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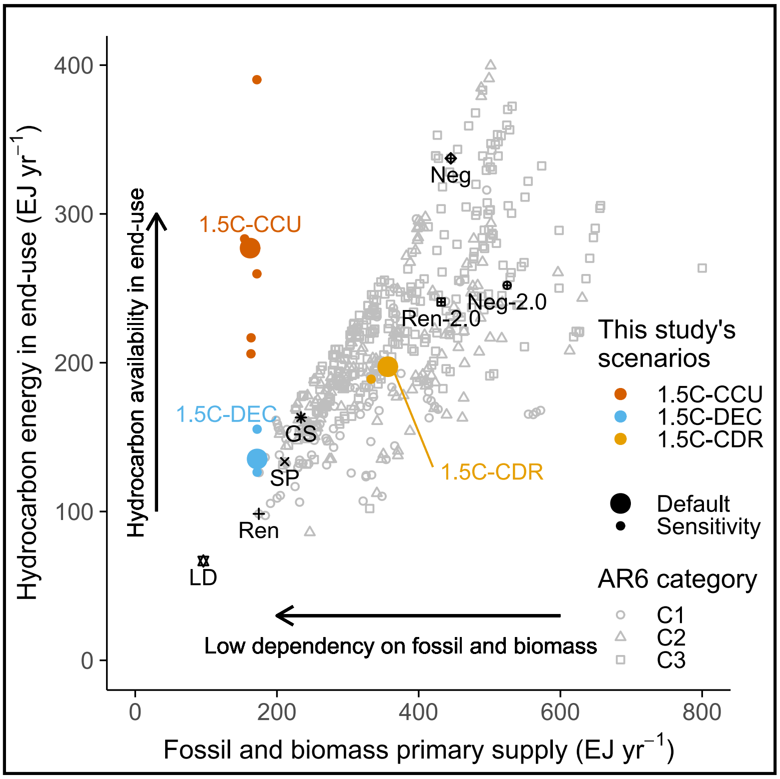
Alternative, but expensive, energy transition scenario featuring carbon capture and utilization can preserve existing energy demand technologies

Graphical abstract



Highlights

- The CCU-based scenario facilitates hydrocarbon availability in energy demand sector
- Non-biomass renewable supply upscales to 600 EJ by 2050 for hydrogen production
- CO_2 uptake from atmosphere through direct air capture reaches 10 Gt-CO_2 by 2050
- The CCU scenario almost doubles mitigation costs relative to other net-zero pathways

Authors

Ken Oshiro, Shinichiro Fujimori,
Tomoko Hasegawa,
Shinichiro Asayama, Hiroto Shiraki,
Kiyoshi Takahashi

Correspondence

ohshiro.ken.6e@kyoto-u.ac.jp

In brief

Existing 1.5°C scenarios generally pose challenges associated with rapid energy demand changes and carbon dioxide removal. It is thus essential to explore alternative scenarios that do not depend on these options. We developed an alternative net-zero emissions pathway depending on carbon capture and utilization. Despite reduced fossil fuel and bioenergy supplies, carbon-neutral synthetic fuel helps avoid rapid changes in energy demand sectors. This scenario involves challenges related to upscaling of non-biomass renewables and direct air capture and associated cost increases.

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Alternative, but expensive, energy transition scenario featuring carbon capture and utilization can preserve existing energy demand technologies

Ken Oshiro,[1,6,*] Shinichiro Fujimori,[1,2,3] Tomoko Hasegawa,[1,2,4] Shinichiro Asayama,[2] Hiroto Shiraki,[5] and Kiyoshi Takahashi[2]
[1]Department of Environmental Engineering, Kyoto University, C1-3, Kyotodaigaku-Katsura, Nishikyo-ku, Kyoto, Japan
[2]Social Systems Division, National Institute for Environmental Studies, Tsukuba, Japan
[3]International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
[4]College of Science and Engineering, Ritsumeikan University, Kusatsu, Japan
[5]Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan
[6]Lead contact
*Correspondence: ohshiro.ken.6e@kyoto-u.ac.jp
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SCIENCE FOR SOCIETY The Intergovernmental Panel on Climate Change summarized various mitigation pathways for accomplishing the net-zero emissions goal in its Sixth Assessment Report. Options include lowering energy demand, electrification, and carbon dioxide removal to offset residual emissions. Because these scenarios raise further challenges, such as food security concerns and stranded asset risks, there is a need to explore diverse net-zero emissions scenarios to inform global, national, and institutional mitigation strategies. We modeled an alternate scenario using carbon capture and utilization where carbon dioxide is captured from the atmosphere and used to make synthetic fuels that could replace fossil fuels. While this scenario has clear advantages in minimizing changes in energy demand sectors like transportation, it is more expensive than existing scenarios and relies on technology still under development.

SUMMARY

To reach net-zero carbon emissions, most climate change mitigation scenarios model a rapid transition from hydrocarbon-based energy to renewables, wide-scale electrification, and offsets to mitigate residual emissions. This requires phasing out existing hydrocarbon infrastructure and adjustments to electrification. Carbon capture and utilization (CCU) to produce synthetic fuels could be an alternative way to reach net zero while maintaining some existing energy infrastructure and minimizing the societal transition required, yet such scenarios remain unexamined. Here, we analyzed a CCU-based net-zero emissions scenario using a global energy system model. We find that synthetic fuel could meet 30% of energy demand by 2050, resulting in maintaining some existing technologies in energy demand sectors. Meanwhile, this scenario requires rapid upscaling of non-biomass renewables and direct air capture. The CCU-based scenario could be an alternative pathway; however, it involves multiple challenges related to technological feasibility and increased mitigation costs relative to net-zero scenarios using renewables, bioenergy, and carbon dioxide removal.

INTRODUCTION

Climate change mitigation scenarios in the context of the 1.5°C goal of the Paris Agreement require accelerated emissions reductions and generally depend on large-scale net-negative emissions in the second half of this century.[1] The Sixth Assessment Report (AR6)[2] of the Intergovernmental Panel on Climate Change (IPCC) presented a wide range of mitigation scenarios and corresponding future energy systems. To interpret these scenarios, illustrative mitigation pathways (IMPs) were described, which represent multiple pathways to achieve net-zero CO_2 emissions. These pathways are generally characterized by decarbonization of energy systems, reduction of energy demand,[3,4] promotion of renewable energy sources and electrification,[5] and the offsetting of residual emissions through carbon dioxide removal (CDR) processes (e.g., bioenergy carbon capture and storage [BECCS] and afforestation).[6,7] In addition to the IMPs, various unique low-emission pathways have recently been analyzed, such as CDR-oriented scenarios based on direct air CCS (DACCS)[8,9] and degrowth scenarios.[10]

However, the current mitigation scenarios would pose several challenges. Dependence on BECCS would direct adverse side effects onto other societal objectives, such as food security concerns raised by converting land used to grow food to growing biofuels.[11,12] Rapid energy systems changes could entail stranded asset risks on emission-intensive infrastructures, resulting in earlier retirement relative to their expected lifetime.[13–15] Moreover, rapid technological changes in the energy demand sectors required for reduced energy demand and electrification may involve technological and social feasibility concerns associated with changes in human lifestyles and behaviors.[16,17] Because each transformation pathway generally involves multiple risks, there is a need for exploration of a diverse portfolio of net-zero emissions pathways to facilitate the achievement of net-zero energy systems.

