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Role of hydrogen-based energy carriers as an alternative option to reduce residual emissions associated with mid-century decarbonization goals

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HIGHLIGHTS

- Hydrogen accounts for 5–10% of total energy in 2050 under 2 °C scenarios.
- Hydrogen share increases for a 1.5 °C goal and reaches 15% if CCS is limited.
- Transport is the largest consumer of hydrogen, followed by industry and power.
- Synthetic hydrocarbons based on hydrogen and direct air capture are an option.
- Holistic energy policy design is needed rather than heavy dependence on hydrogen.

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ABSTRACT

Hydrogen-based energy carriers, including hydrogen, ammonia and synthetic hydrocarbons, are expected to help reduce residual carbon dioxide emissions in the context of the Paris Agreement goals, although their potential has not yet been fully clarified in light of their competitiveness and complementarity with other mitigation options such as electricity, biofuels and carbon capture and storage (CCS). This study aimed to explore the role of hydrogen in the global energy system under various mitigation scenarios and technology portfolios using a detailed energy system model that considers various energy technologies including the conversion and use of hydrogen-based energy carriers. The results indicate that the share of hydrogen-based energy carriers generally remains less than 5% of global final energy demand by 2050 in the 2 °C scenarios. Nevertheless, such carriers contribute to removal of residual emissions from the industry and transport sectors under specific conditions. Their share increases to 10–15% under stringent mitigation scenarios corresponding to 1.5 °C warming and scenarios without CCS. The transport sector is the largest consumer, accounting for half or more of hydrogen production, followed by the industry and power sectors. In addition to direct usage of hydrogen and ammonia, synthetic hydrocarbons converted from hydrogen and carbon captured from biomass or direct air capture are attractive transport fuels, growing to half of all hydrogen-based energy carriers. Upscaling of electrification and biofuels is another common cost-effective strategy, revealing the importance of holistic policy design rather than heavy reliance on hydrogen.

1. Introduction

The climate change mitigation goals described in the Paris Agreement, which include keeping the temperature increase well below 2 °C and pursuing efforts to keep it below 1.5 °C, require substantial transformation of energy and land systems. Existing scenario studies conducted using integrated assessment models (IAMs) have explored several decarbonization pathways consistent with the Paris Agreement climate goals, mainly accomplished using carbon dioxide removal (CDR) or negative emission technologies (NETs) [1]. Some of these pathways, however, depend on large-scale CDR in the second half of this century, and may entail several issues such as food price increases due to land-use changes for bioenergy production [2,3]. In this regard, alternative transformation pathways are expected, including immediate reduction

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of greenhouse gas (GHG) emissions in the mid-century period, rather than depending on large-scale negative emissions [4]. Such transformation pathways would require removal of residual CO_2 emissions from energy sectors, especially the industry and transport sectors, where emissions associated with high temperature, heat demand and long-distance transport are generally difficult to eliminate [5,6].

For mid-century decarbonization pathways without reliance on CDR, IAM-based studies have explored several scenarios accomplished by lowering energy-related emissions through various measures, such as lowering energy demand through lifestyle and social changes and promoting electrification and bioenergy use [7–12]. Among such measures, hydrogen-based energy carriers are expected to eliminate residual emissions, as long as they are obtained from low-emission sources, such as renewable-based electricity or fossil fuels using carbon capture and sequestration (CCS). Hydrogen is expected to reduce emissions where electrification cannot be easily implemented, such as for heavy industries and long-distance transport [6,13–16]. Furthermore, utilization of hydrogen-based synthetic hydrocarbons converted from captured CO_2 using fossil fuels, bioenergy or direct air capture (DAC) in conjunction with low-carbon hydrogen technologies, including e-fuels, may be essential to reducing residual emissions [17]. Even if the CO_2 emissions derived from synthetic hydrocarbon products are not captured and sequestered, these products can be carbon–neutral as long as their carbon is obtained from DAC or biomass and hydrogen from low-carbon sources [18].

Given its characteristics as a low-carbon secondary energy carrier, the potential of hydrogen has been assessed using integrated assessment models (IAMs) and energy system models. For example, previous studies using the MESSAGE [19], TIMER [20], GCAM [21] and TIAM [22] have indicated that hydrogen can be an effective mitigation option if it is supplied from low-emission sources in a cost-competitive manner. While several IAMs and energy system models include hydrogen as a secondary energy carrier [23,24], recent studies have shown that the share of hydrogen as a portion of total energy is less than 3% for most models, even under very stringent mitigation scenarios with warming likely to remain below 1.5 °C [5]. Even when a variety of climate policies and socio-economic conditions are considered, hydrogen penetration is limited while electrification is a robust mitigation option [25].

Nevertheless, several factors have recently been found to enhance the importance of hydrogen in the context of deep decarbonization. First, as solar- and wind-based electrolysis is expected to be a major source of low-carbon hydrogen production in the context of the Paris Agreement mitigation goals [26], the effectiveness of hydrogen utilization depends on competitiveness with other variable renewable energy (VRE) integration options, such as battery storage and demand response (DR) in conjunction with electrification of the energy demand sector. To this end, energy system models must be designed to consider the intermittent nature of VREs and thus support the potential of hydrogen. Also, synthetic hydrocarbons, which include liquid synfuels and synthetic methane, are expected to become increasingly available as carbon capture and utilization (CCU) options in conjunction with DAC and carbon capture for bioenergy to remove residual CO_2 emissions that are difficult to eliminate [27]. Although some recent IAM investigations have considered the role of DAC combined with geological storage for CDR [28,29], their carbon utilization potential in the global energy system remains unclear.

While the previous studies have explored the transformation pathways reducing residual CO_2 emissions towards the mid-century decarbonization goals as reviewed in the previous parts of this section [5,8,9,12], little is known about a potential role of hydrogen-based energy carriers on attaining these goals, especially in the context of the complexity of decarbonized energy systems associated with VRE integrations, and the role of innovative mitigation options, such as utilization of synthetic hydrocarbon converted from hydrogen and carbon captured by DAC. In order to fill these knowledge gaps, it is essential to assess a broad set of scenarios by detailed energy system model with high temporal resolution to represent VRE integration, and to consider availability of key mitigation options, including new technology options such as DAC.

