate for temperate cropland. Therefore, EW deployment may be overestimated in cold-climate regions such as Russia and Canada and underestimated in tropical regions such as India and Thailand.

The cropland area in 2021 was aggregated into 31 regions. The upper bound of EW deployment was defined as the annual carbon removal achieved by applying a fixed amount of rock (15 kg-rock per m² of land) to all cropland (Supplementary Table 4). Carbon removal was assumed to occur only in the first year after application; removal in subsequent years was not considered. In addition, changes in soil and environmental conditions affecting carbon removal were not considered. The resulting global upper limit of EW deployment was 3.84 Gt-CO₂/yr, which was more conservative than the literature estimate of 4.95 Gt-CO₂/yr⁵⁵. The model included BECCS, DACCS, and EW as CDR options. All other technological assumptions and model formulations followed Oshiro & Fujimori (2022; 2024)^{32,33}.

Scenarios

To clarify the difficulty of achieving the 2°C goal with and without CDR, two scenarios were established: CDRoff, which restricted the use of CDR, and Default, which allowed CDR deployment as a comparison case. In CDRoff, the use of BECCS, DACCS, and EW was restricted. However, CCS from fossil fuel combustion and industrial process emissions was allowed. Additionally, CCU, in which captured CO₂ is converted into synthetic fuels, was permitted.

The emissions pathway used in this study was designed to limit global temperature increase to 2°C (hereafter referred to as the 2C scenario) and was based on four requirements. First, cumulative CO₂ emissions were used as the metric for evaluating the temperature goal. Second, for land-use CO₂ emissions, i.e., sources other than energy and industrial processes, we assumed a continuation of current policies and no additional introduction of land-based CDR. Third, for energy- and industrial process-related CO₂ emissions, the pathway up to 2030 followed the NDCs submitted by individual countries. Fourth, the emissions pathway was designed such that net emissions did not become negative by the end of the century.

For the first requirement, cumulative CO₂ emissions over 2020–2100 were used as the evaluation metric. As a benchmark, we adopted the 2°C-consistent cumulative emissions range reported for the AR6 C3 scenario category: 510–800–1140 Gt-CO₂ (5 – 50–95th percentiles). For non-CO₂ greenhouse gases, we assumed emission reductions consistent with the 2°C category in AR6 C3 scenarios.

For the second requirement, when calculating cumulative CO₂-FFI, it was necessary to account for emissions from other sectors, particularly land use. We referred to the AR6 C7 scenario for land-use CO₂ emissions. The C7 scenario limited warming to 4°C with greater than 50% probability and assumed no additional mitigation measures beyond current policies. In particular, it assumed that no additional climate-driven afforestation or soil carbon sequestration was introduced, while forest conservation and afforestation for ecosystem protection purposes continued. The average annual CO₂ removal from land use over the past decade (2013–2022) was estimated to be approximately 2.2 Gt-CO₂/yr³⁷. If this level continues until 2100, cumulative removal over 2020–2100 would amount to 176 Gt-CO₂. Linear interpolation of 5- or 10-year interval data from the C7 scenario yielded a cumulative CO₂ removal of 15.2–163–203 Gt-CO₂ (25–50–75th percentiles) over 2020–2100, which was consistent with the assumption that current removal levels continue. For land-use emissions in the C7 scenario, linear interpolation of 5- or 10-year data produced cumulative CO₂ emissions of 63–140–185 Gt-CO₂ (25–50–75th percentiles) over 2020–2100. In this study, we adopted the median value of 140 Gt-CO₂ as the cumulative land-use CO₂ emissions.

Based on these assumptions, we constructed a CO₂-FFI emissions pathway such that, when cumulative land-use emissions (140 Gt-CO₂) were added, total cumulative emissions fell within the AR6 C3 2°C-consistent range (510–1140 Gt-CO₂). As a result, total cumulative CO₂ emissions under the 2C scenario, including land use, amounted to 1,059 Gt-CO₂, which was consistent with the 2°C goal.

Supplementary Fig. 2 presents the CO₂-FFI emissions pathway, together with a boxplot of CO₂-FFI emissions in the AR6 C3 scenarios. The 2C scenario was designed to ensure that net emissions do not become negative in the second half of the century. Compared with the AR6 C3 scenarios, the emissions constraint in 2060 fell below the 10th percentile. Both CDRoff and Default adopted the same 2C emissions pathway. Additionally, a Baseline scenario without any emissions constraint was defined. Its socioeconomic conditions followed the middle-of-the-road Shared Socioeconomic Pathway, SSP2.