In this context, carbon capture and utilization (CCU) can be an alternative to the reduction of emissions associated with energy use and material feedstocks.[18–22] Synthetic hydrocarbon fuels (synfuels), which are synthesized from CO_2 and hydrogen, can provide carbon-neutral energy as long as both the CO_2 and hydrogen are derived from carbon-neutral sources (e.g., direct air capture [DAC] or biomass with carbon capture and solar or wind power). Though carbon contained in synfuels is eventually released into the atmosphere, in the case where carbon-neutral synfuels replace fossil fuel use in the energy sectors and decrease associated emissions, they contribute to reducing dependencies on CDR to accomplish net-zero emissions. In addition, because synfuels can be distributed and consumed in the form of liquids or gases, which have advantages in terms of energy density relative to other energy carriers, they could contribute to utilizing existing energy infrastructure and technology and to reducing stranded asset risks. In these regards, CCU-based synfuels could potentially be an alternative option of the existing net-zero emissions scenarios.

Although CCU-based synfuels are generally associated with higher production costs due to solar and wind power-based hydrogen production and carbon capture,[23] recent cost decreases in solar and wind power[24,25] and increasing expectations for the implementation of DAC[26,27] would facilitate large-scale CCU implementation. In these contexts, recent studies have indicated that carbon-neutral synfuels can serve as an alternative option to decarbonizing specific sectors, such as transport fuels for the aviation and navigation[28–30] and chemical industries,[22,31,32] without depending on biomass supply. Also, several studies have explored the potential applications of these carriers in specific regions using integrated assessment models.[33,34] Nevertheless, their economy-wide role and the challenges associated with achieving stringent mitigation goals, such as 1.5°C without overshoot, remain unclear.

Here, we assess alternative mitigation pathways that do not depend on rapid demand-side changes, bioenergy, and CDR. To this end, we performed what-if scenario analysis on CCU implementation in the global energy system and quantified associated energy system changes and their impact on mitigation costs. We found that the CCU-based scenario can be an alternative net-zero emissions pathway that does not depend on CDR, bioenergy, or rapid demand-side changes. Despite moderate technological changes in the energy demand sectors, the CCU-based scenario associates drastic changes in the energy supply for synfuel production, which include upscaling of non-biomass renewable energy supply, hydrogen production for synfuels supply, and DACC from atmosphere. It is highlighted that the CCU-based scenario poses economic challenges compared with the CDR- and electrification-based net-zero emission scenarios.

RESULTS

Methods summary

We used the AIM/Technology (Asia-Pacific Integrated Model/Technology)[35] model, which is a bottom-up global energy system model that accurately represents energy technologies in the energy demand and supply sectors. This model includes synthetic liquid fuels and synthetic methane production technologies such as CCU-based energy carriers, which can replace fossil fuel-based liquids and gases in energy demand sectors.

We analyzed three climate change mitigation scenarios to compare the roles and characteristics of CCU in residual emissions. First, as the central scenario in this study, a CCU-oriented scenario (1.5C-CCU) was designed that avoids rapid technological and lifestyle changes in energy demand sectors (e.g., moderate electrification). Furthermore, dependence on fossil fuels and bioenergy is reduced in a manner similar to the IMP-Ren scenario in AR6. Consequently, most of hydrocarbon energy is provided by alternative sources derived from atmospheric carbon, which is converted into synthetic fuels. This scenario has clear advantages in that it does not require drastic changes in energy demand structure and lifestyle; it uses current energy supply infrastructure without dependence on CDR. In contrast to 1.5C-CCU, the other two scenarios phase out hydrocarbons from energy systems (regardless of source) or use CDR implementation to offset residual emissions. The second scenario is 1.5C-DEC (decarbonization), which involves decarbonization of energy systems to reduce residual emissions; this scenario includes demand-side electrification and the upscaling of solar and wind power without dependence on large-scale CDR or bioenergy, and the underlying assumptions are similar to the IMP-Ren scenario in AR6. The third scenario, 1.5C-CDR, is characterized by extensive use of CDR options similar to the IMP-Neg scenario in AR6, whereby residual emissions from fossil fuel use persist.

The quantification of each scenario was implemented in the AIM/Technology model with multiple energy system conditions, in accordance with the underlying scenario. In the 1.5C-CCU scenario, considering the assumptions of low dependence on fossil fuels and bioenergy, constraints were imposed on CDR and CCS implementation, as well as bioenergy potential, because reliance on fossil fuels is generally determined by CDR availability.[36] Furthermore, based on moderate assumptions regarding technological changes in energy demand sectors, the diffusion of non-hydrocarbon-based technologies was limited, including the use of electricity- and hydrogen-based devices (see the experimental procedures for details). Across these three scenarios, the emission pathways were equivalent to the 1.5°C scenario without overshoot and to the C1 category in the

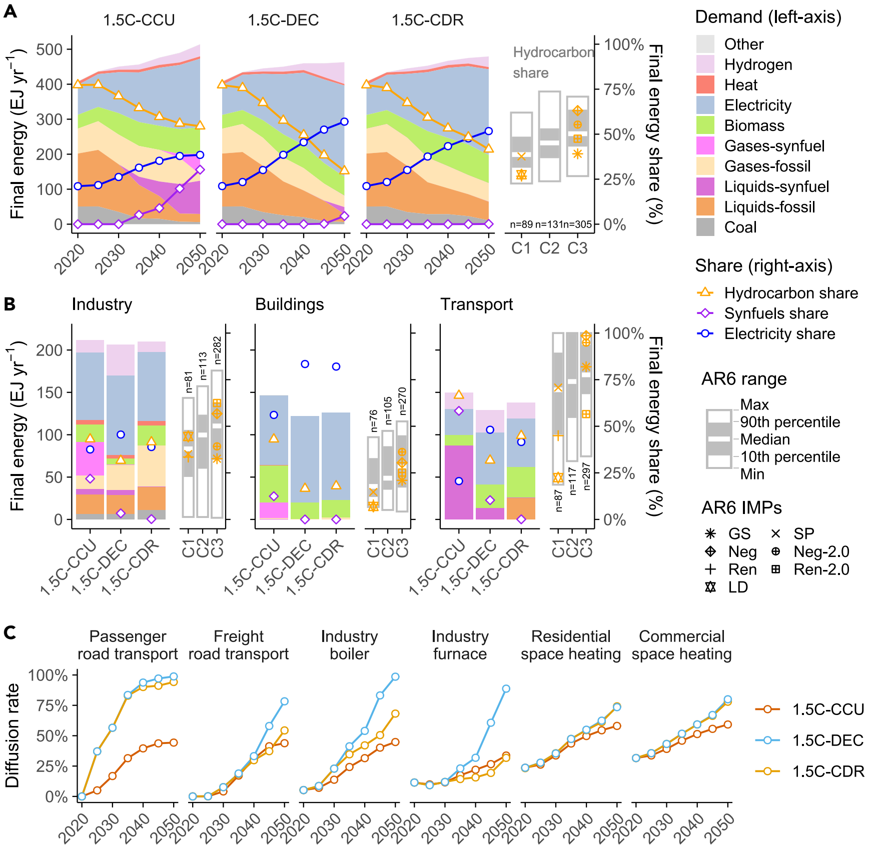

Figure 1. Energy systems and technological changes in energy demand sectors

(A) Final energy demand (left axis) and shares of electricity, synfuels, and hydrocarbon energy in total final energy demand (right axis). Hydrocarbon energy includes synfuels, as well as biomass and fossil fuels. Biomass includes both solid and liquid bioenergy. Boxplots illustrate the share of hydrocarbon energy in 2050 obtained from the IPCC AR6 Scenario Database[38] for each climate category and the illustrative mitigation pathways (GS, gradual strengthening; Neg, net negative; Ren, renewables; LD, low demand; SP, shifting global pathways). See also Figure S1 for the sensitivity scenario results.

