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Full Length Article

Development of a computable general equilibrium model representing direct air capture and carbon dioxide utilization

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ABSTRACT

The establishment of stringent climate goals resulted in the development of various technologies contributing to climate change mitigation. While most of them were developed, at least partially, for other purposes, carbon dioxide removal (CDR) and carbon dioxide capture, utilization and storage (CCUS) are the only technologies developed solely for the purpose of mitigation. Direct air capture (DAC) contributes to climate-change mitigation through CDR and the supply of low-emission fuels. Integrated assessment models (IAMs) have incorporated the latest mitigation technologies, supporting technology development and deployment as well as climate policy formulation. Most scenario studies targeting DAC have applied IAMs with partial equilibrium models at their core. This study developed a computable general equilibrium (CGE) model capable of analyzing mitigation scenarios considering DAC-related technologies. The model represents carbon dioxide capture via DAC, underground storage of captured carbon dioxide (DACCS), and the production and consumption of synthetic fuels. The model was applied to estimate mitigation scenarios based on the 1.5 °C climate goal, resulting in an estimated recovered CO_2 by DAC of 14.3 Gt-CO_2/year, of which 12.8 Gt-CO_2/year was used for CDR. The remaining 1.51 Gt-CO_2/year was used to produce synthetic fuels, supplying 27.2 EJ/year of liquid and gaseous fuels. These results demonstrate that DACCS can reduce the economic impact of emission reductions. However, the results also imply that greater synthetic fuel use could increase costs if consumers make irrational choices. A comparison of the mitigation scenarios quantified in this study confirmed that the CGE model is capable of quantifying mitigation scenarios that consider DAC-related technologies. We anticipate that this model will contribute to the formulation of mitigation policies and to the analysis of their economic impacts.

1. Introduction

The Paris Agreement established long-term international climate goals of maintaining the global mean temperature increase at well below 2 °C and pursuing efforts to limit this increase to 1.5 °C. These goals require the urgent development of practical strategies for the substantial reduction of greenhouse gas (GHG) emissions. Climate-change mitigation scenario studies have contributed to climate policies at both national and global scales by providing information on the energy-system transformations required to reduce GHG emissions and their associated impacts on society, the economy, and land use [1]. To date, such mitigation scenarios have been quantified mainly by process-based integrated assessment models (IAMs) [2–9]. IAMs can be classified based on their core model or their primary governing principles. They have been used selectively based on their characteristics (Table 1) and have made broad contributions to research on climate change.

IAMs with a computable general equilibrium (CGE) model at their core describe how equilibria of demand, supply, and prices are achieved across entire economies based on assumed production and demand functions [18,19]. As these IAMs are economic models that encompass multiple sectors and goods, they can account for spillover effects resulting from inter-sectoral and inter-regional linkages, thereby calculating economic losses per sector and price fluctuations of goods associated with climate policies. CGE models generally represent the energy supply and demand in each sector based on social accounting matrices, making it challenging to account for energy-related

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technologies, particularly emission-reduction technologies that are not yet commercially available [20]. However, driven by the diversification of roles expected by recent mitigation scenario studies and recent IAM development, CGE models must increasingly incorporate new emission-reduction technologies such as hydrogen utilization and carbon capture and storage (CCS). CGE models incorporating these new technologies have been applied to analyze the impacts of climate policies on energy systems and the economy, as well as United Nations Sustainable Development Goals [21]. To date, these models have provided crucial information for climate policy formulation.

With the establishment of stringent temperature goals, various technologies for mitigating climate change are being developed and deployed. Direct air capture (DAC), a technology that recovers carbon dioxide (CO_2) directly from the atmosphere using liquid solvents or solid sorbents, has garnered significant attention as an emerging emission-reduction technology. CO_2 captured via DAC can be stored underground, combined with CCS. This technology (DACCS) contributes to climate-change mitigation as a carbon dioxide removal (CDR) technology. Furthermore, CO_2 captured by DAC can be reacted with hydrogen derived from renewable energy to produce synthetic fuels. Synthetic fuels come in gaseous and liquid forms and can be easily stored, traded, and applied to a wide range of sectors [22]. Utilizing these synthetic fuels can reduce emissions in sectors in which electrification for emission reduction is difficult [23,24]. Technologies that convert biomass into liquid or gaseous fuels, as well as those that combine bioenergy with CCS (BECCS), can also enable the supply of low-carbon fuels and the CDR. Compared to technologies that utilize bioenergy, technologies utilizing DAC do not require large-scale land-use changes; however, they have drawbacks, including low conversion efficiency, high synthetic fuel production costs, and the requirement of significant energy to separate the CO_2 from the absorbents [25,26]. Research investigating the potential of emission-reduction technologies and their impacts on energy systems within climate-change mitigation scenarios has increased in recent years. Under stringent temperature targets, the use of DACCS has been shown to reduce mitigation costs potentially, mitigate impacts on household consumption, and suppress food price increases by reducing biomass demand; however, in addition to the energy required to operate DAC facilities, the reduced need for emission reductions in other sectors may lead to increased energy consumption [27–30]. Mitigation scenario studies assuming the use of CO_2 captured by DAC for synthetic fuel production have indicated that synthetic fuels are primarily consumed in the transportation sector, that synthetic fuel consumption increases when CCS and biomass utilization are restricted, and that under stringent emission-reduction targets, the use of synthetic fuels contributes to lowering the cost of emission reductions [17,31–33]. However, the use of synthetic fuels raises concerns about their lower energy conversion efficiency compared to electricity, as well as the risk of being locked into fossil fuels if their expansion does not progress as expected [26].

Although DACCS has been introduced into some recent CGE models [34,35], global-scale IAMs with a CGE model at their core have been unable to account for the use of synthetic fuels [36]. Therefore, recent mitigation scenario studies have lacked economic analyses of the latest emission-reduction technologies related to DAC. To understand the behavior of CGE models incorporating DAC-related technologies, we developed a CGE model capable of analyzing mitigation scenarios considering DACCS and synthetic fuel utilization. The basis for the proposed model is the Asia-Pacific Integrated Model-Hub (AIM-Hub), a CGE-based IAM that incorporates CO_2 capture via DAC, its underground storage, and its use in the production and consumption of synthetic fuels. The AIM-Hub model incorporates various emission-reduction measures such as detailed power generation methods, CCS, and biomass production and utilization. Considering DAC-related technologies within this model enables analysis of the role played by the latest emission-reduction technologies in achieving the temperature goals outlined in the Paris Agreement, along with the economic impacts of deploying these technologies.

2. Methodology

2.1. Overview

This study expanded the AIM-Hub model to include new sectors representing emerging mitigation technologies: the DAC, synthetic fuel production, and CO_2 storage sectors. The DAC sector recovers CO_2 from the atmosphere and sells it as a commodity. The synthetic fuel production sector produces fuels usable in the transportation, industry, and residential sectors. Generally, fuels produced through chemical processes, regardless of the raw materials (shale oil, oil sands, coal, biomass, etc.), are called synthetic fuels. The synthetic fuel production sector produces alternative fuels for transport fuels (kerosene, diesel, and heavy fuel) and city gas (methane) using hydrogen produced from renewable energy and atmospheric CO_2, through methanation, Fischer-Tropsch process, and their separation and purification. These fuels are only intended for use as energy sources and not as feedstock. Using the proposed model and these new sectors, we estimated mitigation scenarios aligned with the 1.5 °C temperature goal outlined in the Paris Agreement. To assess the impact of these newly represented sectors, we estimated multiple mitigation scenarios, varying the settings of parameters related to the newly added sectors, and identified those parameters that significantly affected the results.

2.2. AIM-Hub model

The AIM-Hub model has a recursive dynamic CGE model at its core; it is widely used to estimate climate-change mitigation scenarios and analyze the social and economic impacts associated with climate-change mitigation [21,37]. The model is formulated as a mixed complementarity problem, which finds equilibrium solutions annually from the base

Table 1
Types of process-based IAM and examples of models.

Types of core model	Short description	Strength	Weakness	Examples
Computable general equilibrium (CGE) model	Based on the social accounting matrix (SAM), CGE models have detailed representations of sectors and goods, and simulate the impact of policy implementation on the economy, including inter-sector and inter-regional ripple effects.	CGE can capture the impact of policy implementation on the economy not only from macroeconomic indicators but also from the prices of goods and economic losses in each sector.	The representation of specific technologies is poor. It is difficult to consider technologies that have not yet been put into practical use.	AIM-Hub [10] EPPA [11] FARM [12] GEME3 [13]
Partial equilibrium model	Partial equilibrium models represent specific technologies related to energy demand and supply and simulate cost-optimal pathways to achieve policy objectives.	This type of model can contribute to concrete plans for implementing policies. The representation of the latest mitigation technologies is progressing.	It is difficult to analyze in detail the impact that policy implementation has on society and the economy.	MESSAGEix-GLOBIOM [14] MARKAL/TIMES [15] GCAM [16] AIM-Technology [17]

year (2005) through 2100. It incorporates 43 industrial sectors, a government sector, a household sector, and an investment sector. In the household sector, a fixed proportion of income earned from labor and capital is allocated to consumption, with expenditures on each good determined by a linear expenditure system function. The remaining income is directed toward investment or savings. The savings rate is endogenously determined to balance savings and investment, while a fixed coefficient determines the amount paid for each good for capital formation. Each industrial sector possesses its own capital stock, which undergoes investment and a 4 % annual rate of capital depreciation. Production activities in the industrial sectors are represented by a nested constant elasticity of substitution function. Production coefficients for energy and value addition in the energy supply sector are fixed. The consumption of energy goods is determined by a logit function that accounts for their heterogeneity. Generally, CGE models are calibrated using a social accounting matrix. The AIM-Hub model was calibrated for the base year 2005 using the Global Trade Analysis Project database [38]. To enhance the accuracy of energy consumption and GHG emission estimates, the period from 2007 to 2015 within the model's calculation horizon was calibrated using an energy balance table developed by the International Energy Agency [39]. During this period, annual calibrations are performed to adjust model parameters such as coefficients representing household consumption preferences, industrial sector energy efficiency, and fuel source shares, and to estimate stock formation.