IPCC AR6 scenario data

For comparison with IPCC AR6 scenario data, we used the World v.1.1 AR6 dataset (AR6_Scenarios_Database_World_v1.1)³⁴, which was downloaded from the AR6 Scenario Explorer

(<https://data.ece.iiasa.ac.at/ar6/>). The C3 category was employed as the comparator, given that its climate scenarios aligned with ours by limiting peak warming to 2°C by this century with a 67% likelihood.

Feasibility Assessment

To assess the feasibility of the scenarios, we evaluated low-carbon energy deployment, technological requirements, mitigation costs, and related factors following the assessment frameworks of Brutschin et al., (2021)³⁵ and the IPCC (2023)³⁶. The evaluation framework consisted of 26 indicators grouped into four categories: technological, geophysical, economic, and socio-cultural dimensions. For each indicator, we defined a medium-concern threshold and a high-concern threshold. Based on these thresholds, feasibility was classified into three levels: low, medium, and high difficulty. Table 2 presents the evaluation categories, corresponding indicators, and their threshold values. The method used to calculate the indicators is described in the Supplementary Note 1.

Table 2
Feasibility Assessment Criteria

Category	Target Technology / Energy		Indicator	Medium-Concern Threshold	High-Concern Threshold	Reference
Technological	Power sector	Wind / Solar	10-year change in share of electricity generation	10pp	20pp	a
		Biomass / Biomass + CCS	10-year change in share of electricity generation	2pp	5pp	a
	Industry sector	Electricity / Biofuels / Hydrogen	10-year change in share of final energy by sector	10pp	15pp	a
	Buildings sector	Electricity / Biofuels	10-year change in share of final energy by sector	10pp	15pp	
	Transportation sector	Electricity / Biofuels / Hydrogen	10-year change in share of final energy by sector	10pp	15pp	
	Hydrogen production	Electrolytic hydrogen	10-year change in share of electricity consumption relative to total electricity generation	10pp	15pp	
	Carbon capture	DAC	10-year change in share of electricity consumption relative to total electricity generation	10pp	15pp	
Geophysical	Energy supply	Solar	Annual primary energy supply	1600 EJ/yr	50000 EJ/yr	a

Category	Target Technology / Energy		Indicator	Medium-Concern Threshold	High-Concern Threshold	Reference
		Wind	Annual secondary energy supply from wind	830 EJ/yr	2000 EJ/yr	a
		Bioenergy	Annual primary energy supply	100 EJ/yr	245 EJ/yr	a
	Geological storage		Cumulative CO ₂ storage	1290 Gt-CO ₂	1460 Gt-CO ₂	b
Economic	Energy investment		Relative to Baseline	1.2	1.5	a
	Carbon price (1)		Carbon price (5% discount rate)	60 US\$/t-CO ₂	120 US\$/t-CO ₂	a
	Carbon price (2)		10-year increase factor	—	×5	a
	Stranded assets	Coal-fired power	Share of existing capacity	20%	50%	a
Socio-cultural	Energy demand	Total / Industry / Buildings / Transportation	10-year reduction rate in energy demand	10%	20%	a

Declarations

Code availability

The source code used for figure production from the scenario data is provided in the GitHub repository (<https://github.com/shotaromo/AIMT-CDRoff>; <https://doi.org/10.5281/zenodo.20304562>). The source code of the AIM-Technology model is available at the GitHub repository (https://github.com/KUAtmos/AIMTechnology_core; <https://doi.org/10.5281/zenodo.8401421>)⁵⁶. Some input data used in the AIM-Technology model are derived from proprietary datasets and are not publicly available due to licensing restrictions. They are available from the corresponding author, subject to the terms and conditions of the data providers.

Competing Interests Statement

The authors declare no competing interests.

Author Contribution

H.E. and S.F. conceptualized the research. H.E. contributed to scenario design. All authors participated in the interpretation of the results. K.O. developed the model. H.E. conducted the analysis, created the figures, and wrote the first draft of the paper. H.E., S.M. and S.F. contributed to the final manuscript.