In this study, we aimed to explore the role of hydrogen-based energy carriers in the context of the mid-century mitigation pathways while considering the complexity and uncertainty of energy system transformation associated with the decarbonization goal of the Paris Agreement. To this end, we developed an energy system model that can consider the complexity of energy system transformation, particularly for the conversion and end use of hydrogen-based energy carriers, with high resolution that can support appropriate exploration of the potential of hydrogen. The scenario analysis includes uncertainties on energy system transformations that are relevant to hydrogen generation and consumption, as well as key mitigation options such as CCS, bioenergy, and new technologies for the utilization of hydrogen-based energy carriers. Consequently, this study elucidates the process of large-scale penetration of hydrogen and its implications for energy system transformation and mitigation costs.

2. Methods

2.1. Energy system model

2.1.1. Model structure

In this study, we developed the AIM/Technology model, which is a partial equilibrium global energy system model characterized by detailed descriptions of energy technologies in the energy demand and supply sectors, based on the previously reported AIM/Enduse model [30]. This model has been utilized for global energy system analysis as a stand-alone model or coupled with a computable general equilibrium (CGE) model [31]. The model structure and energy demand sector data are generally consistent with AIM/Enduse [Global] [32], while those for energy supply sectors are updated based on the AIM/Enduse [Japan] framework [33]. AIM/Technology has detailed electricity dispatch information with a 1-hour time step for representative days based on a combination of season (summer, winter) and peak load (peak, non-peak), allowing hydrogen generation through electrolysis using excess VRE supply to be assessed endogenously. AIM/Technology performs recursive dynamic simulation with a one-year step, with new installation of technologies determined so that the total energy system cost is minimized, which includes annualized capital cost, operation and management (O&M) costs, and energy and emission costs. Details of the model structure, including its energy system representation and theoretical formulation, are summarized in Appendix B.

2.1.2. Representation of hydrogen-based energy carriers

In this study, several secondary energy carriers based on hydrogen are included as energy technology options for AIM/Technology. In addition, several end-use technologies using hydrogen-based carriers are considered, such as hydrogen-based direct reduced iron (DRI) in the steelmaking process, hydrogen and ammonia in industrial furnaces and boilers, power generation using hydrogen and ammonia, synthetic liquid fuels or methane used as liquid or gas fuels in each energy demand sector, fuel cell electric vehicles and fuel cell use in the buildings sector, which were included in the AIM/Enduse framework [33] (Table A 1). The parameter assumptions for the conversion to new hydrogen generation and end-use technologies, such as conversion efficiency and technology costs, are assumed based on International Energy Agency (IEA) estimates [27], as summarized in Table 1. It should be noted that capital cost is predefined in this model, therefore it is not calculated endogenously based on technological learning curve. More detailed information on the cost assumptions is summarized in Appendix B. Also, as the existing infrastructure for energy transport is not explicitly modeled, construction costs for new infrastructure are not considered in this model. Ammonia and synthetic liquid fuels can be traded across regions, as can fossil fuels and biomass. The average production costs of

Table 1
Parameter assumptions for production of hydrogen-based energy carriers. Numbers in parentheses are for the H2lowcost scenario.

		Capital cost (US$/kW)	O&M cost (US $/kW)	efficiency (–)
Hydrogen	Electricity	1014 (652)	15 (10)	69%
	Coal	2670	134	60%
	Coal with CCS	2780	139	58%
	Gas	910	33	76%
	Gas with CCS	1360	41	69%
	Biomass	2333	222	60%
	Biomass with CCS	3091	290	55%
Ammonia [1]	Electricity	855 (760)	13 (11)	53%
	Coal	2175	109	48%
	Coal with CCS	2810	141	48%
	Gas	905	23	49%
	Gas with CCS	1260	32	49%
	Biomass	6320	316	41%
	Biomass with CCS	8165	408	41%
Synthetic hydrocarbons	Synthetic liquid fuel	760 (565)	30 (23)	73%
	Synthetic methane	735 (565)	30 (23)	77%

[1] Ammonia production costs are presented in US$/t-$NH_3$.

hydrogen and other energy carriers such as electricity are estimated based on capital and energy costs (see Supplementary note 1.1 for details). Parameter assumptions for energy demand technologies are summarized in Table 2. Devices that use synthetic hydrocarbon and hydrogen-based navigation are not shown here, as no additional investment in them is assumed. Currently, hydrogen is mainly consumed in oil refining or fertilizer production as feedstock that is mainly made from coal or natural gas [27]. In this model, these hydrogen demands for feedstock are not accounted as final energy use of hydrogen, but consumption of fossil fuel resources, in accordance with the accounting method in the IEA energy balances [34]. By contrast, hydrogen demand for energy use, such as fuel cell electric vehicle (FCEV), is included in final energy demand of hydrogen. Also, hydrogen consumption for hydrogen-DRI in steelmaking process is included in final energy use in this model.

The introduction of DAC based on hydroxide sorbents is modeled based on technology parameters obtained from the literature [29], in which capital and O&M costs are 1146 and 42 US$/t-$CO_2$, respectively, with energy inputs of 1.3 GJ/t-CO_2 of electricity and 5.3 GJ/t-CO_2 of heat. The heat demand for DAC is supported by natural gas, biomass or electricity.

Table 2
Parameter assumptions for hydrogen-based technologies in energy sectors.

Sector	Technology	Capital cost	O&M cost	Energy specification
Industry	Hydrogen DRI	855 US$/t	154 US $/t	9.6 GJ_{H2}/t 1.9 GJ_{Heat}/t
	Hydrogen/ ammonia furnace	163 US$/GJ	–	0%
	Hydrogen/ ammonia boiler	26 US$/GJ	–	0%
Transport	Fuel cell electric vehicle	27,510 US $/vehicle	–	1.43 GJ/km
	Fuel cell truck	103,375 US $/vehicle		4.79 GJ/km
Buildings	Fuel cell in buildings	955 US$/GJ	–	0.86
Power generation	Hydrogen/ ammonia power generation	1000 US $/kW	25 US $/kW	0.61

Note: monetary units for furnace, boiler and fuel cell for buildings represent the unit cost per useful energy output in GJ. Numbers for technology specifications denote energy consumption for hydrogen DRI and transport use, energy efficiency improvements for hydrogen furnaces and boilers compared with devices using fossil fuels, and energy conversion efficiency for fuel cells in buildings and power generation.