2.3. Representation of DAC and synthetic fuel production sectors

Fig. 1 shows the intermediate inputs and production factors used to describe the activities of the newly added DAC sector, the synthetic fuel production sector, and the CO_2 storage sector within the AIM-Hub model, as well as the flows of atmospheric CO_2, synthetic fuels, and storage services produced within each sector. In the AIM-Hub model, the DAC sector inputs production factors and natural gas for the production and sale of atmospheric CO_2. We assume that, following the pilot-scale plant design referenced in the literature which is also used to set the parameters for our DAC representation [25], all CO_2 emitted through the combustion of natural gas to obtain the high-temperature thermal energy required for DAC is captured, along with CO_2 recovered from the atmosphere. The CO_2 emitted from natural gas is stored underground and counted separately from the atmospheric CO_2 produced by the DAC sector, as storage from natural gas with CCS. Furthermore, the energy supply from natural gas for DAC is counted as energy supply from natural gas with CCS. Therefore, when the storage sector stores the

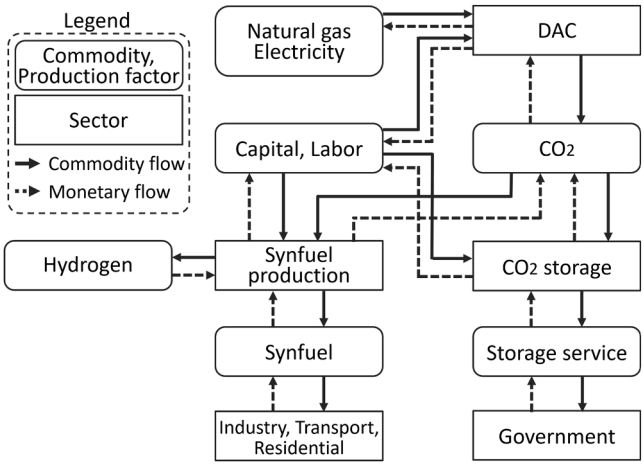

Fig. 1. Flow of goods and production factors in the direct air capture (DAC) sector, synthetic fuel production sector, and carbon dioxide (CO_2) storage sector.

atmospheric CO_2 produced by the DAC sector underground, the amount of purchased CO_2 is counted as carbon removal. Also, synthetic fuels produced using atmospheric CO_2 produced by the DAC sector do not increase atmospheric CO_2 levels when used. The synthetic fuel production sector inputs production factors and intermediate inputs, including hydrogen produced from renewable energy and CO_2 produced by the DAC sector, to produce synthetic fuels available for use in the residential, commercial, industrial, and transportation sectors. In the AIM-Hub model, the selection of energy goods within the energy demand sector is based on a logit function. To represent the wide-ranging applications of synthetic fuels, the parameters of the logit function are set equal to those of petroleum products for synthetic liquid fuels and to those of gas products for synthetic gaseous fuels. The storage sector inputs production factors and CO_2 produced by the DAC sector, provides CO_2 storage services, and achieves carbon removal. The amount of carbon removal is treated as equivalent to the amount of atmospheric CO_2 input into the storage sector. Storage service is treated as a final consumption good, purchased and consumed by the government using carbon pricing revenue. Given its role as a backstop technology for other emission-reduction technologies, as demonstrated in many studies analyzing DAC, the CO_2 storage sector stores CO_2 until the carbon price matches the cost of CO_2 storage, which includes the purchase price of atmospheric CO_2. This activity of the CO_2 storage sector is formulated as part of the mixed complementarity problem, as follows:

$$\frac{\sum_{r\in R} Qsto_r * Psto_r}{\sum_{r\in R} Qsto_r} \geq \mathrm{PGHG\_G} \perp \sum_{r\in R} Qsto_r \geq 0 \tag{1}$$

where R consists of the 17 regions in the AIM-Hub model, $r \in Qsto_r$ is the amount of CO_2 stored by DACCS in region r, $Psto_r$ is the cost of DACCS in region r, and PGHG_G is the carbon price.

Within the model, as CDR progresses through DACCS, the amount of GHGs that other sectors can emit increases under certain emission constraints, resulting in a carbon price decrease. The government purchases storage services until this reduced carbon price equals the cost of DACCS. Eq. (1) only determines the global total CO_2 storage volume. The extent to which each region CO_2 storage relative to the total global CO_2 storage amount is determined based on its CO_2 emissions in 2005. Specifically, the CO_2 storage of a particular region is calculated by multiplying the total global CO_2 storage by the ratio of that region's CO_2 emissions to the total global CO_2 emissions in 2005. The implementation of CDR impacts the economy, land use, and energy systems. Just as there are discussions about the burden-sharing of GHG emission reductions, there are also discussions about the allocation of CDR burden [40]. The mitigation scenario adopted in this study imposes constraints on global CO_2 emissions. In the AIM-Hub model, all revenue from the carbon price is paid from the government to households. When the government makes storage service payments, the amount paid to households from the carbon price revenue decreases accordingly, reducing household consumption. When selecting regions for DACCS deployment to minimize carbon capture and storage costs, DACCS is concentrated in the region with the lowest capture and storage costs. In these cases, when DACCS is excessively deployed in specific regions, the benefit of CDR is shared globally, such that the economic burden of emission reduction is concentrated in the region with the lowest DACCS cost. Thus, to prevent any region from bearing an excessive economic burden due to the introduction of DACCS, the proportion of DACCS across regions was set exogenously; to maintain the same proportion of reductions achieved globally through DACCS, relative to the total reductions from the base year in each region.

2.4. Data and parameter assumptions for DAC technologies

This section presents the data and model settings used to represent the DAC, synthetic fuel production, and CO_2 storage sectors. Liquid solvents or solid sorbents are considered promising materials for DAC.

Liquid-based DAC is easily scalable, with several pilot-scale plants already yielding extensive operational data. In contrast, solid-based DAC does not need high temperatures during operation, enables waste-heat utilization, and promises cost reductions. However, scaling up such facilities presents challenges [41]. For a liquid-based DAC facility capturing 1 Mt-CO_2/year based on carbon engineering operational data, Keith et al [25]. estimated total capital costs at US$793/t-$CO_2$, operating costs at US$30/t-CO_2/year, and natural gas demand at 8.81 GJ/t-CO_2. Assuming a capital recovery rate (annual capital expense divided by capital cost) of 7.5–12.5 %, they estimated that the cost to capture 1 t of CO_2 from the atmosphere to be an average of US $126–170/t-$CO_2$. Based on these previous findings, we considered only liquid-based capture methods and assumed that all energy needed for DAC would be supplied by natural gas. Table 2 shows the settings for each technology considered in this study. For the DAC sector, the capital cost was set at US$84/t-$CO_2$, calculated by discounting the midpoint between the capital costs estimated by Keith et al [25]. and the present value, considering the lifetime and discount rate. Operating costs were set at US$30/t-$CO_2$; operation was assumed to consume natural gas at a rate of 8.81 GJ/t-CO_2. For the CO_2 storage sector, capital costs were set at US$5/t-$CO_2$ and operating costs were set at US$5/t-$CO_2$, based on Hendriks et al [42]. AIM-Hub does not have endogenous constraints on the maximum geological CO_2 storage capacity or the annual rate of storage expansion. The feasibility of these variables is confirmed in the Results and Discussion sections by comparing them with existing literature [43,44]. The costs for synthetic fuel production via electrolysis and hydrogen production were set based on those reported in IEA [45]. The capital cost for electrolysis was set at US$872/kW, with the operating cost set at 2.2 % of the capital cost, a lifetime of 30 years, a capital utilization rate of 34 %, and conversion efficiency of 60 %. The capital cost for synthetic fuel was set at US$565/kW, with the operating cost set at US$20/kW/year, a lifetime of 25 years, conversion efficiency of 73 %, and an intermediate atmospheric CO_2 input of 55.6 t/MJ.

2.5. Scenario

The scenarios applied in this study considered technological variations while limiting the global mean temperature increase to below 1.5 °C (Table 3). Additionally, a baseline scenario was created, which assumed the continuation of current climate policies without implementing additional emission reductions. In all scenarios, future socioeconomic conditions were based on the middle-of-the-road Shared Socioeconomic Pathway (SSP2) [46], a widely used framework in climate-change-related research. The mitigation scenario adopted in this study was based on a pathway from Riahi et al [1]. that limits cumulative CO_2 emissions from 2018 to 2100 to 500 Gt-CO_2, corresponding to the 1.5 °C climate goal. This scenario initiates emission reductions in 2020, with emissions reaching net zero after 2050 (Fig. 2).

In scenarios utilizing DACCS and synthetic fuels, DAC deployment was implemented from 2025, with the storage sector also commencing operations in 2025. Synthetic fuel utilization started the following year, in 2026. To assess the impact of these newly introduced technologies, we designed three scenarios: one without DACCS or synthetic fuels (1.5C_NoDAC), one using only DACCS (1.5C_DAC), and one using both DACCS and synthetic fuels (1.5C_Syn). To identify the settings for the newly modeled sectors that significantly affected the results, we designed scenarios that altered the costs and conversion efficiencies described in Section 2.4. Reducing hydrogen production costs (1.5C_Syn_H2low) decreased both the capital and operating cost of electrolysis by 10 % and increased conversion efficiency by 10 %. Reducing DAC costs (1.5C_Syn_DAClow) lowered DAC capital and operating costs by 20 % and reduced natural gas input for DAC operation by 20 %. Reducing synthetic fuel production costs (1.5C_Syn_Synlow) lowered the capital and operating costs of synthetic fuel production facilities by 10 % and increased conversion efficiency by 10 %. Changing the energy source to electricity (1.5C_SynEle) remained the cost and energy efficiency settings at their default but changed the energy source to electricity. These scenarios assume developments in DAC-related technologies and the operation of DAC utilizing solid sorbents. Several studies have estimated the cost of DACs, with the cost range being US $60–1000 [47]. To assume a pessimistic view of technological development, increasing DAC costs (1.5C_Syn_DAChigh) increased DAC capital and operating costs by 50 % and also increased natural gas input for DAC operation by 50 %. The demand of synthetic fuels is influenced by

Table 2
Model settings for each technology considered in this study.

Technology	Cost type	Value
DAC	Capital cost	84 USD/t-CO_2
	O&M cost	30 USD/t-CO_2
	Energy demand	8.81 GJ/t-CO_2
CO_2 storage	Capital cost	5 USD/t-CO_2
	O&M cost	5 USD/t-CO_2
Electrolyzer	Capital cost	872 USD/kW
	O&M cost	19.2 USD/kW
	Operating rate	34 %
	Efficiency	60 %
Synfuels	Capital cost	565 USD/kW
	O&M cost	20 USD/kW/yr
	Efficiency	73 %
	CO_2 demand	55.6 t/MJ

Table 3
List of scenarios adopted in this study.

Scenario name	Climate policy	DACCS	Synfuel	Cost, intermediate input, and elasticity assumptions
Baseline	-	-	-	Default
1.5C_noDAC	1.5C	-	-	Default
1.5C_DAC	1.5C	X	-	Default
1.5C_Syn	1.5C	X	X	Default
1.5C_Syn_H2low	1.5C	X	X	H2 low cost
1.5C_Syn_DAClow	1.5C	X	X	DAC low cost
1.5C_Syn_Synlow	1.5C	X	X	Synfuel low cost
1.5C_ Syn_ElyDAC	1.5C	X	X	DAC with electricity
1.5C_ Syn_DAChigh	1.5C	X	X	DAC high cost
1.5C_Syn_ela1	1.5C	X	X	Increase price elasticity in the transportation sector by 25 %
1.5C_Syn_ela2	1.5C	X	X	Increase price elasticity in the transportation sector by 50 %

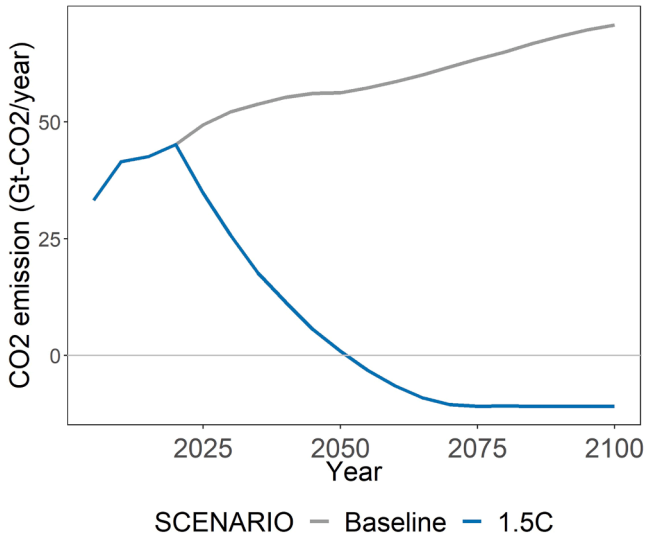

Fig. 2. CO_2 emission pathway (after Riahi et al [1].).

the demand-side representation in the AIM-Hub model. Two sensitivity scenarios (1.5C_Syn_ela1, 1.5C_Syn_ela2) modified the price elasticity of energy goods in the transportation sector, which consumes the most synthetic fuels.