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Data Availability

The scenario data generated in this study have been deposited in the Zenodo repository (<https://doi.org/10.5281/zenodo.20304562>). Some input data used in the AIM-Technology model are derived from proprietary datasets and are not publicly available due to licensing restrictions. They are available from the corresponding author, subject to the terms and conditions of the data providers.

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Figures

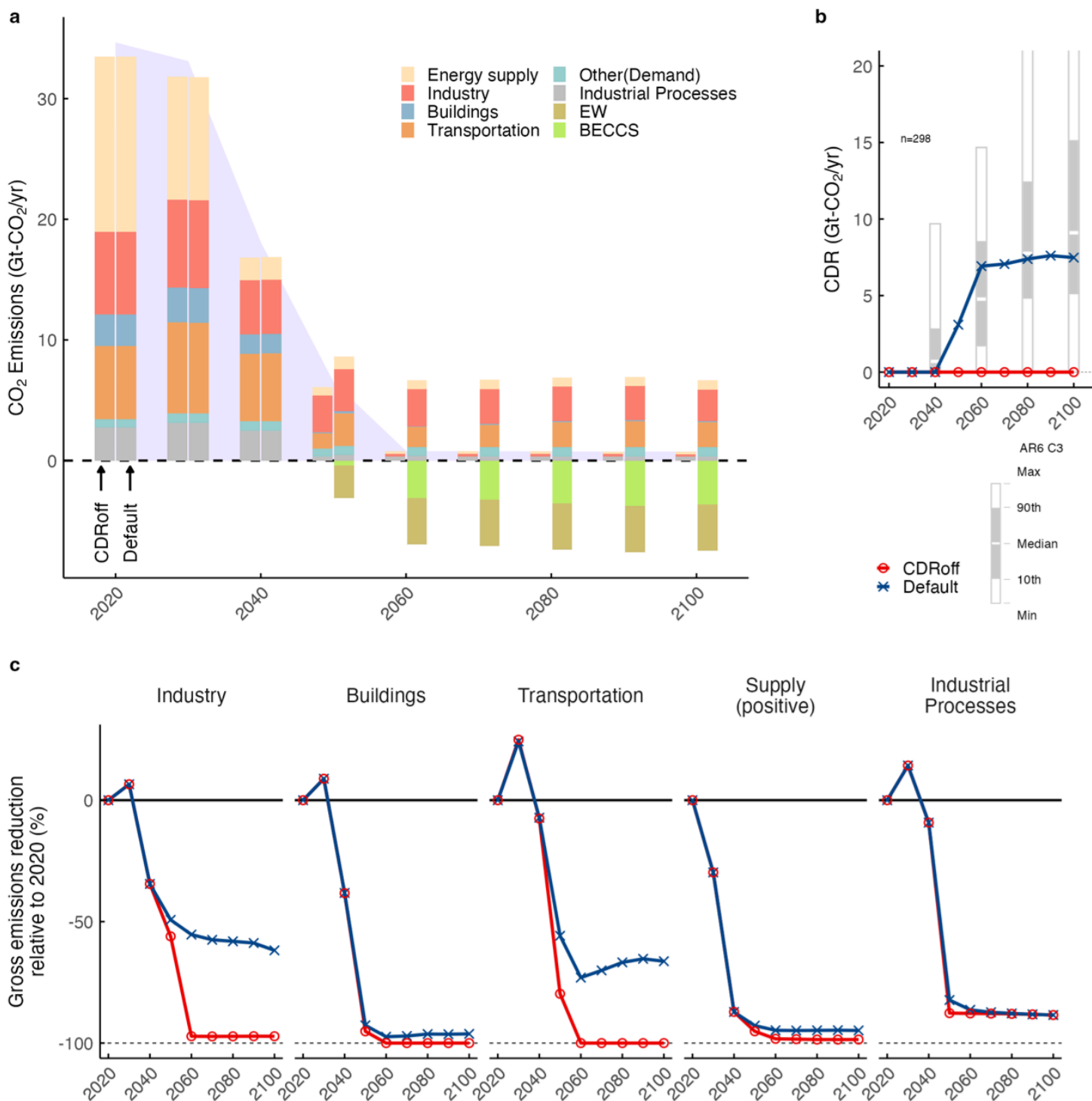


Figure 1

Sectoral emissions under the 2°C-consistent pathway without CDR. **a** Sectoral emissions. For each year, the left bar represents CDRoff and the right bar represents Default. The purple shading indicates net emissions.

b Amount of CDR. The box plots show AR6 C3 scenarios; "n" denotes the number of available scenarios. **c** Gross emissions reduction rates by sector relative to 2020 levels. Negative emissions from CDR are not included.