2.2. Scenarios

To elucidate the behavior of hydrogen-based energy carriers in energy system transformation, a broad set of scenarios was assessed, with various combinations of climate targets and technology portfolios (Table A 2). First, multiple emission scenarios were employed with varying levels of stringency with regard to climate policies, to explore the role of hydrogen diffusion on climate change mitigation. Second, several technology availability scenarios were assessed to explore the possibility of upscaling hydrogen usage considering uncertainties in the availability of other decarbonization options, as assumptions about the availability and cost of low-carbon technologies affect the degree of difficulty of mitigation [35,36]. The socio-economic conditions were based on SSP2 of the Shared Socio-economic Pathways (SSPs) [37]. Each scenario was named with a combination of budget category and technology portfolio, i.e., 1000-Default for the scenario with a 1000-Gt CO_2 budget and the default technology option.

2.2.1. Climate targets

We consider multiple carbon budgets between 2018 and 2100, in the range of 500–1400 Gt CO_2 with 100-Gt CO_2 increments, which is roughly the budget range covered in the Paris Agreement climate goals [38,39]. The CO_2 budgets of 500 to 900 Gt correspond to 1.5 °C, while the 1000 to 1400 Gt CO_2 budgets are associated with 2 °C warming. Under the mitigation scenarios, the pathways for CO_2 emissions from energy and industrial processes derived from each carbon budget were imposed as emission constraints, using values obtained from AIM/Hub results in the literature [40,41]. Mitigation began immediately in 2020, and existing mitigation frameworks such as the nationally determined contributions (NDCs) were not considered. The emissions constraint was imposed on global collective emissions and each region reduced its emissions based on globally uniform carbon prices. In the NoPol scenario, no additional climate policies were considered.

2.2.2. Technology dimensions

The technology scenarios were designed to explore the possibility of hydrogen upscaling in the context of the availability of other key mitigation options, economic assumptions associated with hydrogen, and the availability of hydrogen itself, as summarized in Table 3. First, in the default scenarios, all technology options were available with default

Table 3
Technological scenario descriptions.

Scenario	Specification	Motivation
Default	All modeled technology options are included with default parameter settings.	
CCSoff	Geological storage is unavailable.	Limited low-carbon and CDR sources, given uncertainties such as storage potential
LimBio	Dedicated bioenergy is excluded.	Limited low-carbon and CDR sources, given potential risks such as those to food security
H2off	Hydrogen conversion and use, including synthetic hydrocarbons, is unavailable.	Limited use of hydrogen, given that the associated technology is not yet mature
VRElowcost	Technology costs for VREs, including solar PV and wind power, were almost halved from the default assumptions.	Enhanced hydrogen penetration due to reduced production cost
H2lowcost	Assumed technology costs for hydrogen conversion are reduced	Enhanced hydrogen penetration due to reduced production cost

assumptions of their technological performance and costs, as listed in Table 1. Second, the CCSoff and LimBio scenarios assumed no availability of CCS and dedicated energy crops, respectively, as previous studies have indicated their impacts on deep decarbonization scenarios [42,43], given the concerns associated with geological storage and land-use changes. In the CCSoff scenarios, while geological storage is unavailable in all regions throughout the simulation period, utilization of captured carbon as a synthetic hydrocarbon is possible. Third, the H2off scenario, in which hydrogen-based energy carriers are unavailable, was developed to evaluate the impact of hydrogen utilization on the energy system and mitigation costs. Finally, the VRElowcost and H2lowcost scenarios were prepared to assess the potential of hydrogen diffusion when hydrogen production is reasonably implemented. In the VRElowcost scenarios, costs for solar photovoltaic (PV) and wind power were approximately half of those in the default scenario, matching the levels indicated in the International Renewable Energy Agency (IRENA) estimates [44,45]. The hydrogen generation cost in the H2lowcost scenarios is based on IEA data [27] and is summarized in Table 1.

3. Results

3.1. Hydrogen penetration and residual emissions

First, the results for final energy demand are summarized in Fig. 1a, as the use of hydrogen-based energy carriers in other sectors, namely power generation, was trivial relative to the total energy system, as described in the following sections. Fig. 1a depicts total energy demand by energy carrier under representative climate policy scenarios, including the 1000, 700 and 500 scenarios. The results for all scenarios are shown in Fig. A1. Note that the 500-CCSoff scenarios is not presented, as no feasible solution was obtained under that scenario. Hydrogen-based energy carriers, including hydrogen, ammonia and synfuels, increase gradually from 2030 and account for 5–15% of total energy demand in 2050 under stringent mitigation scenarios such as the 500 scenarios, whereas under higher-budget scenarios, namely those of 1000 Gt CO_2 or more, hydrogen-based energy carriers account for 5% or less of total final energy demand. The availability of technologies affects the diffusion rate of hydrogen-based energy carriers, especially in the CCSoff scenarios, where such carriers reach 17% of energy demand by 2050. Synfuels are used extensively in the CCSoff scenarios, reaching around half of total hydrogen-based energy carrier supply in 2050 in the 700-CCSoff scenario. While hydrogen enters the energy system through decarbonization measures, its usage is generally limited. Instead, electricity and bioenergy play major roles in most scenarios.

CO_2 emissions from each energy sector and industrial processes are illustrated in Fig. 1b and Fig. A2. Stringent mitigation and CCSoff scenarios, where increases of hydrogen-based energy carriers are observed, are characterized by lower residual emissions from energy demand