(B) Sectoral final energy demand in 2050. Energy used for feedstock is included in the industry sector.

(C) Shares of non-hydrocarbon-based technologies, including electricity and hydrogen, in terms of technology stock capacity. See also Figure S2 for the sensitivity scenario results.

IPCC AR6,[2] whereby CO_2 emissions from energy sectors decreased to nearly net-zero status by 2050.[1,37] We also performed sensitivity scenario analyses, as summarized in Table S1. Details of the scenario settings are provided in the experimental procedures section.

Technological changes in energy demand sectors

In the 1.5C-CCU scenario, CCU-based energy carriers, including synthetic liquid fuels and methane, supply approximately 30% of global energy demand by 2050 compared with approximately 5% and nearly 0% in the 1.5C-DEC and 1.5C-CDR scenarios, respectively (Figure 1A; Table S2). By contrast, the electrification rate is approximately 38% in the 1.5C-CCU scenario as estimated by the energy system model with the technology constraints summarized in Table S1. This is a unique characteristic of the 1.5C-CCU scenario compared with the 1.5C-DEC and 1.5C-CDR scenarios, where electrification is approximately 50%. This unique trend is robust across all sensitivity scenarios of 1.5C-CCU, as the synfuel share in final energy reaches about 20% in the LimElec−− case (Figure S1). Because of the limited electrification level in the 1.5C-CCU scenario, the share of hydrocarbon energies, including fossil fuels, biomass, and synfuels, is 54% of the total final energy demand, whereas those shares in the 1.5C-DEC and 1.5C-CDR scenarios are only 29% and 41%, respectively. This unique trend is also present in the comparison with AR6 scenarios because hydrocarbon consumption in the 1.5C-CCU scenario is above the 90th percentile range of category C1 scenarios.

Figure 1B summarizes sectoral energy demand composition and the shares of electricity, synfuels, and hydrocarbon energies in 2050. Across all scenarios, the transport sector was the greatest consumer of synfuels, which replaced fossil fuel-based liquid fuels. In the 1.5C-CCU scenario, the share of synfuels reaches nearly 60% of total transport energy demand in 2050. In the industry and buildings sectors, CCU-based energy carriers are mainly supplied as gaseous synthetic methane in the 1.5C-CCU scenario, where they supply approximately 22% and 13% of sectoral energy demands, respectively. Figure 1C illustrates the diffusion rates of non-hydrocarbon-based technologies in terms of existing stock capacity. In all energy demand sectors, technological change is moderate in the 1.5C-CCU scenario, particularly relative to the 1.5C-DEC scenario, which requires drastic technological change to support rapid electrification. Similar trends are observed across the sensitivity scenarios of the 1.5C-CCU scenario, where the diffusion of non-hydrocarbon-based technologies is moderate relative to the 1.5C-DEC scenario (Figure S2).

Energy supply associated with synfuel production

Figure 2A shows a secondary energy flow diagram associated with synfuel production in 2050. In the 1.5C-CCU scenario, electricity generation increases to nearly 700 EJ per year by 2050 to meet the energy demand for synfuel production, as well as the energy demands for direct electrification and hydrogen production. Substantial energy losses occur between secondary and final energy conversion processes in the 1.5C-CCU scenario. The main factor that drives such losses is electrolysis in the synfuel production process, which requires approximately 40% of the generated electricity, along with other energy transformation losses, including transmission, storage losses, and curtailment (Figure S3). In the 1.5C-CCU

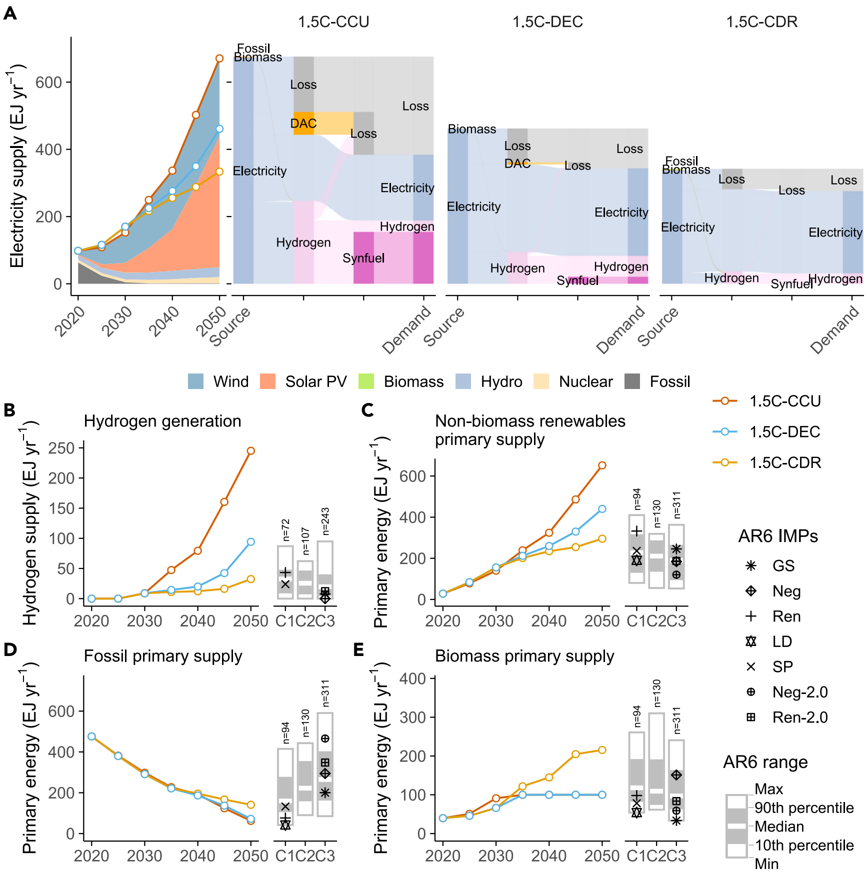

Figure 2. Energy system transformation in energy supply sectors

(A) Line plots on the left show total electricity supply in each scenario, with electricity generation sources in the 1.5C-CCU scenario shown as stacked areas. Right panels show secondary energy flow diagrams associated with electricity and synfuel production in 2050 under each scenario. Gray areas represent energy losses including conversion, storage, and distribution losses, curtailment, and electricity consumption for DAC. See also Figure S5 for the sensitivity scenario results.