3. Results

3.1. Impact of DACCS and synthetic fuel use on energy systems and the economy

We examined the impacts of considering DAC, underground storage of captured CO_2, and the production and consumption of synthetic fuels in the AIM-Hub model on scenario quantification for three mitigation scenarios: one without DAC-related technologies (1.5C_noDAC), one using only DACCS (1.5C_DAC), and one using both DACCS and synthetic fuels (1.5C_Syn).

In the scenario with neither DAC nor synthetic fuels, the carbon price rose rapidly from around 2040, reaching US$1160 by 2100, which fell in the range of the scenarios categorized in C1 (limit warming to 1.5 °C (>50 %) with no or limited overshoot) and C2 (return warming to 1.5 °C (>50 %) after a high overshoot) of IPCC Working Group III's classification in the sixth assessment report database (AR6 database) [48] (Fig. 3, Panel a). In contrast, the scenarios using only DACCS and those using both DACCS and synthetic fuels resulted in carbon prices stabilizing at approximately US$160/t-$CO_2$ at around 2040, and the carbon price in 2100 was below the range of the scenarios categorized into C1 and C2. This carbon price broadly corresponds to the sum of the cost of capturing CO_2 via DAC and costs related to the transport and underground storage of the captured CO_2. AIM-Hub considers a constant elasticity in the selection of energy commodities. Even if a mitigation technology is feasible below a certain carbon price, that technology may not be selected, leading to a higher carbon price. On the other hand, DACCS, as represented in this study, is implemented only when the mitigation cost is purely lower than the carbon price, because DACCS was modeled to function as a backstop technology for other emission-reduction technologies. In addition to the way DACCS is represented in the model, the assumption of relatively low carbon capture costs based on Keith et al. [25], and the lack of constraints on geological CO_2 storage, are the reasons why the carbon price fell significantly compared to the scenario without DAC and was below the range of the AR6 database. In the 1.5 °C mitigation scenario, CO_2 emissions reached net zero by midcentury and continued to decline thereafter, removing approximately 10.8 Gt-CO_2/year from the atmosphere by the end of the century (Fig. 3, Panel c). Gross negative CO_2 emissions came from AFOLU, energy supply, and DACCCS. CDR by BECCS was counted as a negative emission in the energy supply sector because BECCS can supply energy and remove CO_2 at the same time. While all three mitigation scenarios produced comparable net CO_2 emissions, their compositions differed significantly. When DAC and synthetic fuels were not used (1.5C_NoDAC), decarbonization was achieved by midcentury through negative CO_2 emissions in the energy supply sector. Subsequently, CO_2 removal in the energy supply sector continued to increase until the end of the century, even after decarbonization was achieved. The amount of CDR by BECCS was 9.29 Gt-CO_2/year in 2100. In scenarios that used only DACCS (1.5C_DAC), CDR via DACCS accounted for a large proportion after 2050. After achieving decarbonization, the amount of DACCS changed significantly, and reached 15.3 Gt-CO_2/year in 2100. This amount of CDR exceeded the range of the C1 and C2 scenarios in the AR6 database (Fig. 3, Panel b). Comparing the scenarios with and without DAC (1.5C_NoDAC vs. 1.5C_DAC), the implementation of DACCS replaced the emission reduction in transport sector and CDR by BECCS, which have relatively high mitigation cost, resulting in an increase in transportation sector emissions and decrease in CDR by BECCS (5.39 Gt-CO_2 in 2100). When both DACCS and synthetic fuels were used (1.5C_Syn), compared to only DACCS (1.5C_DAC), CDR by DACCS decreased by 2.42 Gt-CO_2 in 2100, and emissions from the industrial and transportation sectors decreased instead (Fig. 3, Panel d) due to the synthetic fuel utilization. However, comparing the scenario without DACCS nor synthetic fuel, emissions from the transport sector are higher because the contribution of DACCS to the emission reduction is higher than synthetic fuel.

In all mitigation scenarios, renewable energy and fossil fuels with CCS became the primary energy sources (Fig. 4, Panel a). Comparing scenarios with and without DAC deployment (1.5C_noDAC vs. 1.5C_DAC), the use of DAC reduced the energy supplied by renewable energy and increased that from fossil fuels. Notably, the energy supply increased under natural gas with CCS, because this energy source is required to operate DAC. The use of DAC reduced biomass supply at the end of the century from 208 to 143 EJ/year, as it replaced mitigation measures using BECCS or bio-liquids. Comparing scenarios with and without synthetic fuel use (1.5C_DAC vs. 1.5C_Syn), renewable energy supply increased, particularly from wind, whereas that from oil and natural gas decreased (Fig. 4, Panel b).

All mitigation scenarios reduced CO_2 emissions by significantly increasing the share of final energy consumption represented by electricity (Fig. 4c). Comparing scenarios with and without DAC (1.5C_noDAC vs. 1.5C_DAC), electricity consumption in 2100 decreased from 416 to 370 EJ/year, and hydrogen consumption decreased from 16.7 to 8.19 EJ/year when DAC was used. Conversely, the consumption of petroleum-derived liquid fuels increased. In the mitigation scenario considering synthetic fuel use, 25.5 EJ/year of synthetic liquid fuel and 1.71 EJ/year of synthetic gaseous fuel were consumed by the end of the century. Comparing scenarios with and without synthetic fuel use (1.5C_DAC vs. 1.5C_Syn), synthetic fuel use reduced petroleum-derived liquid fuel consumption from 72.8 to 45.9 EJ/year (Fig. 4, Panel d).

The economic impacts of climate-change mitigation, including gross domestic product (GDP) and household consumption losses compared to the baseline scenario, as well as changes in goods prices and consumption are shown in Fig. 5. Regardless of synthetic fuel availability, estimated GDP losses reached approximately 5 %, while household consumption losses reached a maximum of approximately 6 %. Comparing scenarios with and without both DACCS and synthetic fuels (1.5C_Syn vs. 1.5C_NoDAC), the economic impact was greater when both DAC and synthetic fuels were used until 2045, and then greater without synthetic fuels from 2050 onwards. Focusing on changes in goods prices due to emission reductions, in all scenarios, prices excluding services and transportation increased with the implementation of climate-change mitigation measures (Fig. 5, Panel b). Prices for services and transportation decreased due to reduced demand resulting from lower household income associated with mitigation. Comparing goods price changes with and without DACCS use (1.5C_noDAC vs. 1.5C_DAC), energy and food prices declined after 2040 when DACCS was used (1.5C_DAC). Comparing goods price changes with and without synthetic fuel use (1.5C_DAC vs. 1.5C_Syn), food prices declined from 2025 and energy prices increased after 2040 when synthetic fuels were used (1.5C_DAC).

3.2. Comparison between scenarios with different technical settings

Fig. 6 shows relative price differences among scenarios with varied costs and efficiencies for each technology compared with the reference mitigation scenario (1.5C_Syn). Varying the technological assumptions directly affected the prices of carbon, energy goods, and captured atmospheric CO_2 (Fig. 6). In the scenario assuming lower hydrogen production costs (1.5C_Syn_H2Low), the price of hydrogen decreased by more than 10 %, and those of synthetic fuels followed the same pattern. In the scenario assuming lower CO_2 capture costs via DAC (1.5C_Syn_DACLow), the price of atmospheric CO_2 decreased by approximately 20 %, leading to a corresponding drop in the carbon price of US$29.2 in 2100. Synthetic fuel prices also decreased because atmospheric CO_2 is used as an intermediate input in synthetic fuel production. In the scenario assuming lower synthetic fuel production costs

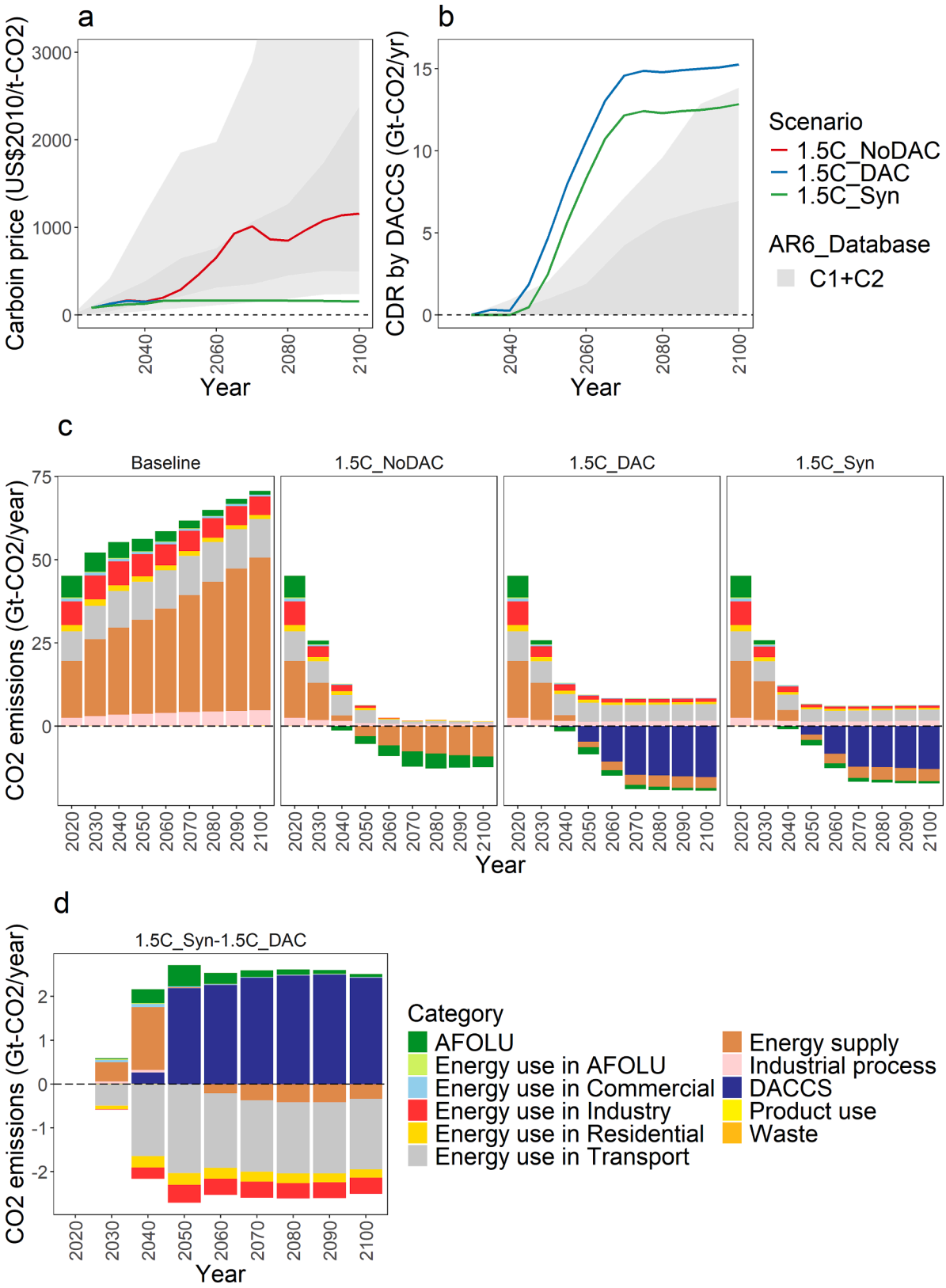

Fig. 3. Carbon prices and CO_2 emissions. Panel a shows the carbon price. Panel b shows the amount of CDR by DACCS. In panel a and b, shaded area shows the p5-p95 and quantile range of the scenarios categorized into C1 and C2 in the AR6 database. Panel c shows the CO_2 emissions by sources. Panel d shows the difference between 1.5C_Syn and 1.5C_DAC in the CO_2 emissions.