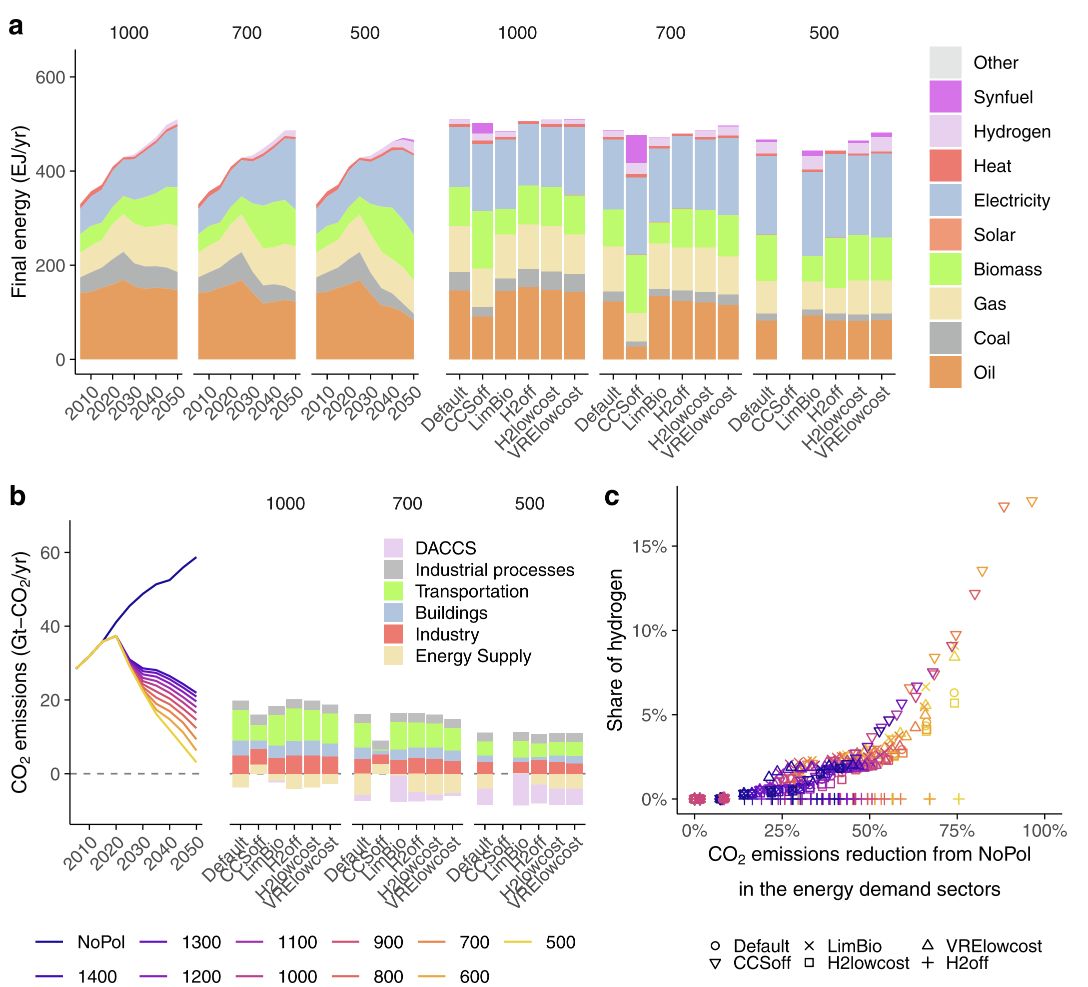

Fig. 1. a) Final energy demand by energy carrier. The left stacked panels represent time series of final energy demand in the default technology scenario, and the right bar plots show the corresponding values in 2050 under each technology scenario. Ammonia use is included with hydrogen. b) CO_2 emission trajectories from energy and industrial processes across scenarios (left). The right stacked bar plots show the corresponding values in 2050 for each technology scenario by sector. The 500-CCSoff scenario is not shown, as no feasible solution was obtained. c) Relationship between CO_2 emissions reduction relative to the NoPol scenario in energy demand sectors and share of hydrogen-based energy carriers.

sectors. In the 500 scenarios, residual emissions from energy demand sectors and industrial processes account for around 10 to 11 Gt CO_2/yr in 2050, of which 8 to 9 Gt CO_2/yr is offset by negative emissions of energy supply sectors. In the 700-CCSoff scenario, residual emissions from energy supply and demand sectors and industrial processes fall to around 9 Gt CO_2/yr, as CCS-based negative emission are unavailable in CCSoff scenarios. In these scenarios, which have the greatest diffusion rate of hydrogen-based energy carriers in 2050 among all scenarios, residual emissions of the transport and buildings sectors are reduced to almost zero and less than 1 Gt CO_2/yr, respectively.

The relationship between CO_2 emissions from energy demand sectors and the share of hydrogen-based energy carriers in final energy demand is depicted in Fig. 1c. The share of hydrogen under each scenario and its relationship with total CO_2 emissions are summarized in Fig. A3. With the exception of H2off scenarios, upscaling of hydrogen-based energy carriers occurs, particularly where CO_2 emissions of energy demand sectors are reduced to half of the level under the NoPol scenario. Meanwhile, in moderate emissions reduction cases, hydrogen-based energy carriers remain at 3% or less of total final energy demand.

3.2. Sectoral impacts of hydrogen consumption

To explore the role hydrogen plays among low-carbon energy carriers, the share of final energy consumption from hydrogen by sector is shown in the top panels of Fig. 2 for comparison with those from other non-fossil-based energies. The bottom panels illustrate the development of various energy carriers in each sector. Sectoral final energy demand under all scenarios is shown in Fig. A4. While both low-carbon energy carriers, namely hydrogen and electricity, contribute to reducing the emissions associated with fossil fuel use, the characteristics of hydrogen and electricity penetration vary by sector. First, the share of hydrogen-based energy carriers is largest in the transport sector, especially under CCSoff scenarios, where it reaches around 50% of transport energy demand, followed by the industry sector, where hydrogen reaches around 9% of demand. Electrification is also a driver of reduced direct emissions in both sectors, as the share of electricity increases to around 16% and 35% of the transport and industry sectors over the analysis period, respectively. As these sectors are characterized by a portion of emissions that cannot be easily decarbonized through conventional mitigation measures, such as high-temperature heating and long-distance transport