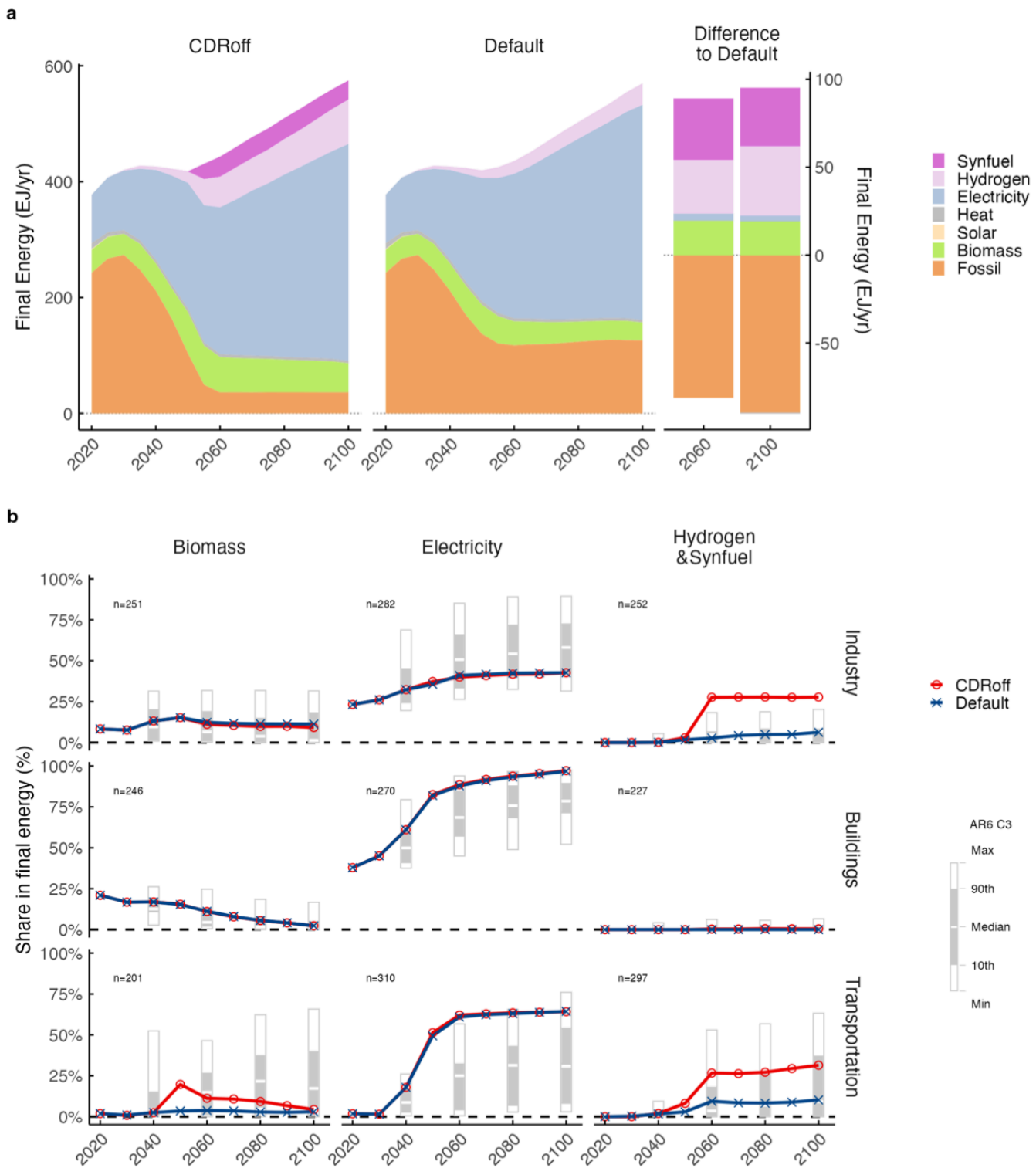


Figure 2

Low-carbon fuel pathways in final energy. **a** Final energy consumption in CDRoff and Default, including a breakdown of the differences between CDRoff and Default (2060, 2100). **b** Shares of bioenergy, electricity, hydrogen & synfuel by sector (industry, buildings, and transportation). Box plots represent AR6 C3 scenarios (2040, 2060, 2080, 2100). “Hydrogen & Synfuel” includes hydrogen-based energy carriers such as ammonia and

synthetic fuels in addition to hydrogen, but in the AR6 C3 scenario, only hydrogen is accounted for. “n” indicates the number of available scenarios.