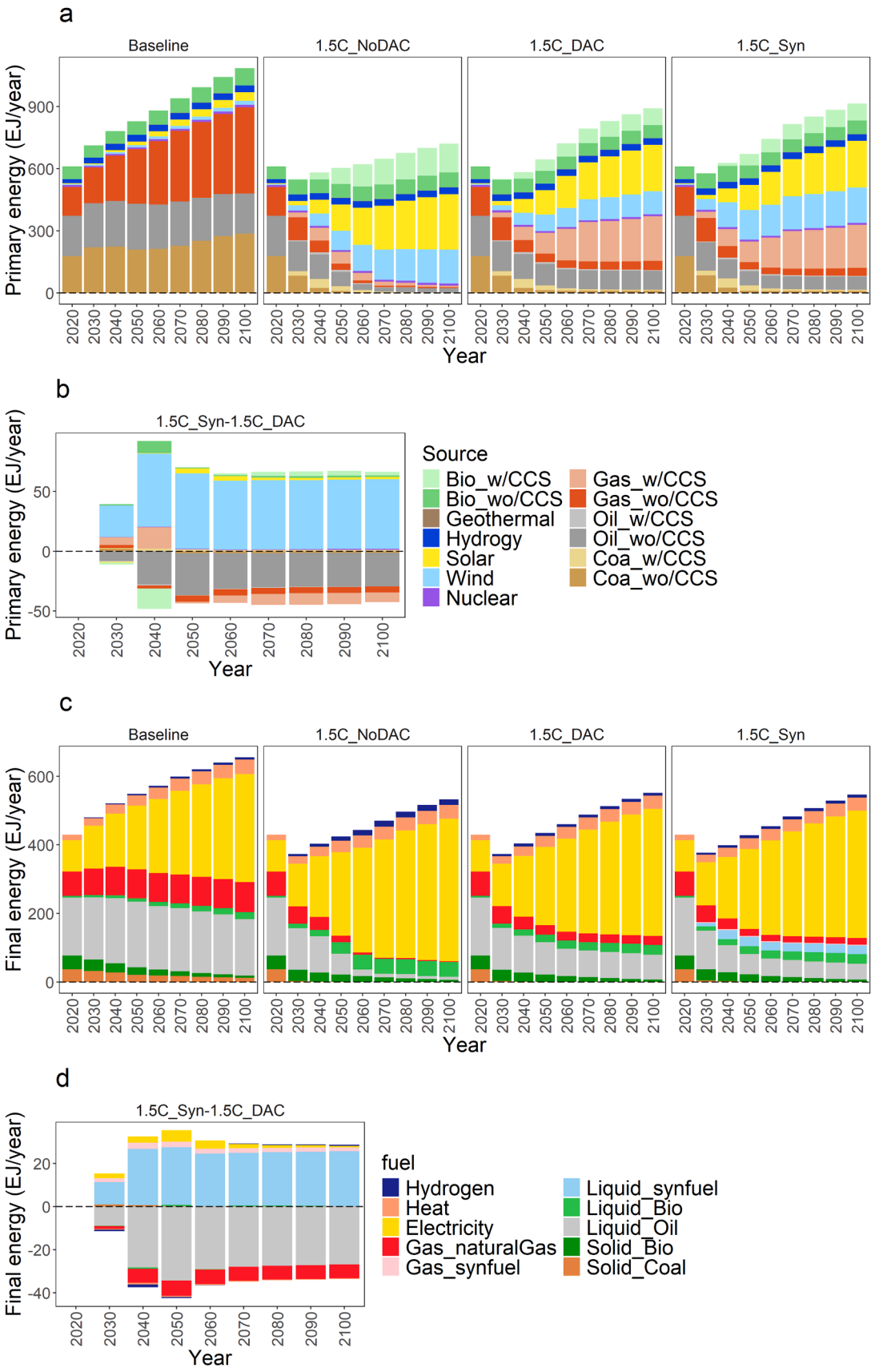

Fig. 4. Energy system changes over time. Panel a shows primary energy supply by sources. Panel c shows final energy consumption by energy commodities. Panel b and d show the difference between 1.5C_Syn and 1.5C_DAC in the primary energy and final energy consumption.

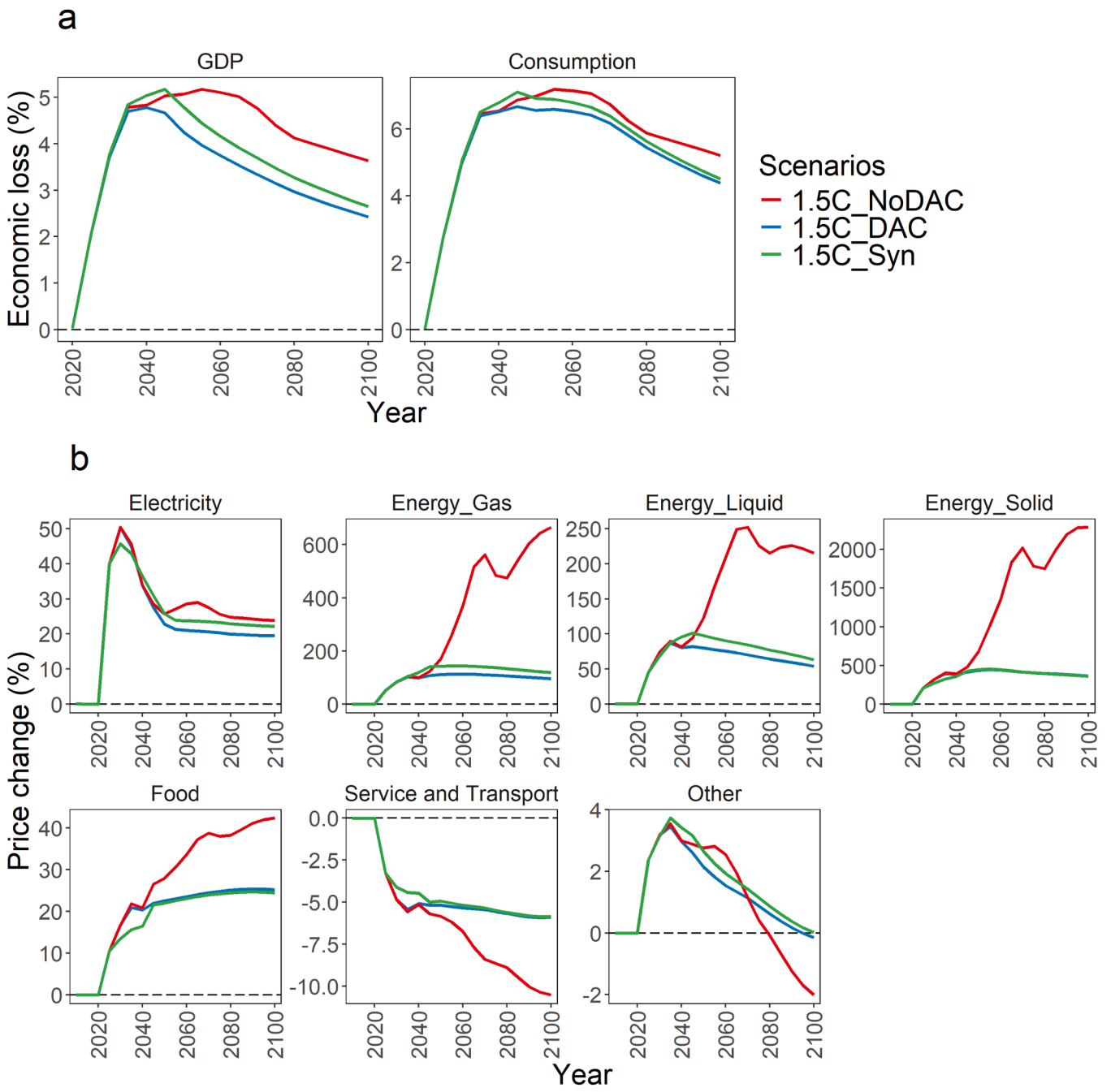

Fig. 5. Economic impacts under the mitigation scenarios compared to the baseline scenario. Panel a shows the GDP and household consumption loss due to the implementation of mitigation policy. Panel b shows the price change due to the implementation of mitigation policy.

(1.5C_Syn_SynLow), synthetic liquid fuel prices fell by about 7 %, and synthetic gaseous fuel prices fell by about 12 %. In the scenario assuming the DAC is powered by electricity, (1.5C_Syn_ElyDAC), the price of atmospheric CO_2 increased by approximately 130 % and the carbon price was US$ 344, which is the highest price in all scenarios. The reason the price of CO_2 increased was that, unlike other scenarios which assumed the use of natural gas whose demand decreased due to the implementation of mitigation policies, this scenario assumed the use of electricity, whose demand increased significantly due to the implementation of the policies. In the scenario assuming higher CO_2 capture costs via DAC (1.5C_Syn_DAChigh), the price of atmospheric CO_2 increased by approximately 50 %, leading to an increase in the carbon price of US $75.1 in 2100.

Differences in commodity prices resulting from changes in technology settings affected the methods and quantities of hydrogen and carbon utilization (Fig. 7 and 8). In the reference scenario (1.5C_Syn) considering DACCS and synthetic fuels, 46.0 EJ/year of hydrogen was produced by the end of this century, with 81.1 % used for synthetic fuel production (Fig. 7). The produced synthetic liquid fuels were used primarily in the transportation sector, while synthetic gaseous fuels were used mainly in the residential sector. DAC captured 14.3 Gt-CO_2/year of CO_2, 89.4 % (12.8 Gt-CO_2) of which was used to achieve CDR and 10.6 % (1.51 Gt-CO_2) of which was used to produce synthetic fuels (Fig. 8). In the scenario assuming lower hydrogen production costs (1.5C_Syn_H2Low), direct hydrogen use increased by 163 %, and synthetic fuel production increased by approximately 9.81 %. In the scenario assuming lower CO_2 capture costs (1.5C_Syn_DACLow), CDR via DACCS increased, while CDR via BECCS decreased. However, synthetic fuel production