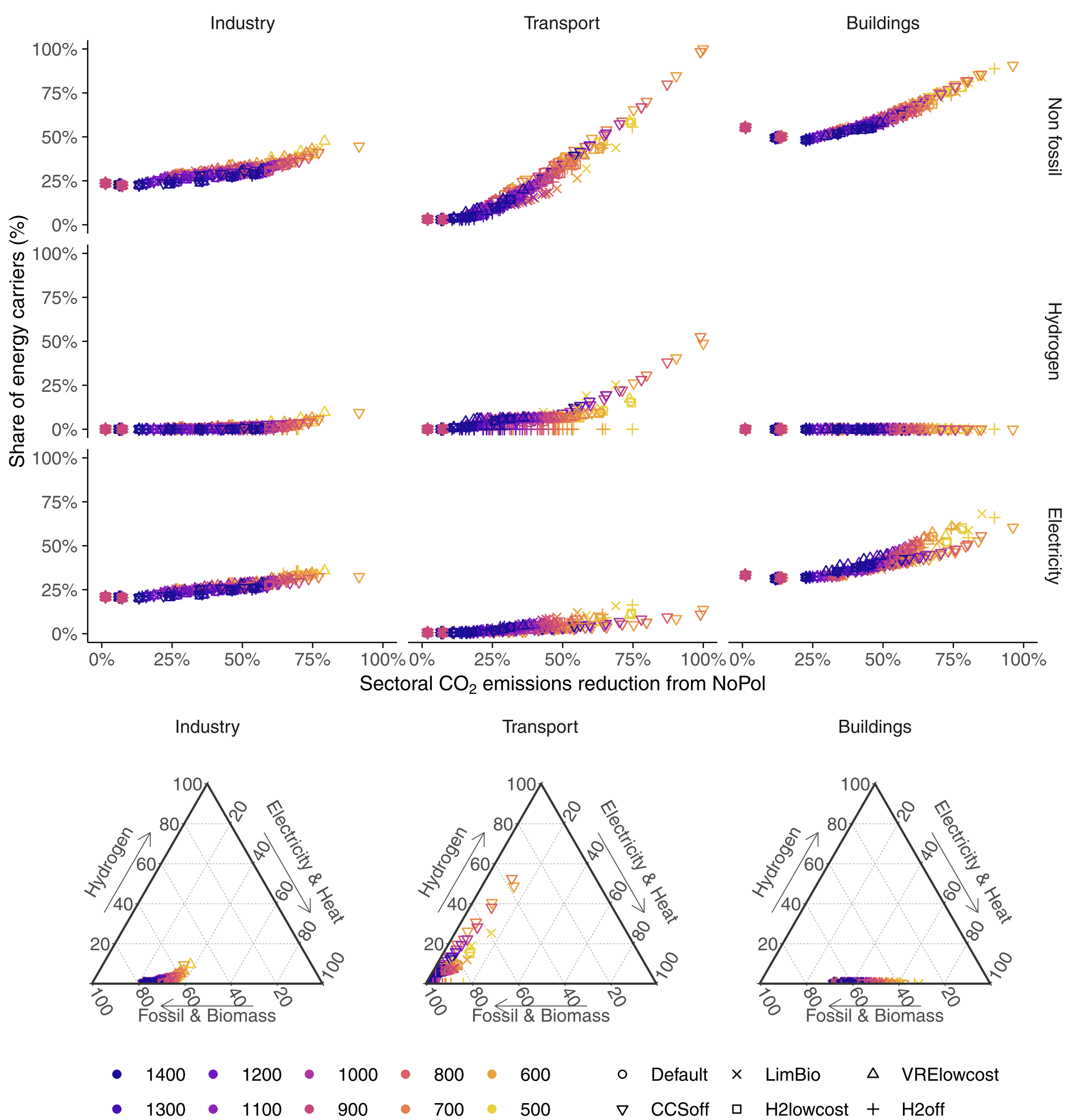

Fig. 2. Top panels show the relationship between the CO_2 emissions reduction relative to NoPol and the share of each energy carrier by sector for non-fossil energy carriers, including electricity, hydrogen-based, heat and renewable carriers, in which hydrogen-based carriers include synfuels and electricity. The CO_2 emissions presented here include only direct emissions, while indirect emissions induced by secondary energy use are not included. Bottom panels show the development of final energy share by energy carrier over the period of 2020–2050. Here, hydrogen includes ammonia and synfuels.

[6], hydrogen based-energy carriers can contribute greatly to reducing residual emissions. In particular, fossil fuel use in the transport sector must be phased out without CCS (CCSoff scenarios), and a substantial reduction of residual emissions from the demand sector is required due to upscaling of hydrogen-based energy carriers including synfuels, as well as electrification and biofuels.

In contrast, in the buildings sector, hydrogen is negligible across all scenarios, despite CO_2 emissions from the buildings sector being reduced by around 90% relative to NoPol under stringent mitigation scenarios. Instead, electrification is the largest contributor in the buildings sector, accounting for up to two-thirds of total final energy demand, as electrification is relatively cost efficient in the buildings sector.

3.3. Hydrogen supply and demand

Fig. 3a shows hydrogen supply by source in 2050 under representative scenarios, including hydrogen for conversion to ammonia and synthetic hydrocarbons as well as direct hydrogen usage. Consumption of hydrogen-based energy carriers by sectors is also illustrated and is generally smaller than total hydrogen supply, due to losses in the conversion from hydrogen to synthetic hydrocarbons and distribution losses. Hydrogen supply and demand across all scenarios is summarized in Fig. A5. Hydrogen production ranges around 10–30 EJ/yr in 2050 in the default technology scenarios and is generated primarily through electrolysis and low-emission sources, such as biomass and fossil fuels with CCS. As power generation is also nearly decarbonized, mainly, through upscaling of solar PV and wind power (Fig. A6), hydrogen production through electrolysis is also decarbonized in the mitigation scenarios. Therefore, hydrogen penetration in the energy demand sectors results in reduced global CO_2 emissions under these scenarios. Although electrolysis is a major source of hydrogen generation across all mitigation scenarios, its share and the underlying alternative energy sources vary among climate policy scenarios. In the 1000 scenarios, fossil fuel usage with CCS supports around half of total hydrogen production, whereas bioenergy with CCS (BECCS) is used with lower budgets, such as the 700 and 500 scenarios. In the CCSoff scenarios, hydrogen production reaches 100 EJ/yr or more and is converted using electricity or biomass without CCS, as an alternative option to geological storage of CO_2. In the VRElowcost scenario, the share of electrolysis reaches almost 100% of hydrogen production, as the price of low-carbon electricity decreases due to VRE cost reductions. In terms of synthetic fuel production, because carbon is captured by, nearly, carbon–neutral sources, namely biomass and DAC (Fig. A7), the shift from fossil fuels to