(B and C) Hydrogen supply (B) and primary energy supply (C) of non-biomass renewables, including energy supply for both electricity and heat generation, along with comparisons with AR6 scenarios (GS, gradual strengthening; Neg, net negative; Ren, renewables; LD, low demand; SP, shifting global pathways). Left, line plots represent 1.5°C scenarios assessed in this study. Right, boxplots for 2050 based on the AR6 Scenario Database in each climate category. Hydrogen supply includes hydrogen used for synfuel production.

(D and E) Primary energy supply from fossil fuels and biomass. Right boxplots represent AR6 scenarios.

scenario, electricity consumption for DAC is approximately 10% of the total electricity generated; CO_2 capture via DAC reaches approximately 10 Gt-CO_2 per year by 2050, mainly because of CCU demands (Figure 4A).

Considering the requirement for low-carbon electricity, the 1.5C-CCU scenario poses multiple challenges to energy supply sectors despite moderate technological changes in energy demand sectors. First, the 1.5C-CCU scenario is characterized by large-scale hydrogen production, reaching approximately 250 EJ per year by 2050, which includes hydrogen for synfuel production and the direct use of hydrogen, as well as hydrogen in the form of ammonia (Figures 2B and S4). In contrast, hydrogen production reaches approximately 40 and 100 EJ per year by 2050 in the 1.5C-CDR and 1.5C-DEC scenarios, respectively; these values are similar to or greater than the range in the AR6 scenario. Second, the 1.5C-CCU scenario includes a massive non-biomass renewable energy supply that mainly depends on solar and wind, which exceeds 600 EJ per year by 2050 in the 1.5C-CCU scenario (Figures 2C and S5). By contrast, the 1.5C-CCU scenario shows lower dependence on both fossil fuels and bioenergy. The fossil fuel primary supply is reduced to approximately 60 EJ per year by 2050 in the 1.5C-CCU scenario as well as in the 1.5C-DEC scenario, equivalent to the lowest level in the AR6 scenario ranges (Figure 2D). Bioenergy supply is limited to 100 EJ per year in the 1.5C-CCU scenario (Figure 2E). Meanwhile, the 1.5C-CDR scenario is characterized by large-scale fossil fuel and bioenergy use, reaching about 140 and 210 EJ per year in 2050, respectively.

The 1.5C-CCU scenario is characterized by substantial availability of hydrocarbon energy for energy demand sectors, including fossil fuels, biomass, and synfuels, along with low dependence on fossil fuels. Conventional mitigation scenarios show a clear correlation of primary energy supply from fossil fuels and biomass with the consumption of hydrocarbon energy carriers (Figure 3). All AR6 scenarios, including IMPs, 1.5C-DEC, and 1.5C-CDR, show similar trends because hydrocarbon energy carriers are generally supplied by fossil fuels or biomass. In the 1.5C-CCU scenario, hydrocarbon energy usage in energy demand sectors reaches approximately 280 EJ per year, despite the reduction of fossil fuel and biomass primary energy supply to approximately 160 EJ by 2050, because DAC is a major carbon source for the energy system in this scenario.

Carbon sources and utilization in energy systems

The 1.5C-CCU scenario requires CO_2 capture from the atmosphere via DAC, reaching approximately 10 Gt-CO_2 per year by 2050; the 1.5C-DEC scenario requires approximately 1 Gt-CO_2, and the AR6 scenarios require <2 Gt-CO_2 (Figures 4A and S6). In contrast to the extensive reliance on DAC, the implementation of CDR and CCS is lower in the 1.5C-CCU scenario than in the 1.5C-DEC, 1.5C-CDR, and AR6 scenarios. CDR implementation is limited to 1 Gt-CO_2 per year in the 1.5C-CCU scenario, whereas it reaches 2.3 and 6.5 Gt-CO_2 per year by 2050 in the 1.5C-DEC and 1.5C-CDR scenarios, respectively (Figure 4B). CCS implementation, specifically stored carbon in geological storage, reaches approximately 3.4 Gt-CO_2 per year by 2050 in the 1.5C-CCU scenario even when CCS requirements for industrial process emissions are included (Figure 4C). This value is lower than the values in the 1.5C-DEC and 1.5C-CDR scenarios, as well as the values in most AR6 scenarios.

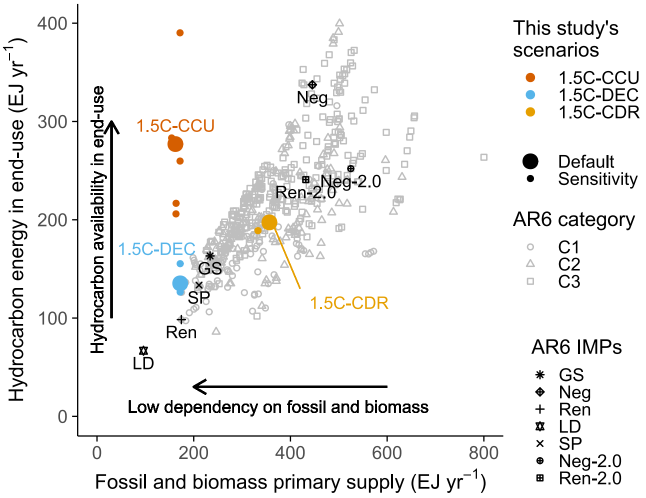

Figure 3. Comparison of fossil fuel and biomass primary energy supplies and the consumption of hydrocarbon energy carriers in energy demand sectors in 2050

Hydrocarbon energy carriers in energy demand sectors include solids, liquids, and gases obtained from fossil fuel, bioenergy, and synthetic hydrocarbons. The illustrative mitigation pathway (IMP) scenarios in AR6 are indicated by black dots, whereas other AR6 scenarios in the C1–C3 categories are indicated by gray dots (GS, gradual strengthening; Neg, net negative; Ren, renewables; LD, low demand; SP, shifting global pathways).

Figure 4D is a diagram of carbon flow in 2050 associated with energy systems; it includes DACCS, which is not always considered a part of the energy system. Although the main carbon source is fossil fuels in the near term (Figure S7), carbon flow in 2050 considerably varies among the three scenarios in this study. In the 1.5C-CDR scenario, carbon sources remain largely dependent on fossil fuels, with a nearly equal amount sequestered in underground storage to meet net-zero emissions for the energy sector. The 1.5C-DEC scenario shows the smallest carbon flows both from the atmosphere and fossil fuels, based on the underlying assumption of decarbonization. In contrast to these two scenarios, 1.5C-CCU uses carbon from the atmosphere, which is mostly converted into synfuels that eventually return the atmosphere. Consequently, the total carbon uptake of the energy system in 1.5C-CCU is almost 2-fold greater than the uptake in 1.5C-DEC even though its dependence on fossil fuel resources is smallest among the three scenarios.