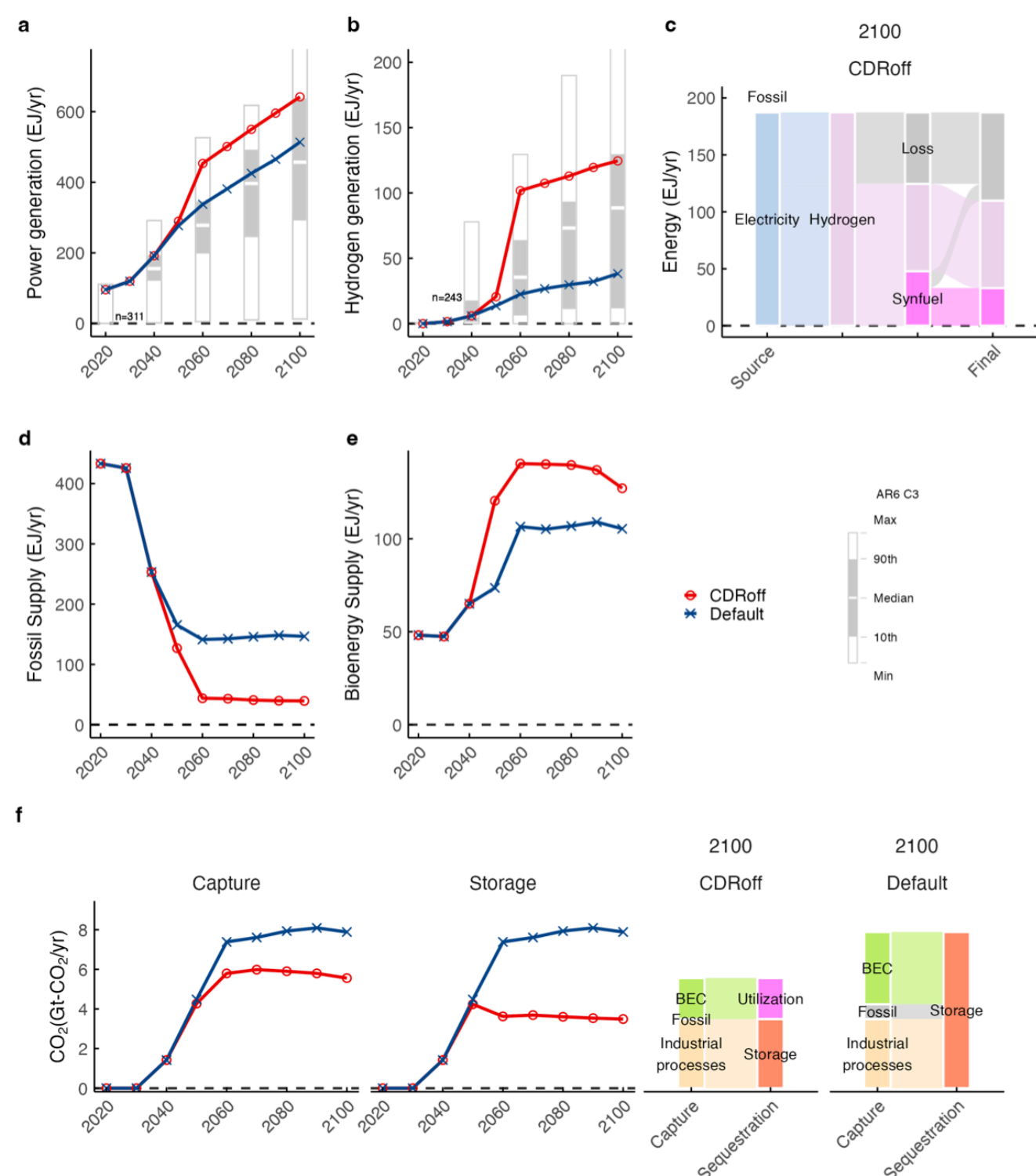


Figure 3

Energy supply and CO₂ capture, storage, and utilization flows. **a-b**, Electricity generation (**a**) and hydrogen production (**b**). Box plots show the AR6 C3 scenarios (2040, 2060, 2080, and 2100); “n” denotes the number of available scenarios. **c** Energy flows associated with hydrogen and synthetic fuel production (CDRoff, 2100). **d**

Fossil fuel supply. **e** Bioenergy supply. **f** The left-hand line graphs show CO₂ capture and geological storage, respectively, while the right-hand panel shows the flow of captured CO₂ (capture method—storage or utilization, 2100). Only CO₂ captured by engineered capture technologies is included; CO₂ removal via EW is excluded.