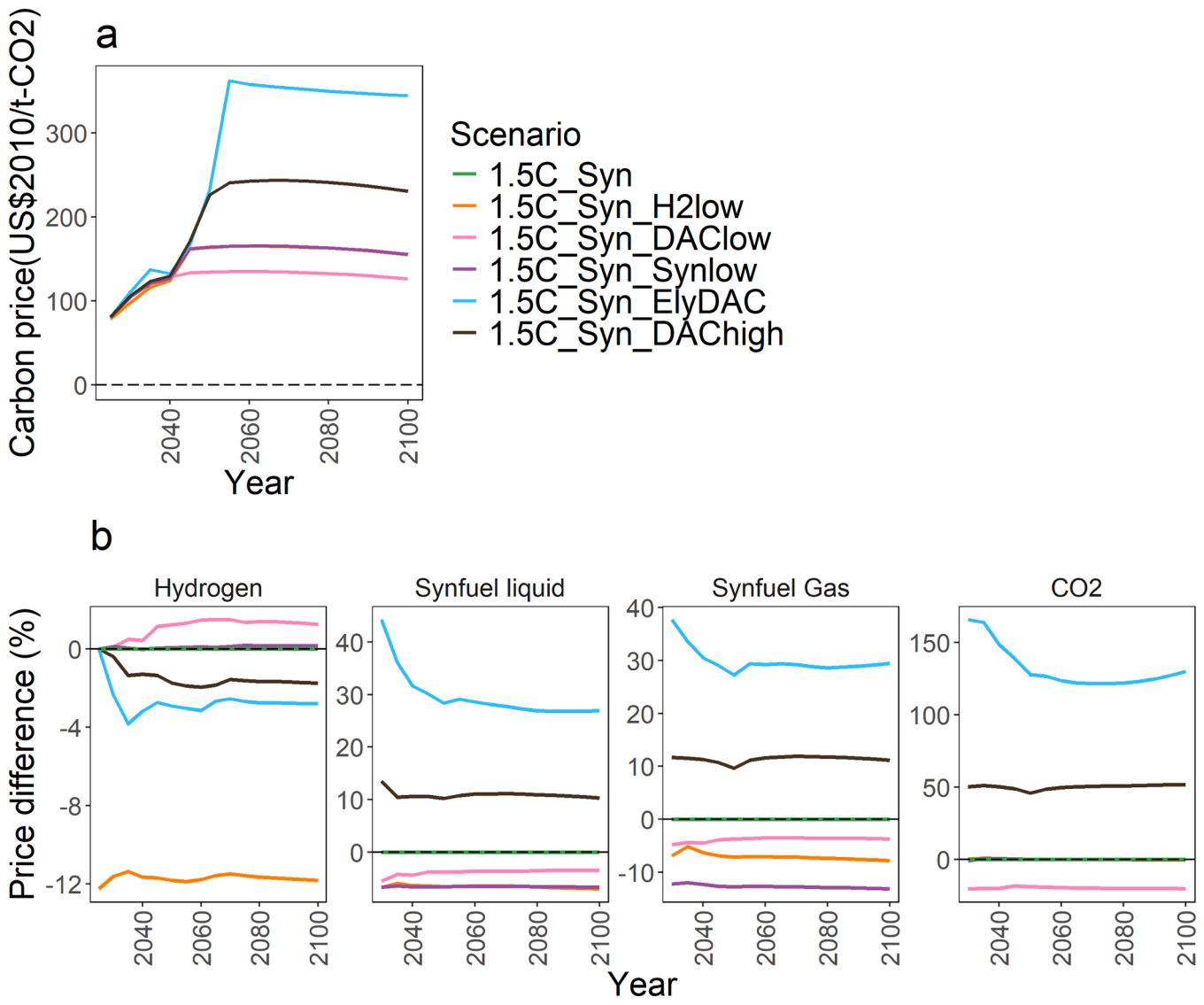

Fig. 6. Impacts of changes in technical settings on price changes for carbon (Panel a) and various goods (Panel b) compared to the 1.5C_Syn scenario.

remained largely unchanged. In the scenario assuming lower synthetic fuel conversion costs (1.5C_Syn_SynLow), end-of-century synthetic fuel production increased by approximately 13.8 %, making it the scenario with the highest synthetic fuel utilization. In the scenario assuming the DAC is powered by electricity (1.5C_Syn_ElyDAC), CDR via DACCS decreased by 61.4 %, while CDR via BECCS increased by 53.3 % and direct hydrogen use increased by 47.7 %. In the scenario assuming higher CO_2 capture costs (1.5C_Syn_DAChigh), CDR via DACCS decreased by 12.0 % and synthetic fuel production decreased by 31.5 %.

Annual geological CO_2 storage increased as emission constraints became stricter. Even after emission constraints stabilized in 2070, annual CO_2 storage continued to increase gradually with economic growth (Fig. 9, Panel a). In the scenario using only DACCS (1.5C_DAC), the annual CO_2 storage in 2100 was 25.8 Gt-CO_2/year, and the cumulative CO_2 storage up to 2100 was 1330 Gt-CO_2, the highest amount of CO_2 storage among all scenarios (Fig. 9, Panel b). In the scenario using synthetic fuels (1.5C_Syn), the annual CO_2 storage in 2100 was 23.5 Gt-CO_2/year, and the cumulative CO_2 storage up to 2100 was 1200 Gt-CO2, showing the effect of reducing reliance on geological storage through the use of synthetic fuels. The cost of CO_2 capture by the DAC affected the amount of CO_2 storage. In the scenario with high DAC capture costs (1.5C_Syn_DAChigh), the annual CO_2 storage amount in 2100 was 20.2 Gt-CO_2/year. In the scenario with low DAC capture costs (1.5C_Syn_-DAClow), the annual CO_2 storage amount in 2100 was 25.4 Gt-CO2. When the DAC is powered by electricity (1.5C_Syn_ElyDAC), there is no need to store CO_2 underground from the combustion of natural gas to operate DAC. Therefore, the natural gas consumption decreased to 87.7 EJ/year in 2100, and the CO_2 storage amount also decreased. The cumulative CO_2 storage amount up to 2100 was 954 Gt-CO_2, which is the lowest amount of CO_2 storage among all scenarios.

Comparing household consumption across scenarios, reductions in hydrogen production costs and DAC costs demonstrated the effects of increasing GDP and household consumption (Fig. 10, Panel a). Reducing hydrogen production costs (1.5C_Syn_H2Low) ultimately increased household consumption in the first half of this century, whereas reducing DAC costs (1.5C_Syn_DACLow) increased household consumption in the latter half of this century. The scenario that assumed reduced synthetic fuel production costs (1.5C_Syn_H2Low) had a limited effect on increasing household consumption. Focusing on changes in the prices of goods within household consumption, assuming low conversion costs for synthetic fuels (1.5C_Syn_SynLow) resulted in lower prices for solid, liquid, and gaseous fuels in the first half of the century, and a decline in liquid fuel prices in the latter half of the century (Fig. 10, Panel b). In the scenario assuming low hydrogen production costs

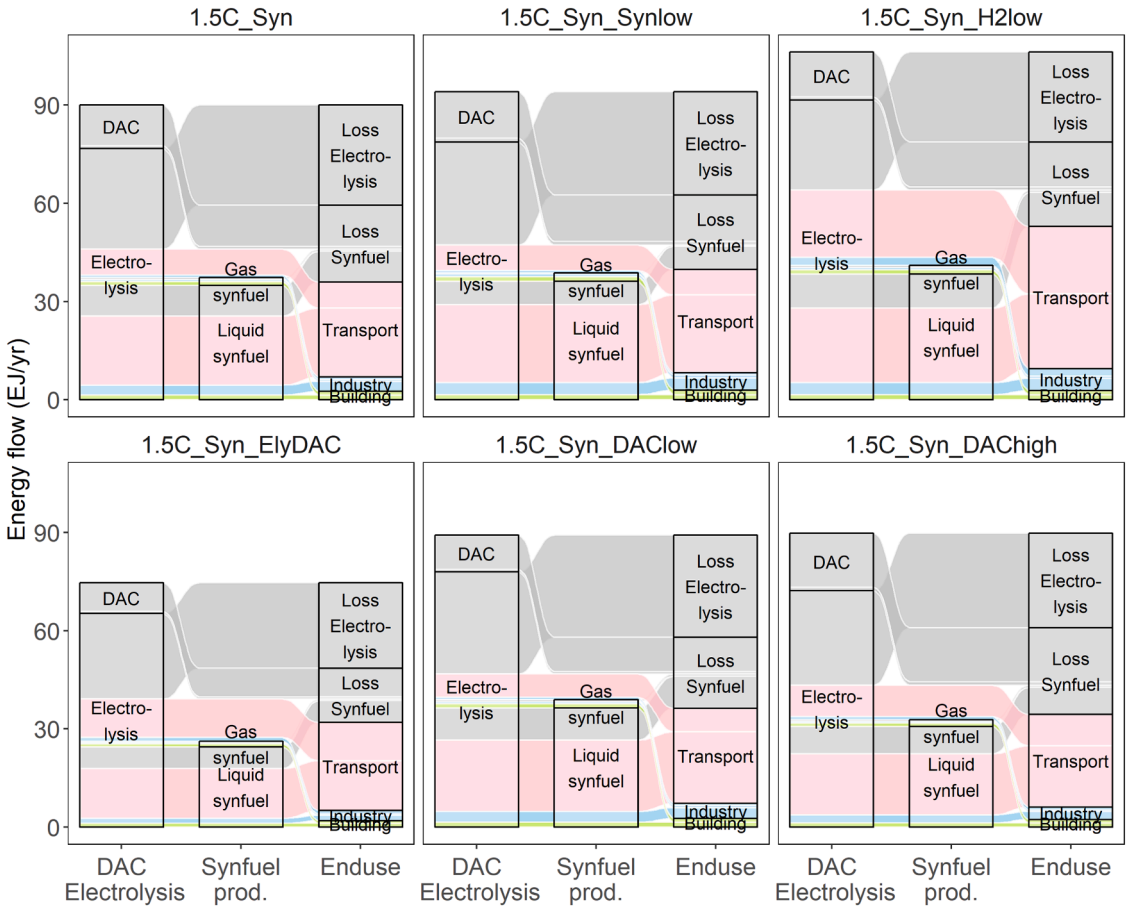

Fig. 7. Energy flows related to hydrogen and synthetic fuels productions in 2100.

(1.5C_Syn_H2Low), price changes for solid, liquid, and gas fuels were similar to those in the scenario assuming low synthetic fuel conversion costs. Hydrogen use partially competed with electricity use, leading to decreased electricity prices. When low DAC was assumed (1.5C_Syn_DACLow), the decline in carbon prices led to lower solid, liquid, and gas fuel prices in the latter half of this century. Furthermore, as DAC replaced biomass-based mitigation measures, land-use competition eased, reducing food prices. The increased cost of carbon capture by DAC and the operation of DAC powered by electricity increased losses in GDP and household consumption, particularly in the second half of this century (1.5C_Syn_DACHigh and 1.5C_Syn_ElyDAC). In these scenarios, the price of solid, liquid, and gaseous fuels rose due to the increase in carbon prices. Food prices also rose due to increased demand for biomass. In scenarios assuming the operation of DAC powered by electricity, the rise in electricity prices was particularly pronounced due to the increase in electricity demand.

Fig. 11 shows the results of a sensitivity analysis performed on price elasticity in the selection of energy goods in the transport sector to consider the impact of energy commodity selection, assuming a constant elasticity in the AIM-Hub model on the estimation of synthetic fuel consumption. Increased elasticity reduced synthetic fuel consumption (Fig. 11, Panel b) and increased CO_2 removal by DACCS (Fig. 11, Panel c). In particular, the use of synthetic fuels decreased in the first half of this century, when emission constraints were relatively less severe. Furthermore, economic losses were reduced through the selection of more efficient energy commodities (Fig. 11, Panel a).