Economic implications

Figure 5A compares cumulative additional energy system costs from 2021 to 2050. Under the 1.5C-CCU scenario, these costs constitute approximately 2.1% of the global gross domestic product (GDP); this value is almost 2-fold greater than the costs in the 1.5C-DEC and 1.5C-CDR scenarios (1.3% and 1.2%, respectively). The 1.5C-CCU scenario involves higher carbon prices relative to the other scenarios, exceeding 1,000 \$USD t-CO_2^{-1} in 2050; the 1.5C-DEC and 1.5C-CDR scenarios have carbon prices near 800 and 400 \$USD t-CO_2^{-1}, respectively (Figures 5B, S8A, and S8B). According to the sensitivity scenario analysis, the optimistic assumptions concerning key technology options (AdvTech) result in a reduction in the cumulative energy system costs and carbon price to approximately 1.6% of the GDP and 800 \$USD t-CO_2^{-1} in 2050 relative to the default 1.5C-CCU scenario. Nevertheless, the costs in the 1.5C-CCU-AdvTech scenario are still higher than those in the 1.5C-DEC-AdvTech and 1.5C-CDR-AdvTech scenarios because of decreases in the costs of solar and wind power in those scenarios. This comparison highlights the economic challenges of the CCU scenario compared with other mitigation options.

The increased mitigation cost in the 1.5C-CCU scenario is associated with the synfuel production cost. Although the average production cost of electricity gradually decreases to approximately 15 \$USD GJ^{-1} in 2050 because of decreases in renewable energy costs, the cost of synfuels is approximately 4-fold greater than the cost of electricity; it reaches approximately 60 \$USD GJ^{-1} by 2050 (Figure 5C). According to the synfuel cost composition shown in the right panel of Figure 5C, increases in synfuel costs are mainly driven by the hydrogen supply cost, which constitutes approximately two-thirds of synfuel costs because of the energy losses illustrated in Figure 2A. Even under the AdvTech assumption, the synfuel production cost exceeds 40 \$USD GJ^{-1} in 2050, as the hydrogen cost constitutes about 60% of the total cost of synfuel. Thus, synfuel is much more costly than the direct use of hydrogen and electricity, which accounts for about 20.8 and 12.2 \$USD GJ^{-1} in 2050, respectively.

The 1.5C-CCU scenario shows unique characteristics in terms of sectoral energy investment, although all scenarios decrease investments in other energy supplies, including fossil fuel extraction, relative to the no-policy scenario (Figure 5D). In the 1.5C-CCU scenario, investments in energy demand sectors in 2041–2050 are lower than in 1.5C-DEC because of moderate energy demand technological changes; however, total energy investment reaches approximately USD \$7 trillion per year because of the upscaling of electricity, hydrogen, and CO_2 capture via DAC. The regional investments illustrated in Figure S8C reveal similar trends among regions, although those trends are stronger in the OECD (Organization for Economic Co-operation and Development) and Asian regions under 1.5C-CCU than under other scenarios because of their high demand for synfuels (Figure S9).

DISCUSSION

We assessed three illustrative scenarios for achieving net-zero CO_2 emissions. In contrast to the 1.5C-DEC, 1.5C-CDR, and AR6 scenarios, where residual emissions are generally reduced through energy system decarbonization or CDR, the 1.5C-CCU scenario exhibits distinct characteristics (Table 1). Here, we discuss these characteristics in greater detail.

First, the CCU scenario makes hydrocarbon energy carriers available to energy demand sectors; this has the advantage of increasing energy density while lowering dependence on fossil fuels and bioenergy. Because most synfuels are derived from renewable-based hydrogen and carbon captured via DAC in this scenario, synfuels can be considered carbon-neutral hydrocarbons that reduce residual CO_2 emissions in the energy sector. This finding emphasizes the advantages of the CCU-based scenario, which could help to avoid drastic changes in demand-side technology, infrastructure, and lifestyle without dependence on CDR and bioenergy. The CCU scenario could reduce the lock-in and stranded asset risks of hydrocarbon-based energy

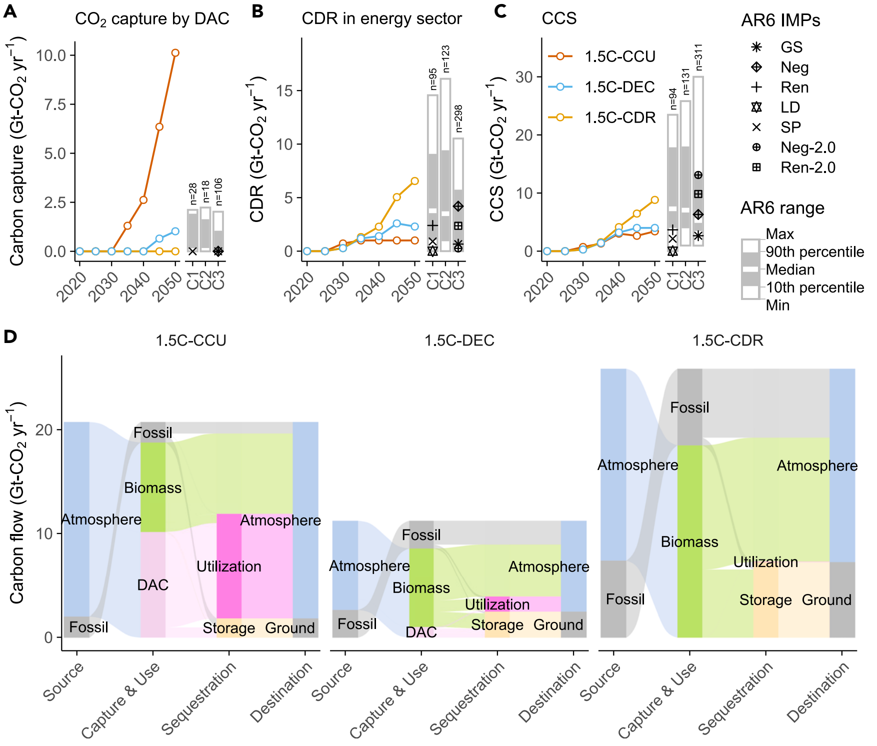

Figure 4. Carbon capture, utilization, and storage associated with energy sectors

(A) CO$_2$ capture through direct air capture (DAC). Boxplots illustrate those obtained from the IPCC AR6 Scenario Database[38] for each climate category and the IMPs (GS, gradual strengthening; Neg, net negative; Ren, renewables; LD, low demand; SP, shifting global pathways).

(B) Carbon dioxide removal (CDR) implementation in the energy sector in Gt of CO$_2$ stored, including bioenergy with carbon capture and storage (BECCS) and bioenergy with CCS (DACCS). Direct air carbon capture and utilization (DACCU) and bioenergy carbon capture and utilization (BECCU) are not considered in CDR because their carbon is eventually released into the atmosphere when synfuels are consumed in the energy sector.

(C) CCS implementation in the energy and industrial process sectors in Gt of CO$_2$ stored.

(D) Diagram of global carbon flow associated with energy systems in 2050. Left bar represents the source of carbon, namely fossil fuels and the atmosphere. Right bar represents the final destination of carbon. See also Figure S7 for the time series results.

demand technologies and infrastructure (e.g., internal combustion engine vehicles and natural gas pipelines[13–15]).