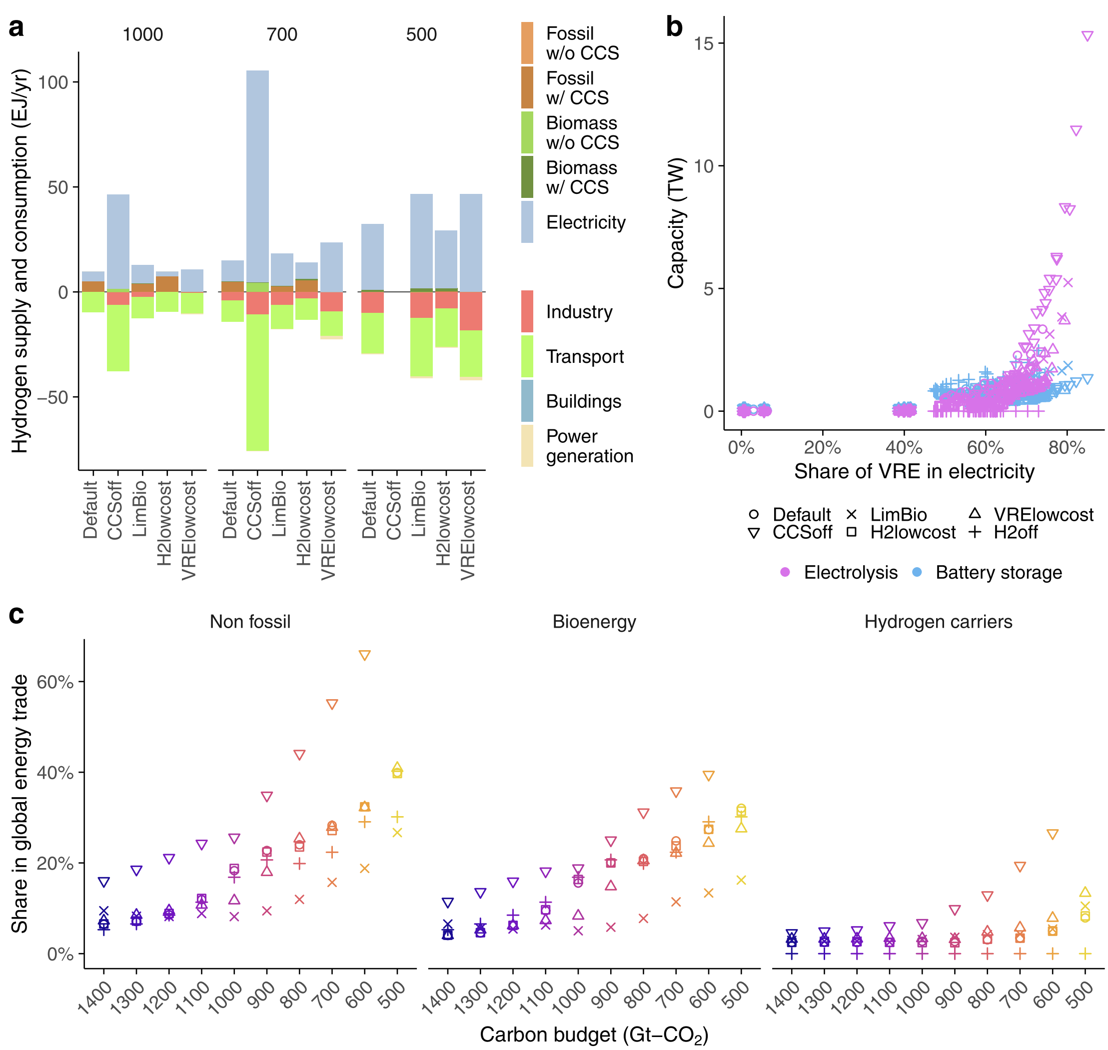

Fig. 3. a) Hydrogen supply by source and consumption by sector in 2050 under representative scenarios. Positive and negative values denote supply and consumption, respectively. Here, the H2off scenarios are not shown because both supply and consumption were zero. b) Capacity of battery storage and hydrogen production through electrolysis as a function of the VRE share in electricity generation. c) Shares of non-fossil energy carriers, bioenergy and hydrogen-based carriers in the global energy trade in 2050.

synthetic fuels in the transport sector contributes to decarbonization, even if CO_2 emitted from synfuel combustion is not captured.

While hydrogen production through electrolysis is expected to contribute to effective use of excess VRE supply, the upscaling of hydrogen production under stringent mitigation scenarios in this study is mainly due to VREs installed specifically for hydrogen production rather than a buffer of redundant VRE. It is due to rapid upscaling of hydrogen use in the energy demand sectors in the stringent mitigation scenarios in order to reduce emissions that are difficult to eliminate. While the installed capacity of electrolysis increases at a similar pace to batteries where the share of VRE remains around half or less, a steep rise in electrolysis capacity occurs where the VRE share exceeds around half of the electricity supply. By contrast, battery storage contributes to integration of VREs across the most mitigation scenarios (Fig. 3b, Fig. A8). Especially in the H2off scenario where effective use of VREs through electrolysis is unavailable, capacity of battery storage reaches up to 2.5 TW by 2050.

On the demand side, the transport sector is the largest consumer of hydrogen-based energy carriers under scenarios with budgets of 1000 Gt CO_2 or more, while the share of use in industry increases under stringent mitigation scenarios, nearly equaling the transport sector under 500 Gt CO_2 scenarios (Fig. 3a, Fig. A5b). Furthermore, the use of hydrogen and ammonia in the power sector as fuels for electricity generation increases under stringent mitigation conditions, reaching up to 1.4 EJ of total hydrogen consumption by 2050 under the 500 Gt CO_2 scenarios. However, their contributions to global total power generation are around 1% or less in 2050 (Fig. A6).

Stringent climate policies and technological constraints on alternative decarbonization options enhance international trade in hydrogen through transport of ammonia and synthetic liquid fuels. Fig. 3c summarizes the share of each energy carrier in global energy trade in 2050 (full results are shown in Fig. A9). The shares of non-fossil-based energy carriers, including bioenergy and hydrogen-based energy carriers, rise with increasing stringency of mitigation, and exceed those of fossil fuels in 2050 under the 700-CCSoff scenario. For all mitigation scenarios excluding LimBio, the share of bioenergy trade exceeds that of hydrogen, as bioenergy is another tradable low-emission energy carrier [46]. In the CCSoff scenarios and very stringent mitigation scenarios, such as the 500 scenarios, the share of hydrogen in global energy trade exceeds 10%. The international trade of hydrogen contributes to supplying hydrogen-based energy carriers in the specific regions where potential of low-carbon hydrogen sources, such as solar and wind, is limited or costly.