4. Discussion

For a mitigation scenario aligned with the 1.5 °C climate goal considering only DACCS without synthetic fuels, the proposed model estimated that CDR by DACCS would be 4.66 Gt-CO_2/year in 2050 and 15.3 Gt-CO_2/year in 2100. Under the same scenario, cumulative CO_2 removal by DACCS over the entire calculation period was estimated at 686 Gt-CO_2. Under the 1.5 °C mitigation scenario considering synthetic fuels, the estimated consumption of synthetic fuels in 2050 was 29.3 EJ/year. Fuhrman, McJeon [27] examined the impacts of CDR on energy systems, water resources, and food production, and estimated that for an emissions pathway when the global average temperature rise slightly exceeds 1.5 °C before stabilizing at 1.5 °C, DACCS would capture approximately 12.0 Gt-CO_2/year by 2050 and approximately 16.1 Gt-CO_2 by 2100. Our estimates are lower, particularly for 2050, due to differences in the timing of achieving net zero in the emissions pathway. The emissions pathway assumed in this study reached net zero after 2050, and the amount of CO_2 removed by DACCS increased significantly at around the same time. In contrast, the emissions pathway assumed by Fuhrman, McJeon [27] achieved net zero around 2040, with a substantial increase in CO_2 removal via DACCS starting at around the same time. Both this study and Fuhrman, McJeon [27] demonstrated that the use of DACCS after achieving net zero further reduces emissions to negative values. Realmonte et al. (2019) analyzed the role of DACCS under stringent mitigation scenarios using two IAMs, and estimated a CDR by DACCS of 820–870 Gt-CO_2 by 2100 under 1.5 °C mitigation scenarios. Their study employed intertemporal optimization models to estimate mitigation scenarios, such that emission pathways were calculated endogenously based on assumed technologies and climate policies; to enable more effective use of DACCS, the timing of achieving net zero was delayed compared to scenarios without DACCS, resulting in significantly increased CDRs in the latter half of this century. The emission pathways exogenously set in the present study were similar to

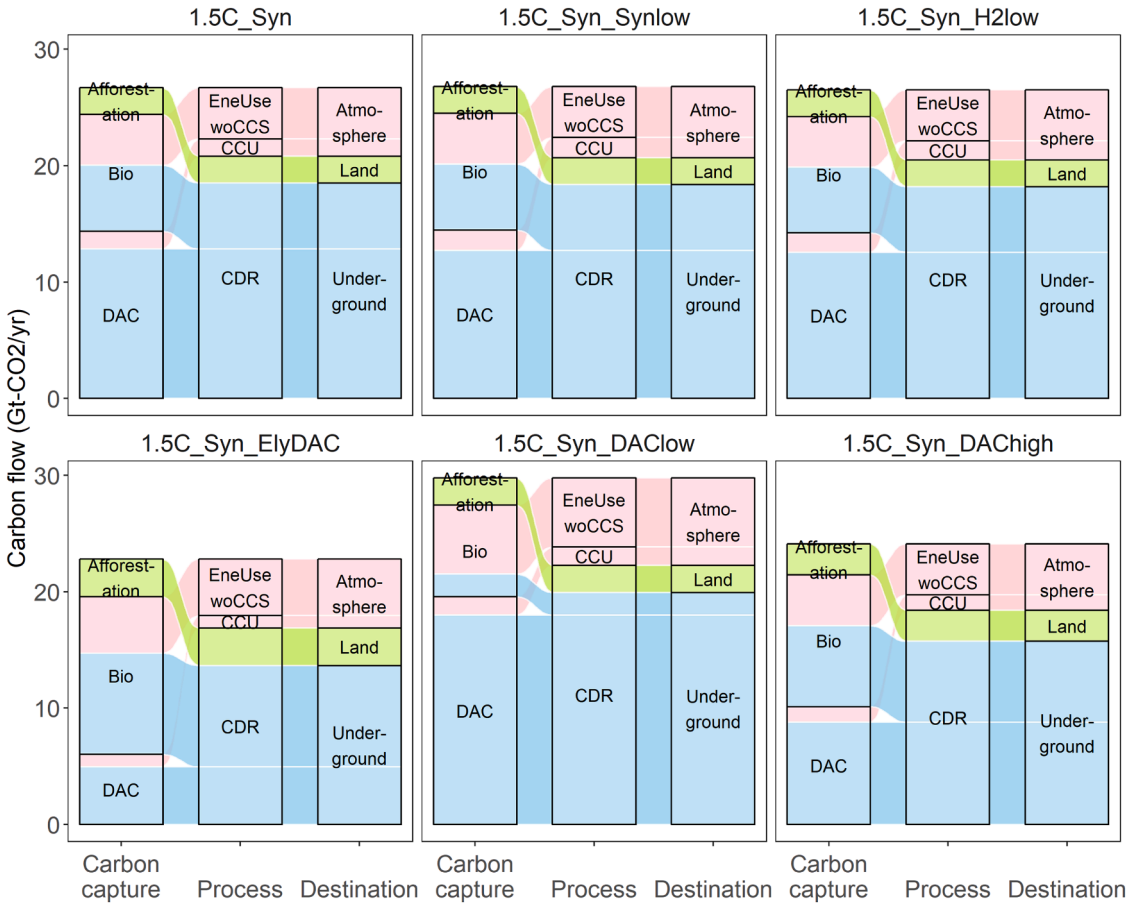

Fig. 8. CO_2 flow related to CDR and production and consumption of fuels which does not increase atmospheric CO_2 in 2100.

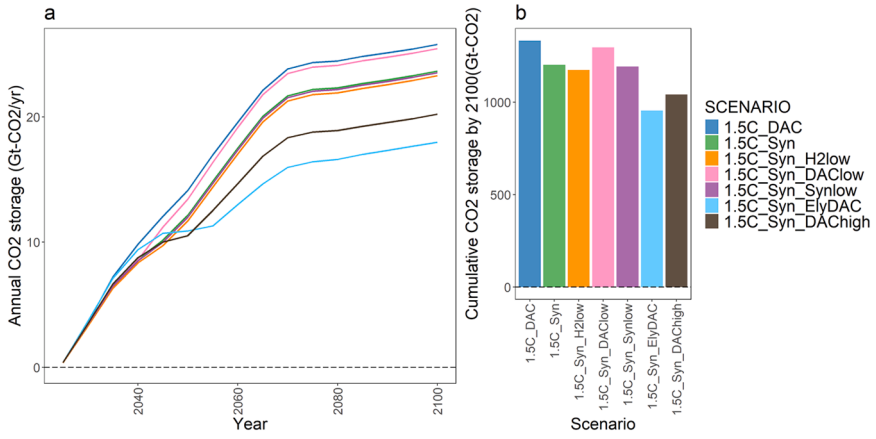

Fig. 9. CO_2 geological storage. Panel a shows the annual amount of CO_2 storage. Panel b shows the cumulative amount of CO_2 storage by 2100.

those estimated by the models of Realmonte et al. (2019), without assuming DACCS. Consequently, the CO_2 removal by DACCS until 2100 estimated in this study was lower than these previous results. Oshiro and Fujimori (2022), who explored the role of hydrogen in decarbonization pathways through the midcentury, estimated synthetic liquid fuel consumption at 4.7 EJ/year and CDR via DACCS at 4.4 Gt-CO_2/year in 2050. These synthetic fuel consumption values are less than one sixth the estimates obtained in the present study, whereas the CDR via DACCS estimate of the previous study was comparable to our value for the scenario that did not consider synthetic fuels. The emission pathways established in the present study and those established by Oshiro and Fujimori (2022) were nearly identical. The models used in both studies employed similar settings for costs and conversion efficiencies regarding DAC and synthetic fuel production. Our estimated CDR volume by DACCS was either close to those of previous studies or differed only to an extent explainable by differences in emission pathways. However, our synthetic fuel consumption estimates differed significantly from those of previous studies, due to differences in the representation of new technologies and in the model structure. The model developed in this study assumes that DACCS functions as a backstop technology relative to other emission-reduction technologies, removing CO_2 until the carbon price equals the cost of removing carbon via DACCS. This estimation method

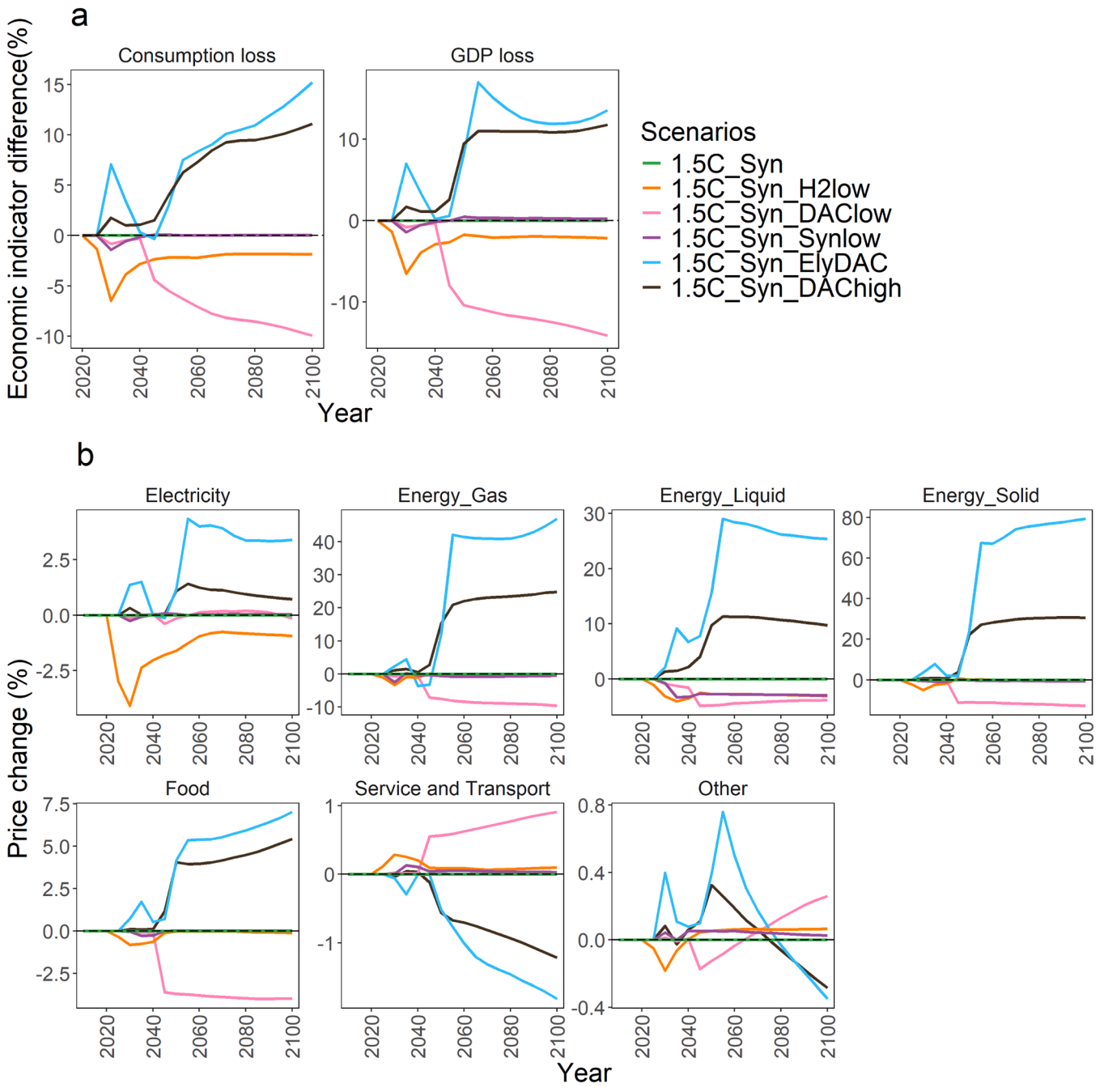

Fig. 10. Economic impacts of various scenarios compared to the 1.5C_Syn scenario.