Second, despite moderate demand-side technological changes, the CCU scenario requires dramatic transformations in energy supply sectors, including the upscaling of hydrogen generation and non-biomass renewable energy supply mainly from solar and wind power; these transformations generally exceed the ranges of the AR6 scenarios. Moreover, the CCU scenario requires large-scale deployment of DAC, reaching approximately 10 Gt-CO$_2$ per year by 2050. While a recent study presented a scenario where DAC implementation reaches about 10 Gt-CO$_2$ per year by the end of this century with limited biomass supply,[39] the CCU scenario in this study still poses technical challenges associated with rapid upscales of such emerging technologies.

Third, the CCU scenario exhibits unique characteristics in terms of carbon flow associated with energy systems. The representative mitigation pathways in AR6 are generally characterized by decarbonization of energy systems through the reduction of energy demand or use of renewables (i.e., carbon usage itself is diminished). By contrast, the CCU scenario depends on hydrocarbon energy carriers in energy demand sectors, whereas its dependence on fossil fuels and bioenergy supplies is the smallest among the three scenarios. This characteristic may affect the commonly used concept of decarbonization because decarbonization is generally regarded as an emissions reduction approach almost equal to fossil fuel usage, whereas the energy system in our CCU scenario heavily relies on carbon that is released into the atmosphere.

Fourth, the CCU scenario involves increases in mitigation costs that almost double energy system costs relative to other scenarios, mainly because of additional investment in synfuel supply. Although technological development and cost decreases in key energy technologies (e.g., solar, wind, hydrogen, and synfuel production, as well as DAC) could contribute to the reduction of synfuel production costs, direct electrification is generally a more attractive option in terms of cost.

The CCU scenario has multiple implications for future climate policies and mitigation scenario assessments. First, the model results indicate that CCU-oriented scenarios are possible solely under specific conditions that include limited availability of demand-side electrification, CDR, and bioenergy under the cost-optimal conditions. This indicates that these mitigation options are economically attractive compared with CCU implementation. Thus, CCU may not hinder the technological development and policy supports needed for other mitigation options, particularly the direct electrification of energy demand sectors. Second, CCU has potential as an alternative mitigation option for tackling residual emissions without biomass and CDR technologies (e.g., BECCS and DACCS[40,41]) as long as renewable-based hydrogen and DAC are available economically. Several studies have mentioned the feasibility concerns associated with the large-scale deployment of bioenergy and CDR, such as water use, pressures on land, and associated risks to food security and biodiversity.[11,42–44] Hence, a CCU-based energy system transformation would facilitate net-zero emissions, given the challenges associated with CDR and bioenergy.

It should be highlighted that the CCU scenario could also be associated with several feasibility concerns. Despite the decreases in solar and wind costs in recent years, along with advances in DAC technology, additional technological

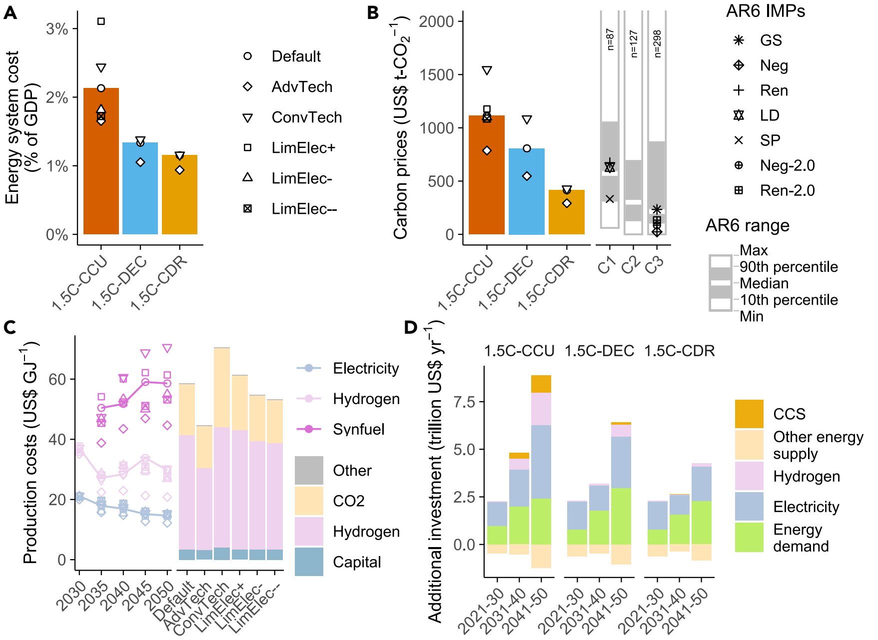

Figure 5. Economic implications of the CCU scenario

(A) Cumulative additional energy system costs between 2021 and 2050 as a fraction of GDP, discounted by 5% per year. Colored bars represent the default cases and points represent sensitivity cases.

(B) Carbon prices in 2050. Right bar plots represent AR6 scenarios. The range of 0–2,000 \$USD t-CO$_2^{-1}$ is illustrated. Boxplots illustrate those obtained from the IPCC AR6 Scenario Database[38] for each climate category and the IMPs (GS, gradual strengthening; Neg, net negative; Ren, renewables; LD, low demand; SP, shifting global pathways). See also Figure S8 for the sensitivity scenario results.

(C) Average energy production costs of electricity, hydrogen, and synfuels in the 1.5C-CCU scenario (left) and synfuel cost composition in 2050 (right). The CO$_2$ cost includes costs for carbon capture; the impact of carbon prices is excluded. Other components include costs associated with electricity use in synfuel production and costs associated with international trading of synfuels.

(D) Annual mean additional investment from each sector according to decade, relative to the no-policy scenario. The CCS sector includes investment for DAC. Investments in synfuel production are included in the hydrogen sector.

developments and associated policy supports are needed to support the energy supply transformation in the CCU scenario. In addition, the CCU scenario may involve economic concerns due to increased mitigation costs and energy prices relative to the electrification and CDR-based scenarios. This implies the need for additional policy interventions for alleviating impacts on poverty and inequality.

Nevertheless, although decarbonization scenarios based on low energy demand and renewables are attractive possibilities, the energy demand side may be affected by technological and social forms of inertia associated with the lock in of existing infrastructure and human lifestyles and behaviors that prevent the necessary rapid changes. Considering the potential for changes in energy demand, CCU could provide an important alternative approach for rapid emissions reduction without reliance on bioenergy and CCS. From this perspective, technological development and associated policy supports for CCU technologies are effective methods to maintain various options for net-zero emissions.

Considering the challenges associated with the CCU scenario, future research should focus on its potential implementation, such as the effective use of existing energy infrastructure (e.g., natural gas pipelines). Furthermore, the potential use of CCU for feedstock and its possible contribution to national mid-century net-zero targets should be explored because synfuels offer advantages for long-distance international energy trade compared with other low-carbon energy carriers. Additionally, because comparisons between the CCU scenario and CDR or bioenergy-oriented scenarios involve multiple sustainability considerations, the sustainability implications of the CCU scenario should be explored in greater detail. Such research could include the impacts of additional water and resource usage for DAC,[45,46] the health impacts of air pollutants released from hydrocarbon combustion,[47] and the poverty and inequality associated with high energy expenditures[48,49] driven by synfuel costs that are incurred while reducing the capital cost burden of electrification.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Ken Oshiro (ohshiro.ken.6e@kyoto-u.ac.jp).