3.4. Cost effectiveness of hydrogen and its implications

Fig. 4a shows a comparison of global average production costs between electricity and hydrogen, and Fig. 4b depicts their average costs

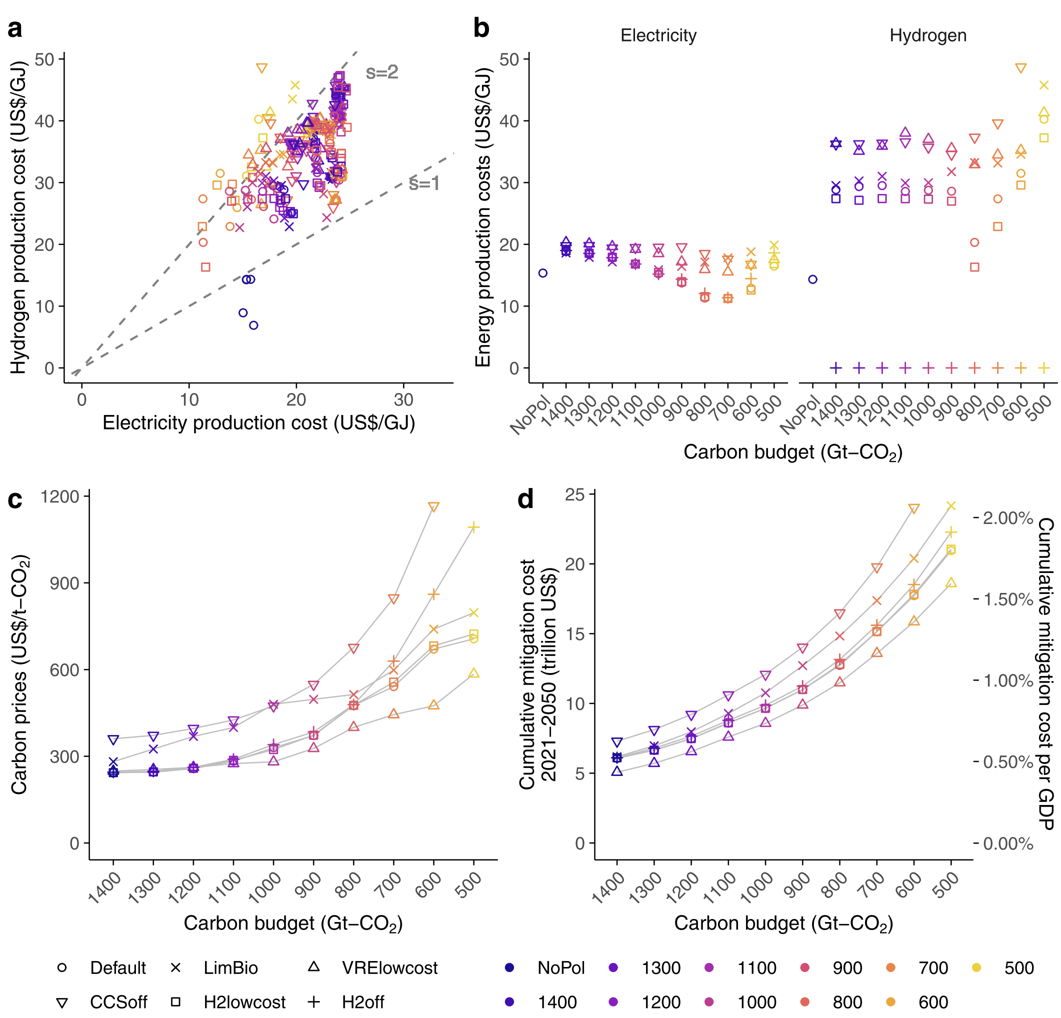

Fig. 4. a) Comparison of global average production costs for electricity and hydrogen. Diagonal dashed lines represent the ratio between hydrogen and electricity production costs, where *s* indicate slope. b) Global average production costs of electricity and hydrogen in 2050 across climate policy scenarios. Production costs include the effect of carbon prices. c) Carbon prices in 2050. d) Cumulative mitigation costs between 2021 and 2050 discounted at 5%. Discounted cumulative mitigation costs relative to gross domestic product (GDP) are labeled on the right axis.

across mitigation scenarios in 2050. With the exception of the NoPol scenarios, the production cost of hydrogen exceeds that of electricity in all scenarios, reaching double the cost of electricity production. In the NoPol scenario, hydrogen is produced mainly from fossil fuels without CCS, and where the conversion efficiency is comparable with that of electricity, the cost gap is small. In contrast because hydrogen is obtained primarily through electrolysis and nearly a third of electricity input is lost to conversion losses, the gap between electricity and hydrogen production costs increases in the mitigation scenarios. Furthermore, the cost gap between hydrogen and electricity increases under stringent mitigation scenarios, as the cost of hydrogen rises with the stringency of mitigation, while the change in electricity cost is moderate across all climate scenarios. This difference arises because the effect of carbon price revenue associated with BECCS, which can compensate for the increase in capital cost of low-carbon generators under stringent mitigation scenarios, in electricity generation is larger, while revenue associated with hydrogen generation is limited. In addition, especially under CCSoff scenarios, increased mitigation stringency results in a substantial increase in hydrogen generation, which indicates the need to produce hydrogen in a costly manner. These cost gaps between hydrogen and electricity lead to limited hydrogen diffusion, especially in the buildings sector, where electrification is available in addition to hydrogen. Nevertheless, hydrogen diffusion is crucial for mitigation in situations where electrification is not easily achieved despite the cost gap, such as for high-temperature processes in industry and long-distance transport, including road transport, maritime navigation and aviation. Among the hydrogen-based energy carriers, the average production costs of synthetic hydrocarbon and captured CO_2 are also summarized in Fig. A10. As the production cost of synfuel is generally higher than that of oil product, upscaling of synfuels in the final energy sectors is also limited.

Fig. 4c and d show carbon prices in 2050 and cumulative mitigation cost by 2050 under each technology constraint scenario. The cumulative mitigation cost presented here is the net present value accumulated between 2021 and 2050 relative to the corresponding NoPol scenarios, discounted at a 5% discount rate. In scenarios with high carbon budgets of 1000 Gt CO_2 or more, carbon price increases under CCSoff and LimBio are relative to the default scenario, while H2off scenarios have the second greatest increases after CCSoff scenarios in low-budget cases of 500–700 Gt CO_2. Cumulative mitigation costs for H2off also increase in these low-budget cases, although they do not reach the levels of CCSoff and LimBio. These cost implications suggest that the availability of hydrogen-based energy carriers becomes critical in cases where residual emissions must be substantially reduced; bioenergy and CCS are effective under moderate mitigation levels but hydrogen is not always the best option when other decarbonization options, such as electrification and bioenergy, are available.