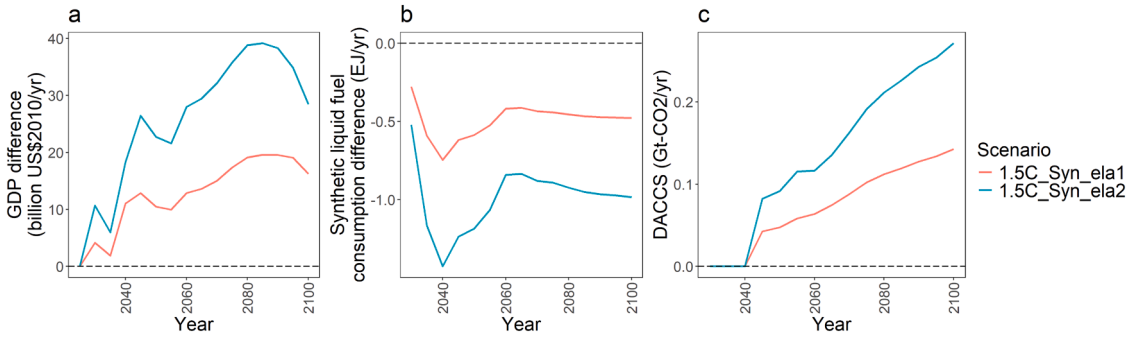

Fig. 11. Sensitivity analysis. All panels show the difference from the reference scenario (1.5C_Syn).

shares a common approach with models that determine technology deployment levels to minimize energy system costs, which explains why our estimated CDR volume by DACCS was close to those estimated in previous studies. In contrast, representations of synthetic fuel consumption differ considerably between our proposed model and the energy-system models used in previous studies. Energy-system models consider detailed energy supply and end-use technologies and determine synthetic fuel consumption to minimize energy-system costs while meeting a given level of service demand. Consequently, synthetic fuels with high production costs are introduced only in limited sectors, such as aviation and maritime transport, with few emission-reduction options. In contrast, the model developed in this study estimates the share of energy commodities using a logit function with a fixed elasticity, without representing specific energy end-use technologies. This formulation represents irrational consumer choices driven by preferences for specific energy commodities or end-use devices, as well as consumer inertia. The proposed model assumes a society in which consumers accept the increased costs associated with using synthetic fuels while maintaining lifestyles comparable to those using conventional petroleum and gaseous fuels. Consequently, synthetic fuels are consumed even when their price exceeds that of other energy goods, resulting in higher estimated synthetic fuel consumption compared to previous studies. The amount of CO_2 removed by DACCS estimated in this study was less than the amount removed in the aforementioned literature. However, the amount of carbon removed by DACCS estimated in this study was at the upper end of the range of the scenarios categorized into C1 and C2 in the AR6 database (0–18.9 (min-max), 0–13.8 (p5-p95)) or exceeded that range. The amount of CO_2 removed by DACCS depends not only on the technical assumptions of the DAC, but also on assumptions about geological storage, land cover, and demand-side conditions. Even in a scenario that limits the rise in global average temperature to below 1.5 °C, there is considerable uncertainty in the amount of CO_2 removed by DACCS.

In the mitigation scenario considering only DACCS, the utilization of DACCS replaced emission reductions achieved using bio-liquid fuels and electrification in the transportation sector, in addition to emission reductions by BECCS. It mitigated increases in food prices due to land use competition. Changes in mitigation measures and socio-economic impacts resulting from using DACCS share common characteristics with previous studies. DACCS reduced the cost of emission reductions. In addition, investments in DAC adoption and final energy consumption by DAC were included in the GDP, thereby mitigating GDP losses resulting from mitigation policy to achieve the emission level of the scenario. Newly considered emission-reduction technologies also demonstrated reduced household consumption losses in the latter half of this century. However, this effect was smaller than the effect on GDP. The DAC sector newly expressed in this study was solely related to CO_2 capture; storage services produced by the storage sector were not included in household consumption. In the AIM-Hub model, carbon price revenues flow from the government to households, funding storage services produced by the storage sector, with the amount paid to households decreasing by the amount paid for storage services. Consequently, the household consumption loss improvement rate was lower than the GDP loss improvement rate achieved through the introduction of new technologies. Fossil fuel consumption significantly increased due to rising petroleum-derived liquid fuel consumption in the transport sector and natural gas demand for DAC operations. The side benefit of climate change mitigation, such as reducing air pollutant emissions from burning fossil fuels, mitigating environmental impacts associated with fossil fuel extraction, and reducing sustainability concerns, are undermined due to the large scale DAC implementation. The increased demand for fossil fuels due to DAC can be partially addressed by utilizing DAC using solid sorbent and replacing energy sources with renewable energy or waste heat. In this study, the scenario in which the DAC powered by electricity was designed to understand the model's behavior. This scenario demonstrated that using electricity as the energy source for the DAC reduced the use of geological storage and the consumption of natural gas, while increasing the GDP loss. DACs utilizing solid sorbents also have economic advantages such as being able to operate using waste heat or surplus renewable energy and being able to operate in small-scale facilities. It is difficult to consider these advantages with a CGE model alone. To estimate a scenario that fully considers the advantages of DACs utilizing solid adsorbents, it will be necessary to integrate it with a bottom-up model.

In mitigation scenarios that considered synthetic fuel usage, energy supply from oil and natural gas decreased compared to scenarios that considered only DACCS, while solar and wind energy supply increased. Furthermore, biomass supply decreased in the first half of this century, leading to lower food prices. Focusing on final energy consumption, the use of synthetic fuels as alternatives reduced the consumption of petroleum-derived liquid fuels, reflecting the indirect electrification effect of synthetic fuels. However, the inclusion of synthetic fuels increased the economic impact on GDP and household consumption associated with mitigation policy implementations, despite the increased options for mitigation technologies. Particularly in the first half of this century, in the scenario considering use of synthetic fuel (1.5C_Syn), the economic impacts exceeded those in the scenario without DACCS nor synthetic fuel (1.5C_NoDAC). The proposed model estimates consumer energy commodity choices using a logit function under a constant elasticity, taking into account consumer behavioral inertia and preferences. The logit function allows for estimations that conserve the balance of physical quantities while assuming a constant elasticity. The logit function has shown high performance in predicting fuel substitutions in industrial energy demand [49] and has been used to forecast the demand for crude oil and natural gas [50,51]. Synthetic fuels produced by reacting renewable energy-derived hydrogen with CO_2 can replace most liquid and gaseous fuels used for energy purposes derived from fossil fuels. Therefore, there is a certain justification for representing the consumption of synthetic fuels with a logit function. The logit function estimates consumer selection by assuming a constant elasticity of energy commodity prices; therefore, even under relatively lenient emission constraints, expensive synthetic fuels are used to some extent. A sensitivity analysis of the transportation sector's energy goods choices to price elasticity showed that rising price elasticity reduced the consumption of synthetic fuels, particularly in the first half of this century, mitigating economic impacts. This suggests that irrational consumer choices of energy goods increased the consumption of synthetic fuels, exacerbating economic impacts. From the latter half of the century, economic impacts diminished due to increased demand for emission-free liquid fuels, driven by population and economic growth, as well as stringent emission constraints. However, because it is more economically efficient to storage the CO_2 captured by DAC and perform CDR rather than using it to produce synthetic fuels under the costs set by this study, the scenario considering the use of synthetic fuels (1.5C_Syn) had a greater economic impact throughout the calculation period than the scenario not considering the use of synthetic fuels (1.5C_DAC). To estimate mitigation scenarios that explore the economic effects of synthetic fuels, it is necessary to link the proposed model with an energy-system model and exogenously set the timing for initiating synthetic fuel use, the sectors utilizing synthetic fuels, and the consumption levels of synthetic fuels.

When assumptions about production costs and conversion efficiencies for newly considered technologies related to DAC and synthetic fuel production are varied, the consumption levels of associated goods and their economic impacts change. Reducing hydrogen-production costs and increasing conversion efficiency from renewable electricity resulted in an approximately 12 % decrease in hydrogen prices and more than doubled hydrogen consumption by the end of this century. The decline in hydrogen prices led to a reduction of over 6 % in synthetic liquid fuel prices. However, the increase in synthetic liquid fuel consumption was limited to 9.81 %. When synthetic fuel production costs were reduced and conversion efficiency from hydrogen was increased,

synthetic liquid fuel prices decreased by over 6 %, and synthetic liquid fuel consumption increased by 13.8 %. Synthetic fuel consumption was less sensitive to price changes compared to hydrogen due to the logit function used to determine the share of energy commodities in final energy consumption, which resulted in high consumption sensitivity to price changes for energy goods with prices closest to the cheapest energy goods. Conversely, energy goods with prices significantly exceeding those of the cheapest energy goods exhibited low sensitivity to price changes. Even when synthetic fuel prices were reduced, consumption did not change significantly because the price remained higher than competing energy commodities. Reducing the cost of CO_2 capture via DAC lowered the price of atmospheric CO_2 as a commodity by 20 % and increased CDR via DACCS by 40.2 %. Reducing DAC costs significantly lowered the prices of solid, liquid, and gas fuels by changing the carbon price. Increased CDR via DACCS, substituted for BECCS, reduced biomass demand, thereby lowering food prices. These changes improved the economic impacts on GDP and household consumption in the latter half of this century. Various technologies have been developed to achieve DAC, each with different CO_2 capture costs and requiring different types of energy inputs.

Literature estimating the capacity of geological CO_2 storage have shown a global technological potential of over 4900 Gt-CO_2 [43,49]. However, the use of the capacity may be limited by various factors. Gidden et al. (2025) estimated the technical potential of geological storage and the potential considering the restrictions on the use of geological storage to minimize the risks of leakage and well development. The result shows that the potential considering the restrictions was 1460 Gt-CO_2. In all the scenarios estimated in this study, the estimated CO_2 storage amount fell below the geological storage capacity estimated by Gidden et al. (2025). However, these scenarios were calculated over a period up to 2100, and storage use may be limited when considering longer-term use. Therefore, considering long-term use of geological storage, it will likely be necessary to limit geological storage use or to operate DACs using electricity.

5. Conclusion

This study developed a CGE model capable of analyzing climate-change mitigation scenarios considering DACCS and synthetic fuels. We newly incorporated sectors capturing CO_2 via DAC, storing captured CO_2 underground, and producing synthetic fuels using captured CO_2 in the AIM-Hub model. To demonstrate the impacts of these newly represented sectors on our calculation results and to identify settings that significantly affected estimation outcomes, multiple mitigation scenarios based on the 1.5 °C climate goal were estimated with modified settings related to the newly added sectors. The model results indicate that by the end of this century, DAC recovered 14.3 Gt-CO_2/year of CO_2, of which 12.8 Gt-CO_2/year was used for CDR. The remaining 1.51 Gt-CO_2/year was used to produce synthetic fuels, supplying 27.2 EJ/year of liquid and gaseous fuels. DACCS deployment replaced emissions reductions achieved through electrification, biomass-based CDR, and bio-liquid fuel supply, thereby suppressing food price increases caused by land-use competition. Furthermore, introducing DACCS reduced the costs of emission reductions and mitigated GDP and household consumption losses due to emission reductions. The use of synthetic fuels reduced emissions in hard-to-abate sectors and suppressed food price increases by lowering biomass demand. On the other hand, under the energy conversion efficiency and cost of synthetic fuel production assumed in this study, it was more economically efficient to store the CO_2 captured by DAC for CDR rather than using it for synthetic fuel production. Therefore, throughout the calculation period, the use of synthetic fuels increased the economic impact associated with the implementation of mitigation policies. Particularly in the first half of this century, when emission constraints were relatively less stringent, irrational consumer choices due to the preferences and inertia increased the consumption of synthetic fuels, thereby increasing the economic loss. This is because the AIMHub model represents the selection of energy commodities using a logit function, taking into account consumer preferences and inertia. Estimated CDR amounts by DACCS were close to those reported in previous studies, but our synthetic fuel consumption estimates were higher than previous estimates due to the characteristics of the CGE model. Our mitigation scenario results based on a 1.5 °C climate goal clarified the impacts of DACCS and synthetic fuel utilization on household budgets and commodity prices. The proposed CGE model successfully analyzed mitigation scenarios considering DACCS and synthetic fuel utilization, and can contribute to the formulation of mitigation policies considering the latest mitigation technologies, as well as to the analysis of their economic impacts.