Materials availability

This study did not generate new unique materials.

Data and code availability

The scenario data generated in this study are available at the Zenodo repository (https://doi.org/10.5281/zenodo.7851215). The source code used for scenario data analysis and figure production is provided in the GitHub repository (https://github.com/kenoshiro/AIM-CCU). The source code of the AIM/Technology model is available at https://github.com/KUAtmos/AIMTechnology_core.

Energy system model

AIM/Technology is a bottom-up global energy system model whereby changes in energy systems and associated emissions are estimated based on linear programming to minimize the total energy system cost.[35] Details of the model version used in this study, including its mathematical equations and technological parameter assumptions, are summarized in the model description document.[50] The energy efficiency and cost parameters of each technology, the energy service demands, and the associated constraints such as energy resource potentials are provided with the model as exogenous parameters. AIM/Technology models various energy technologies across multiple energy sectors. Among energy demand sectors, the industry, buildings, and transport sectors are disaggregated into various industrial products, building energy services, and transport modes. The energy supply sectors include energy extraction from fossil fuels and biomass, along with energy transformation processes such as electricity and hydrogen. More information,

Table 1. Overview of CCU scenario characteristics

Characteristics	Explanation on CCU scenario	1.5C-CCU	1.5C-DEC	1.5C-CDR
Technological changes in the energy demand	reduced transition risks by avoiding rapid changes of energy demand technologies, especially electrification; existing hydrocarbon-based infrastructure can remain, avoiding stranded asset risks; emergency options for energy demand technologies and infrastructure lock in	moderate	large	large
Dependencies on fossil and biomass primary supply	primary energy supply from fossil and biomass are less than 200 EJ per year in 2050, which is almost same level with the IMP-Ren and IMP-SP scenarios in the AR6; low CDR implementation, about 1 Gt-CO_2 per year in 2050; generally associated sustainability concerns can be lower	low	low	medium
Scale of non-biomass renewables	non-biomass renewable supply exceeds 600 EJ per year by 2050, which is higher than the AR6 scenario range; direct electricity use in the final energy demand is less than 200 EJ per year, while the rest is used for hydrogen and synfuel production	very high	high	medium
Carbon-dependent energy demand	despite low dependencies on fossil and biomass extractions, carbon input to energy systems is almost doubled compared with the renewable and electrification-based scenario; carbon capture by DAC increases about 10 Gt-CO_2 per year by 2050; low CCS and CDR implementation	medium	low	medium
Mitigation cost	mitigation costs and carbon prices are almost doubled compared with the renewable and electrification-based scenario, due mainly to synfuel productions, while energy technology investment for energy demand sectors is reduced	high	medium	low-medium

including the source code of the AIM/Technology model, is provided in the data and code availability statement.

For each energy sector, specific energy technologies are modeled. In the power sector, multiple energy sources are converted to electricity, including fossil fuels, renewables, and nuclear. This sector uses a dispatch module with 1 h temporal resolution for representative days. Battery and pumped hydro storage can be used to meet hourly electricity supply and demand, whereas electrolysis can effectively use excess electricity output. Heat-pump water heaters in buildings and battery electric vehicles in the transport sector can be operated as demand-response resources to mitigate the impacts of variable renewable energies. AIM/Technology includes multiple hydrogen-based energies as secondary energy carriers. Hydrogen can be converted from fossil fuels, biomass, and electricity. Fossil fuel-based and biomass-based technologies can be equipped with CCS. The efficiency and cost parameters are based on the International Energy Agency (IEA).[51] The energy potential of dedicated energy crops and costs are based on estimates obtained from AIM/PLUM (AIM/Platform for Land-Use and Environmental Model).[52,53] Wind and solar potentials, as well as their hourly generation profiles, are estimated based on climate, weather, and land information in 0.5° × 0.5° grid cells. In terms of climate conditions, solar irradiance and wind speed data are acquired from the Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2) dataset.[54,55] The climate data are converted into hourly power output and the physical potentials for solar and wind power based on formulae and parameter settings from the literature.[56,57]

Carbon capture from large emission sources and DAC are modeled. CCS from large emission sources includes power and hydrogen generation, oil refining, bioenergy liquefaction, steel and cement production, and furnaces. Figure S10 summarizes the parameter assumptions for DAC, which assume the use of solvent-based DAC that requires high levels of heat. Heat supply for DAC can be provided by natural gas, biomass, electric resistance heating, or hydrogen.

Representation of CCU technologies

AIM/Technology includes synthetic liquid fuels and methane as CCU-based energy carriers, which can replace liquid fuels and natural gas used in both energy demand and energy supply sectors. The assumed production methods are the Fischer-Tropsch process and methanation for liquid fuels and gases, respectively. The synfuels in this study include e-fuels, which are generally derived from renewable electricity, as well as hydrogen from other sources (e.g., fossil fuels and bioenergy, with or without CCS). The model considered synfuels only in terms of energy use rather than as a replacement for petrochemical products. Synthetic methane can be converted to hydrogen through steam methane reforming and is consumed in the energy sectors in this model. The technological parameter assumptions are based on the literature[51] and summarized in Table S3.

In terms of CO_2 utilization, captured CO_2 is converted into synthetic fuels on site, so no transportation cost is imposed for CO_2. Instead, synthetic fuels can be transported across modeled regions using the transport equipment used for oil and natural gas at the same transport cost. The cost information for the transport facilities of each energy carrier is summarized in Table S4 based on the literature.[58,59] For captured CO_2 stored underground by CCS rather than CCU, the transport of captured CO_2 costs 6 \$USD t-CO_2^{-1} based on an assumption for 100 km transport by pipeline.[58] The assumptions for CO_2 capture costs for electricity and hydrogen generation are summarized in Tables S5 and S6, which are based on the IEA document.[51,60] The cost assumptions of DAC in the default technology assumption case are shown in Table S7, which is based on Realmonte et al.[9]

In this model, CO_2 emissions from synthetic hydrocarbons were included in the synfuel conversion processes rather than in the energy demand sectors. Thus, carbon prices were not imposed on the end users of synfuels if the captured CO_2 originated from atmospheric sources (e.g., DAC and bioenergy). Additionally, DAC utilities could not receive any revenue from carbon pricing if the captured CO_2 was used for CCU purposes rather than sequestration.

Scenario framework

Table S1 summarizes the scenario descriptions, including the default scenarios and sensitivity scenarios. The default scenario set in this study includes the 1.5C-CCU, 1.5C-DEC, and 1.5C-CDR scenarios, which differ in terms of key mitigation strategies. The sensitivity scenarios were prepared to consider multiple uncertainties associated with key technologies and the pace of demand-side technological changes. The detailed assumptions are summarized below.