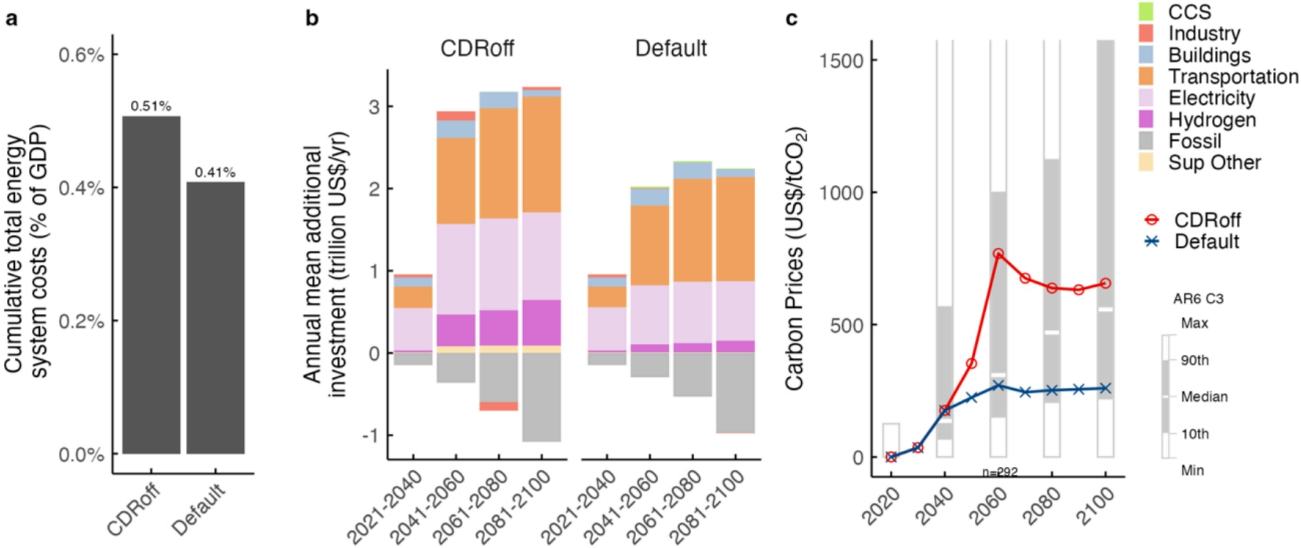


Figure 4

Cost implications. **a** Additional cumulative energy system costs over 2021–2100, expressed as a share of GDP. Values are discounted at a rate of 5%. **b** Average annual additional investment by sector (20-year intervals). “Sup Other” includes costs related to bioenergy and heat supply within the energy supply sector. Costs associated with DAC are included under “CCS”, and costs associated with BEC are included under “Sup Other”. Costs related to the industrial process sector are not included. **c** Carbon price. Box plots represent AR6 C3 scenarios, and “n” denotes the number of available scenarios.