The proposed model had two limitations. First, the mitigation scenarios estimated by our model showed excessive synthetic fuel consumption, resulting in adverse effects on GDP and household consumption in the first half of this century. To estimate mitigation scenarios considering the economic use of synthetic fuels, it will be necessary to link the CGE model with an energy-system model and set parameters for synthetic fuel consumption and geological storage use more cautiously. Second, the utilization of CO_2 captured via DAC was limited to synthetic fuel production or CDR in our model. Captured CO_2 could also be used for mitigation measures in sectors where emission reduction is difficult, such as chemical production and cement manufacturing. Considering these options would enable a more comprehensive evaluation of the value of DAC.

CRediT authorship contribution statement

Osamu Nishiura: Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Shinichiro Fujimori:** Writing – review & editing, Validation, Supervision, Software, Resources, Project administration, Funding acquisition, Data curation. **Ken Oshiro:** Writing – review & editing, Validation, Supervision, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Shinichiro Fujimori reports financial support was provided by Government of Japan Ministry of the Environment. Shinichiro Fujimori reports financial support was provided by Sumitomo Electric Industries Group. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] K. Riahi, C. Bertram, D. Huppmann, J. Rogelj, V. Bosetti, A.M. Cabardos, et al., Cost and attainability of meeting stringent climate targets without overshoot, Nat. Clim. Chang. 11 (2021) 1063–1069.

[2] O. Fricko, P. Havlik, J. Rogelj, Z. Klimont, M. Gusti, N. Johnson, et al., The marker quantification of the shared socioeconomic pathway 2: a middle-of-the-road scenario for the 21st century, Glob. Environ. Chang. 42 (2017) 251–267.

[3] Krey V., Havlik P., Kishimoto P., Fricko O., Zilliacus J., Gidden M., et al. MESSAGEix-GLOBIOM documentation - 2020 release. 2020.
[4] G. Luderer, S. Madeddu, L. Merfort, F. Ueckerdt, M. Pehl, R. Pietzcker, et al., Impact of declining renewable energy costs on electrification in low-emission scenarios, Nat. Energy 7 (2021) 1.
[5] F. Schreyer, F. Ueckerdt, R. Pietzcker, R. Rodrigues, M. Rottoli, S. Madeddu, et al., Distinct roles of direct and indirect electrification in pathways to a renewables-dominated European energy system, One Earth. 7 (2024).
[6] K. Calvin, P. Patel, L. Clarke, G. Asrar, B. Bond-Lamberty, R.Y. Cui, et al., GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems, Geosci. Model. Dev. 12 (2019).
[7] R. Draeger, B.S.L. Cunha, E. Müller-Casseres, P.R.R. Rochedo, A. Szklo, R. Schaeffer, Stranded crude oil resources and just transition: why do crude oil quality, climate ambitions and land-use emissions matter, Energy 255 (2022).
[8] Emmerling J., Drouet L., Reis L., Bevione M., Berger L., Bosetti V., et al. The WITCH 2016 model - documentation and implementation of the shared socioeconomic pathways. 2016.
[9] S. Fujimori, T. Masui, Y. Matsuoka, Development of a global computable general equilibrium model coupled with detailed energy end-use technology, Appl. Energy 128 (2014) 296–306.
[10] Post-2020 Climate Action, Springer, Singapore, 2017.
[11] Y.H.H. Chen, S. Paltsev, A. Gurgel, J.M. Reilly, J. Morris, The MIT EPPA7: a multisectoral dynamic model for energy, economic, and climate scenario analysis | MIT global change, Jt. Program Rep. Ser. Rep. 54 (2022) 3602022.
[12] R.D. Sands, K. Schumacher, H.U.S. Forster, CO2 Mitigation in a Global Context: Welfare, Trade and Land Use, 2014.
[13] Capros P., Denise V.R., Leonidas P., Karkatsoulis P., Fragkiadakis C., Tsani S., et al. GEM-E3 model documentation. 2013.
[14] D. Huppmann, M. Gidden, O. Fricko, P. Kolp, C. Orthofer, M. Pimmer, et al., The MESSAGEix integrated assessment model and the ix modeling platform (ixmp): an open framework for integrated and cross-cutting analysis of energy, climate, the environment, and sustainable development, Environ. Model. Softw. 112 (2019) 143–156.
[15] IEA-ETSAP, optimization modeling documentation, 2021.
[16] Bond-Lamberty B., Pralit P., Lurz J., Pkyle, Kvcalvin, Smith S., et al. JGCRI/gcam-core: GCAM 7.0. Zenodo; 2023.
[17] K. Oshiro, S. Fujimori, Role of hydrogen-based energy carriers as an alternative option to reduce residual emissions associated with mid-century decarbonization goals, Appl. Energy 313 (2022) 118803.
[18] A. Manne, R. Mendelsohn, R. Richels, MERGE: a model for evaluating regional and global effects of GHG reduction policies, Energ. Policy 23 (1995).
[19] H.D. Jacoby, J.M. Reilly, J.R. McFarland, S. Paltsev, Technology and technical change in the MIT EPPA model, Energ. Econ. 28 (2006).
[20] T. Faehn, G. Bachner, R. Beach, J. Chateau, S. Fujimori, M. Ghosh, et al., Capturing key energy and emission trends in CGE models: assessment of status and remaining challenges, J. Glob. Econ. Anal. 5 (2020).
[21] T. Hasegawa, S. Fujimori, P. Havlík, H. Valin, B.L. Bodirsky, J.C. Doelman, et al., Risk of increased food insecurity under stringent global climate change mitigation policy, Nat. Clim. Chang. 8 (2018) 699–703.
[22] A. Nemmour, A. Inayat, I. Janajreh, C. Ghenai, Green hydrogen-based E-fuels (E-methane, E-methanol, E-ammonia) to support clean energy transition: a literature review, Int. J. Hydrog. Energ. 48 (2023).
[23] L. Dray, A.W. Schäfer, C. Grobler, C. Falter, F. Allroggen, M.E.J. Stettler, et al., Cost and emissions pathways towards net-zero climate impacts in aviation, Nat. Clim. Chang. 12 (2022) 10.
[24] C. Breyer, G. Lopez, D. Bogdanov, P. Laaksonen, The role of electricity-based hydrogen in the emerging power-to-X economy, Int. J. Hydrog. Energ. 49 (2024).
[25] D.W. Keith, G. Holmes, D.S. Angelo, K. Heidel, A process for capturing CO2 from the Atmosphere, Joule 2 (2018) 1573–1594.
[26] F. Ueckerdt, C. Bauer, A. Dirnaichner, J. Everall, R. Sacchi, G. Luderer, Potential and risks of hydrogen-based e-fuels in climate change mitigation, Nat. Clim. Chang. 11 (2021) 384–393.
[27] J. Fuhrman, H. McJeon, P. Patel, S.C. Doney, W.M. Shobe, A.F Clarens, Food–energy–water implications of negative emissions technologies in a +1.5 °C future, Nat. Clim. Chang. 10 (2020) 10.
[28] J. Fuhrman, C. Bergero, M. Weber, S. Monteith, F.M. Wang, A.F. Clarens, et al., Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system, Nat. Clim. Chang. 13 (2023) 4.
[29] G. Realmonte, L. Drouet, A. Gambhir, J. Glynn, A. Hawkes, A.C. Köberle, et al., An inter-model assessment of the role of direct air capture in deep mitigation pathways, Nat. Commun. 10 (2019) 1.
[30] J. Strefler, N. Bauer, E. Kriegler, A. Popp, A. Giannousakis, O. Edenhofer, Between scylla and charybdis: delayed mitigation narrows the passage between large-scale CDR and high costs, Env. Res Lett. 13 (2018) 044015.
[31] K. Akimoto, F. Sano, J. Oda, H. Kanaboshi, Y. Nakano, Climate change mitigation measures for global net-zero emissions and the roles of CO2 capture and utilization and direct air capture, Energy Clim Chang-Uk 2 (2021) 100057.
[32] K. Oshiro, S. Fujimori, T. Hasegawa, S. Asayama, H. Shiraki, K. Takahashi, Alternative, but expensive, energy transition scenario featuring carbon capture and utilization can preserve existing energy demand technologies, One Earth. 6 (2023).
[33] S. Mori, O. Nishiura, K. Oshiro, S. Fujimori, Synthetic fuels mitigate the risks associated with rapid end-use technology transition in climate mitigation scenarios, Glob. Environ. Change Adv. 2 (2024).
[34] J. Morris, A. Sokolov, J. Reilly, A. Libardoni, C. Forest, S. Paltsev, et al., Author Correction: quantifying both socioeconomic and climate uncertainty in coupled human–Earth systems analysis, Nat. Commun. 16 (2025) 1.
[35] S. Fujimori, K. Oshiro, O. Nishiura, T. Hasegawa, H. Shiraki, Integration of a computable general equilibrium model with an energy system model: application of the AIM global model, Environ. Model. Softw. 178 (2024).
[36] Z. Liu, M. Zhang, C. Bauer, R. McKenna, The role of low carbon fuels towards net-zero in integrated assessment models and energy system models: a critical review, Renew. Sustain. Energy Rev. 215 (2025).
[37] S. Fujimori, T. Hasegawa, T. Masui, AIM/CGE V2.0: basic feature of the model, in: S. Fujimori, M. Kainuma, T. Masui (Eds.), Post-2020 Climate Action: Global and Asian Perspectives, Springer, Singapore, 2017, pp. 305–328.
[38] Dimaranan B.V. Global Trade, Assistance, and Production: The GTAP 6 Data Base. Center for Global Trade Analysis, Purdue University, 2006.
[39] IEA, World energy balances 2019, 2019, p. p. 793.
[40] C.L. Fyson, S. Baur, M. Gidden, C.F. Schleussner, C.L. Fyson, S. Baur, et al., Fair-share carbon dioxide removal increases major emitter responsibility, Nat. Clim. Chang. 10 (2020) 9.
[41] M. Fasihi, O. Efimova, C. Breyer, Techno-economic assessment of CO2 direct air capture plants, J. Clean. Prod. 224 (2019) 957–980.
[42] C. Hendriks, W.H.J. Crijns-Graus, F. Bergen, Global Carbon Dioxide Storage Potential and Costs, TNO for Rijksinstituut voor Volksgezondheid en Milien, Utrecht, Ecofys, 2004.
[43] Ieaghg. Potential for biomass and carbon dioxide capture and storage. 2011.
[44] M.J. Gidden, S. Joshi, J.J. Armitage, A.B. Christ, M. Boettcher, E. Brutschin, et al., A prudent planetary limit for geologic carbon storage, Nature 645 (2025) 8079.
[45] IEA, CCUS in Clean Energy Transitions, IEA, 2020.
[46] B.C. O'Neill, E. Kriegler, K. Riahi, K.L. Ebi, S. Hallegatte, T.R. Carter, et al., A new scenario framework for climate change research: the concept of shared socioeconomic pathways, Clim. Chang. 122 (2014) 387–400.
[47] J.C. Minx, W.F. Lamb, M.W. Callaghan, S. Fuss, J. Hilaire, F. Creutzig, et al., Negative emissions—part 1: research landscape and synthesis, Env. Res Lett. 13 (2018).
[48] E. Byers, V. Krey, E. Kriegler, K. Riahi, R. Schaeffer, J. Kikstra, et al., AR6 scenarios database, Zenodo (2022).
[49] G. Urga, C. Walters, Dynamic translog and linear logit models: a factor demand analysis of interfuel substitution in US industrial energy demand, Energ. Econ. 25 (2003).
[50] R.M. Mackay, S.D. Probert, Crude oil and natural gas supplies and demands up to the year ad 2010 for France, Appl. Energy 50 (1995).
[51] R.M. Mackay, S.D. Probert, Forecasting the United Kingdom's supplies and demands for fluid fossil-fuels, Appl. Energy 69 (2001).