Quantitative analysis of each scenario was conducted with multiple energy system conditions imposed, in accordance with the underlying scenario and its assumptions. For both the 1.5C-DEC and 1.5C-CCU scenarios, considering their assumptions of low dependence on fossil fuels and bioenergy, limits on CCS implementation and bioenergy potential of 4 Gt-CO_2 year^{-1} and 100 EJ year^{-1}, respectively, were imposed in accordance with the assumption used in previous research.[5] Furthermore, in the 1.5C-CCU scenario, two specific constraints were imposed. First, considering the stringent limitation of fossil fuel usage in this scenario, CDR implementation was constrained to 1 Gt-CO_2 year^{-1} because reliance on fossil fuels was generally determined by CDR availability in this scenario.[36] Second, considering the moderate assumptions for technological changes in energy demand sectors, the diffusion of non-hydrocarbon-based technologies was limited to 50% of new technologies, in accordance with the electrification assumption of shared-socioeconomic pathway 2 (SSP2) in MESSAGE-GLOBIOM (model for energy supply strategy alternatives and their general environmental impacts-Global Biosphere Management).[61] Although the electrification rate is rapidly increasing even in the transport sector in European countries and China, the assumption in the 1.5C-CCU scenario is conservative because electric vehicles continue to comprise <5% of car sales in the United States and OECD-Asia countries.[62] The energy demand technologies that were constrained in the CCU scenario included electric and hydrogen -based industrial boilers and furnaces in the industry sector; battery electric vehicles, plug-in hybrid electric vehicles, and fuel-cell electric vehicles in the transport sector; and electric and hydrogen-based heating devices for space and water heating and for cooking in the buildings sector. The 1.5C-CDR scenario was based on the default parameter assumptions of the AIM/Technology model,[35,50] and no additional constraints were imposed; therefore, CDR technologies were fully available in this scenario.

Under the mitigation scenarios, the trajectories of CO_2 emissions from energy and industrial processes were imposed as emission constraints. Although this study primarily focuses on emissions from energy systems, geological storage constraints in some scenarios were imposed on both energy and industrial process emissions. The emission trajectories were derived from the AIM/Hub model,[63] and the estimated emission pathways are shown in Figure S11. The emissions trajectories are equivalent to emission budgets of 500 and 1000 Gt-CO_2 from 2018 to 2020 without net-negative emissions in the 1.5C and well-below-2°C (WB2C) scenarios, respectively.[1,37] We assumed that mitigation began immediately in 2020; no specific national mitigation policies included in the nationally determined contributions or long-term, low-emission development strategies were considered. Each region reduced CO_2 emissions based on uniform global carbon prices such that global collective CO_2 emissions met the emissions constraint. The no-policy scenario was quantified to determine the additional energy system costs and energy investments incurred when no additional mitigation policy was considered. The socioeconomic conditions of this scenario are equivalent to the SSP2 assumptions.[64]

Sensitivity scenarios

We analyzed sensitivity scenarios in terms of the cost assumptions for key technologies and the pace of technology diffusion in the energy demand sectors, considering the uncertainties and assumed impacts of both challenges and opportunities in the CCU-oriented scenarios.

In terms of key technology cost assumptions, we analyzed both optimistic (AdvTech) and pessimistic (ConvTech) assumptions associated with synfuel production, which includes solar and wind power generation, hydrogen production through electrolysis, synfuel production, and DAC. For these technologies, particularly solar and wind power, cost assumptions could strongly affect the 1.5C-DEC and 1.5C-CDR scenarios; sensitivity analysis was also conducted for these scenarios. The costs of solar and wind power in the AdvTech case were assumed to decrease by 2050 in accordance with International Renewable Energy Agency (IRENA) estimates,[65,66] whereas the assumptions of the default and ConvTech scenarios were based on the IEA World Energy Outlook.[67] Electrolysis and synfuel production costs in the default and ConvTech scenarios were based on IEA estimates.[51] In the ConvTech scenario, we assumed no cost decrease after 2030. In contrast, in the AdvTech case, a dramatic cost decrease was assumed based on an IEA report.[68] Parameter values for DAC were based on the existing literature from multi-model assessment of DAC.[9] Values for the ConvTech scenario used the high estimate, whereas the default and AdvTech scenarios used the low estimates, of parameter values. In the AdvTech scenario, we assumed that the DAC cost decreased from 2030 to 2050 such that it reached the floor cost estimate. Parameter assumptions for these technologies in the sensitivity cases are summarized in Figure S10.

For the 1.5C-CCU scenario, we performed further sensitivity analysis of the constraint on demand-side technological changes, including the LimElec+, LimElec−, and LimElec−− scenarios. The diffusion rate of electrification (including hydrogen) in the new technology installation was assumed to be 50% in the default case, according to the assumptions of SSP2; the rates for the LimElec+ and LimElec− scenarios were assumed to be 10% and 75%, respectively, based on the SSP3 and SSP1 assumptions in the MESSAGE-GLOBIOM model.[61] In addition, because passenger cars and buildings are relatively easier to electrify,[18,36] the LimElec−− case was quantified as a sensitivity scenario. In this case, electrification in the private car and buildings sector was not constrained, whereas the assumptions in the other sectors were the same as in the default 1.5C-CCU scenario.

IPCC AR6 scenario data

The AR6 scenario data used for the analysis in this study were obtained from Byers et al.[38] We used the World v.1.0 dataset for this study. Because some indicators considered in this article were not reported and could not be directly obtained from the database, we calculated these indicators as follows. The hydrocarbon primary energy supply shown in Figure 2D was calculated as the sum of "primary energy|coal," "primary energy|oil," "primary energy|gas," and "primary energy|biomass." The final energy consumption of hydrocarbon energies used in Figures 1 and 2D was calculated as the sum of "final energy|solids," "final energy|liquids," and "final energy|gases," which included bioenergy and other hydrocarbon energy carriers. For the comparison of CO_2 capture through DAC shown in Figure 4A, the amount of carbon utilization by DAC was not reported in the AR6 Scenario Database; thus, we assumed that "carbon sequestration|direct air capture" was equal to CO_2 capture through DAC. Because the level of CDR implementation in the energy sector shown in Figure 4B is not directly reported in the AR6 Scenario Database, it was calculated as the sum of "carbon sequestration|direct air capture" and "carbon sequestration|CCS|biomass" in this article. For scenario categories, we used C1, C2, and C3 for comparison with the 1.5C and WB2C scenarios in this study. The C1 category of AR6 limits the temperature increase to 1.5°C with 50% likelihood of no or limited overshoot in 2100.[2] The C2 category exceeds 1.5°C during this century with 67% likelihood; it shifts to 1.5°C by 2100 with 50% likelihood. The C3 category limits peak warming to 2°C in this century with 67% likelihood. Unless otherwise noted, only categories C1–C3 and the corresponding IMPs are illustrated in the figures in this article.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2023.06.005.

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AUTHOR CONTRIBUTIONS

Conceptualization, K.O. and S.F.; methodology, K.O., S.F., T.H., S.A., H.S., and K.T.; software, K.O., S.F., and T.H.; investigation, K.O.; visualization, K.O.; writing – original draft, K.O.; writing – review & editing, K.O., S.F., T.H., S.A., H.S., and K.T.

DECLARATION OF INTERESTS

The authors declare no competing interests.

INCLUSION AND DIVERSITY

We support inclusive, diverse, and equitable conduct of research.

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