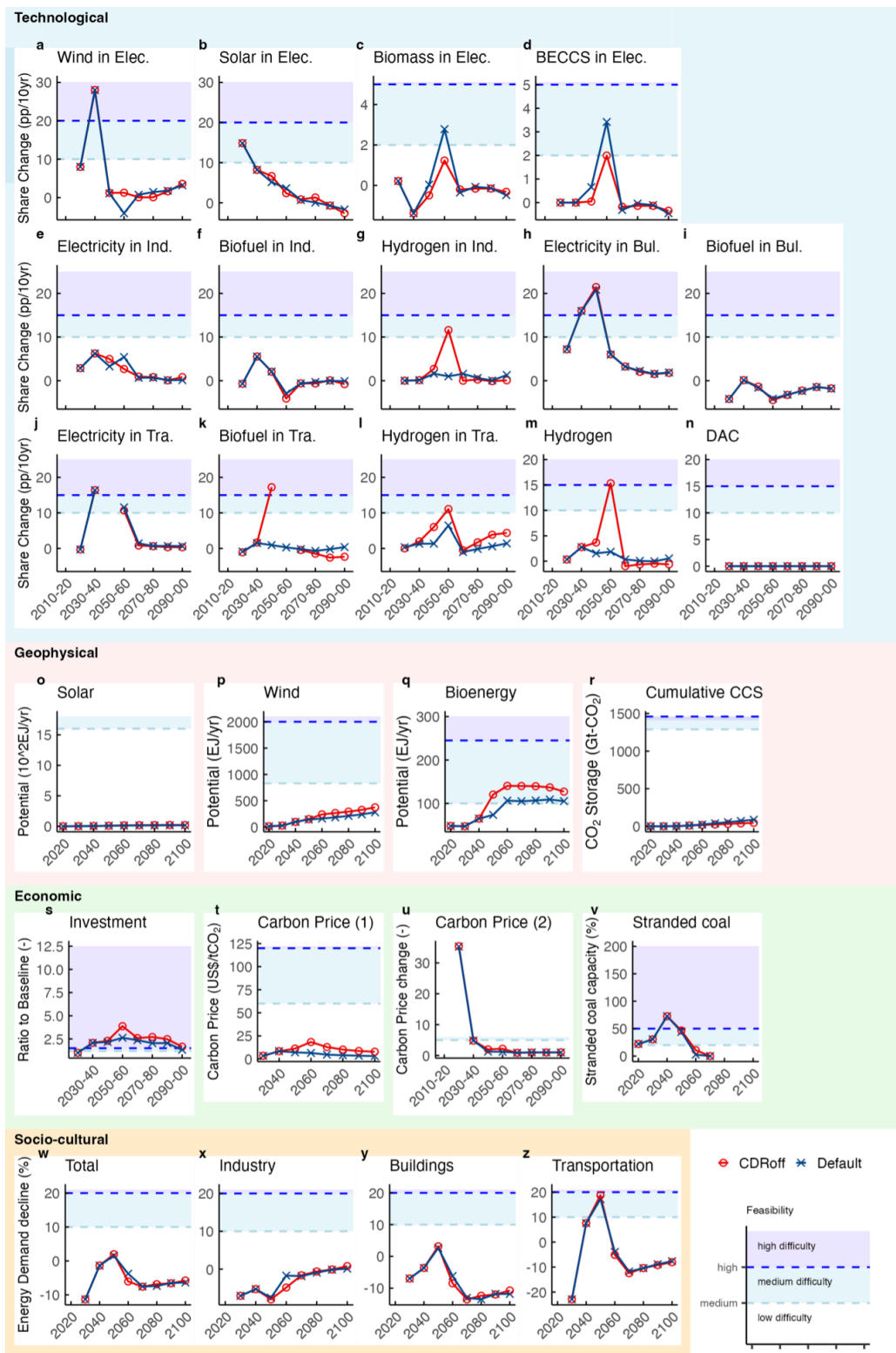


Figure 5

Feasibility assessment. The light blue dashed line indicates the medium-concern threshold, and the dark blue dashed line indicates the high-concern threshold. Light blue shading denotes medium difficulty, and purple shading denotes high difficulty. **a–n** Technological feasibility: wind power (**a**), solar PV (**b**), biomass power (**c**), and biomass power with CCS (**d**); industry sector: electricity (**e**), bioenergy (**f**), and hydrogen (**g**); buildings sector: electricity (**h**) and bioenergy (**i**); transportation sector: electricity (**j**), bioenergy (**k**), and hydrogen (**l**);

electricity required for hydrogen production via electrolysis relative to total power generation (**m**); electricity consumption for DAC (**n**). **o–r** Geophysical feasibility: solar PV (**o**), wind power (**p**), bioenergy (**q**), and cumulative CO₂ storage (**r**). **s–v** Economic feasibility: energy investment relative to the Baseline scenario (**s**), carbon price (**t, u**), and stranded assets from coal-fired power plants (**v**). **w–z** Socio-cultural feasibility: reductions in total final energy demand (**w**), and final energy demand in the industry (**x**), buildings (**y**), and transportation sector (**z**). The high-concern threshold for solar PV (**o**) is not shown.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [CDRoffsupplementaryv1.0.docx](#)