4. Discussion

4.1. Condition and role of hydrogen penetration

Through scenario analysis with various climate policy and technology portfolio settings, we found that large-scale hydrogen penetration occurs mainly under two conditions. First, the stringency of climate policies directly affects the hydrogen diffusion rate. Second, lack of available alternative options for removing residual emissions in energy demand sectors, in particular the lack of CCS, is critical to hydrogen diffusion. These two conditions are commonly characterized by the need to reduce residual emissions in energy demand sectors that are not easily eliminated through electrification, such as high-temperature heating in industrial processes and long-distance transport. In accordance previous studies indicating that the lack of CCS hinders deep decarbonization unless energy demand is drastically reduced [42,43], our results suggest the potential of hydrogen-based energy carriers as an alternative option for deep decarbonization. Moreover, lack of hydrogen availability does not compromise decarbonization goals as long as other low-carbon carriers are available, such as electricity and bioenergy. Nevertheless, based on the cost implications determined in this study, hydrogen utilization is an effective method for avoiding carbon price increases under stringent mitigation scenarios.

The diffusion rate of hydrogen-based energy carriers differs among energy demand sectors. Throughout this study, hydrogen penetration was observed mostly in the transport and industry sectors, while penetration into the buildings sector is limited, which is similar to the results of most IAMs reported previously [5]. Our results indicated that hydrogen-based synthetic fuels can be introduced into the transport sector, with the share of hydrogen-based energy carriers increasing to meet up to half of transport energy demand.

Hydrogen is an attractive secondary energy carrier for VRE sources, namely solar and wind, as upscaling of VRE-based electricity carries integration challenges, such as the need for batteries. For scenarios in which the share of VRE exceeds half of electricity generation, capacity based on electrolysis exceeds that based on battery storage. In addition, ammonia and synfuels promote international trade of low-carbon energies in conjunction with biofuels, which can effectively support the global use of low-carbon energy sources.

4.2. Competitiveness of hydrogen compared with other low-carbon energy carriers

In this study, large-scale hydrogen penetration is observed under specific conditions, while promotion of electrification and bioenergy use occurs under most mitigation scenarios. This difference arises because the production cost of hydrogen can be double or triple that of electricity due to conversion losses and additional investment requirements. Therefore, hydrogen is introduced in limited sectors for which electrification is relatively difficult or costly, such as long-distance transport and high-temperature processes. In sensitivity analysis using scenarios with lower renewable and hydrogen conversion costs, their contributions to further hydrogen penetration are limited compared with the effects of climate policy stringency and CCS constraints. VRE cost does not affect hydrogen penetration strongly, as it leads to reduced electricity prices and, thereby, simultaneously promotes electrification. Although hydrogen conversion cost reduction can narrow the gap between hydrogen and electricity costs to some extent, it does not affect the results greatly, as conversion loss in electrolysis is unavoidable. These findings suggest the importance of developing a holistic energy strategy that considers multiple low-carbon energy carriers, such as electricity and biomass, as well as other mitigation options, such as CCS and DAC.

4.3. Limitations and caveats

Several limitations and caveats to understanding the role of hydrogen in this study remain. First, consideration of infrastructure inertia would affect some of the findings of this study. The current model does not explicitly consider existing energy infrastructure, such as gas distribution pipelines at the district level, transport of captured CO2, electricity grid and electric vehicle charging stations for consumers, while typical average transport cost or transmission losses are imposed. While the results presented in this study can be affected if spatial heterogeneity on energy infrastructures is explicitly considered, the main conclusions of this study in terms of relationship between hydrogen and electricity would not be changed drastically, because consideration of additional infrastructure cost would affect both electricity and hydrogen supply processes. Also, hydrogen-based energy carriers, especially synthetic hydrocarbons in the form of liquids or gases, can be more effective option due to economic advantages from utilizing existing fossil fuel infrastructure without additional investment. In particular, synthetic methane can be distributed using existing pipeline infrastructure, and hydrogen-based energy carriers in the buildings sector become more attractive if infrastructure inertia is included in the analysis. When fossil fuel-based infrastructure in energy demand sectors becomes stranded under rapid mitigation scenarios, as described in previous research [47], hydrogen synfuel is an attractive option.

Second, as this study focuses on hydrogen utilization in the energy sector, carbon utilization as a feedstock is not considered, although it could effectively remove residual CO_2 emissions. While existing research considers bioenergy use and demand reduction as possible options for mitigation non-energy sectors [48], carbon-free synthetic hydrocarbons are another option for reducing emissions associated with high-value chemicals and methanol.

Third, this study considers a limited number of emission scenarios. Although this study assumes that carbon prices are globally uniform, several effort sharing approaches could be implemented to allocate an emission allowance to each region [49]. Furthermore, some nations have announced enhancement of their mid-century mitigation goals to achieve net-zero emissions. With these effort sharing approaches and specific national mitigation targets, the diffusion of hydrogen-based energy carriers may be promoted because the global level of residual emissions that must be eliminated would be higher. Nevertheless, when focusing on emissions at the national level, the allocation of emissions associated with traded energy carriers, such as hydrogen and hydrogen-based synthetic hydrocarbons, must be discussed.

5. Conclusions

This study explored the critical role that hydrogen-based energy carriers can play in removing residual CO_2 emissions under stringent mitigation scenarios, especially those corresponding to the 1.5 °C goal, as well as scenarios in which alternative mitigation options such as CCS are constrained, where their share reaches around 10–15% of final energy demand, although it remains at around 5% or less under other conditions. The transport sector is the largest consumer of hydrogen, followed by the industry and power sectors. In addition to direct use of hydrogen or ammonia, synthetic hydrocarbons converted from hydrogen and CO_2 obtained from biomass or DAC is an option for fueling transport. Meanwhile, as electrification plays a critical role under most mitigation scenarios, the importance of a holistic energy and climate policy that considers several mitigation options for energy supply and demand sectors as well as reliance on hydrogen design is highlighted.

6. Data availability

Scenario data is available at https://doi.org/10.5281/zenodo.5827072. Code used for data analysis and figure creation is available from the GitHub repository at https://github.com/kenoshiro/AIMT-hydrogen.

CRediT authorship contribution statement

Ken Oshiro: Conceptualization, Methodology, Software, Visualization, Writing – original draft. **Shinichiro Fujimori:** Writing – review & editing.

Declaration of Competing Interest

The authors 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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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2022.118803.

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