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SPECIAL FEATURE: ORIGINAL ARTICLE

Energy Scenarios for Long-Term Climate Change Mitigation in Japan

Role of negative emissions technologies (NETs) and innovative technologies in transition of Japan's energy systems toward net-zero CO_2 emissions

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Abstract

This paper explores the role of negative emissions technologies (NETs) in energy systems, bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC) with geological carbon storage (DACCS) in particular, using a bottom-up energy system model TIMES-Japan that participated in the 35th study of the Stanford Energy Modeling Forum (EMF 35 JMIP) focusing on the energy transitions for the long-run climate goals. Modeling results show that large-scale deployment of NETs is essential to achieve the net-zero vision of Japan's long-term strategy, however, these NETs might not be enough in the case of the highest energy service demands. Within the feasible solution space, earlier deployment of BECCS with domestic biomass can contribute effectively to achieve the target with the support of the DACCS at the later period if both technologies are available. It shows feasible results without DACCS only in the lowest energy service demands, implying the importance of urgent research, development, and deployment of DACCS. Furthermore, this study shows that earlier deployment of DAC system with CO_2 utilization in fuel production is a cost-effective way to lead the large-scale deployment of the DAC as NETs.

Keywords BECCS · DAC · Hydrogen · Net-Zero CO_2 emissions · Negative emissions technologies (NETs)

Introduction

Low carbon transitions of energy systems are required globally under the Paris Agreement of the United Nations Framework of Convention of Climate Change (UNFCCC). The framework requires each party to submit long-term strategies of mitigation measures toward the mid-century to the UNFCCC by 2020. In Japan, "Long-term Strategy under the Paris Agreement as Growth Strategy" was published by Ministry of Economy, Trade, and Industry jointly with Ministry of Environment on June 11th 2019, and the mitigation goal in the strategy is to achieve 80% GHG emissions reduction by 2050 and realize a decarbonized society as early as possible in the latter half of this century.

For policy recommendations of research, development, and demonstration (RD&D) strategies to achieve the ambitious mitigation goal, supply–demand structure in energy systems needs to be optimized and analyzed in quantitative manners using comprehensive energy systems models. In the circumstance of net-zero emissions goal, such quantitative analyses require considerations of demand-side innovative technologies and technologies that remove CO_2 from the atmosphere to compensate CO_2 emissions from difficult-to-decarbonized sectors such as heavy industry and heavy-duty transportation, and unavoidable GHG emissions from the agricultural sector (Davis et al. 2018).

Role of NETs on energy systems and emissions reductions are extensively assessed using global integrated assessment models (IAMs) and regional models on EU (Duscha et al. 2018; Fuss et al. 2014), however, it is relatively scarce and imperative to clearly analyze their role to provide the

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information on RD&D needs using national energy system models with detailed demand-side technologies.

In this study, transitions of Japan's energy systems toward net-zero CO_2 emissions goal in the latter half of this century are analyzed using a bottom-up energy system model TIMES-Japan, with consistent pathways of the domestic mitigation targets at 2030 and 2050 submitted to the UNFCCC. Implication and sensitivity from the availability of NETs in energy systems, that is, bioenergy with carbon capture and storage (BECCS) in the power sector and direct air carbon capture and storage (DACCS) in 2050 and 2070 are evaluated. In addition to the consideration of NETs, we implemented innovative technologies such as direct hydrogen reduction (H-DR) in iron and steel industry, high-temperature heat pumps, and the use of direct air capture (DAC) to produce synthesized liquid fuels. We analyzed the timing and the quantity deployed for these innovative technologies using scenarios analysis using the model.

Methods

We use TIMES-Japan version 3.2 to illustrate Japan's transitions of energy systems toward net-zero CO_2 emissions in the latter half of this century. In particular, we explore the implication of the availability of negative emissions technologies in energy systems.

Modeling framework

The energy system model TIMES-Japan, using IEA-ETSAP's TIMES modeling framework (Loulou et al. 2005), originally covers the time periods from 1990 to 2050 with five-year time intervals (Kato and Kurosawa 2019; Kurosawa and Kato 2018; Sugiyama et al. 2019, 2021). The model follows a whole system approach, conducting least-cost optimization calculations under exogenous service-demand assumptions. The objective function is a discounted sum of total energy system cost with a discount rate of 3% per year. Detailed flows of Japan's energy systems are implemented based on MARKAL-JAPAN (Sato 2005), and imported hydrogen has been incorporated as an additional decarbonizing energy carrier into the systems in addition to the domestic hydrogen supply from the hydrogen production processes derived from MARKAL-JAPAN, such as production from fossil fuels processes (coal gasification, and reforming of natural gas, LPG, and naphtha) and water electrolysis. The reference energy system in TIMES-Japan 3.2 consists of 403 processes and 165 commodities.

For electric load curve representation, the annual period is divided into three seasons (i.e. winter, summer, and spring and autumn combined) and each season is also divided into day and night. The annual peak electricity demand is considered. Final energy demand sectors are industries, commercial, residential, and transportations (see Scenario setup–Energy service demand section; see also Fig. 1). Using the fixed energy service demand scenario for each sectors and sub-sectors described in Kurosawa and Hagiwara (2012), energy supplies, conversions, and demand-side systems are optimized. In this study, we extended the time period of the model until 2070 to analyze the implication of the Japanese policy goal of achieving net-zero emissions as early as possible in the latter half of this century.

Fig. 1 Scenarios of energy service demands by sectors in 2030, 2050, and 2070. Values in 2015 are also shown as references

Energy resource assumptions

Following the inter-model comparison study EMF 35 JMIP on the energy systems toward 2050 in this special feature (Sugiyama et al. 2021; Shiraki et al. 2021), we use the consistent assumptions on Variable Renewable Energy (VRE) capacities, the domestic biomass supplies, import price of fossil fuels and hydrogen, nuclear power capacity, and the capacity of geological CO_2 storage in the energy systems of Japan used in TIMES-Japan 3.1 of EMF 35 JMIP.

For VRE, we set the upper limit of their capacities with 260 GW for solar PV in 2050 based on the assessment of Matsukawa et al. (2017), and 100 GW for the wind power generations in 2050 based on Saito et al. (2017). We use the soft linkage method of setting the capacity limits from these regionally detailed solar PV and wind integration models because of the relatively low resolution in time and space of TIMES-Japan for analyzing the power sector. Cost assumptions of VRE and other power generation systems of TIMES-Japan 3.1 are described in the analysis on the role of VRE of EMF 35 JMIP (Shiraki et al. 2021). These upper limits of VRE capacities and the cost assumptions in 2050 are applied to the extended period until 2070. On the domestic biomass supplies, we assume four feedstock types in the analysis (woody chips, round wood, energy crops, and residue and waste), based on chips and wood production from sustainable forestry (Kinoshita et al. 2010), energy crop yields (Kato and Yamagata 2014) combined with currently abandoned paddy fields and fallow land in Japan, and other feedstocks (residues and waste) from the biomass strategy of Ministry of Agriculture, Forestry and Fisheries, Japan (MAFF 2006). Using the literature, we set the upper limits of total domestic biomass supplies as 1500 PJ yr^{-1} in 2050 (Kato and Kurosawa 2019), consisting from economically viable wood chips as 15 PJ yr^{-1}, lignocellulosic crops produced on the abandoned cropland and fallow paddy field as 285 PJ yr^{-1}, residues and waste as 815 PJ yr^{-1}, and sustainable use of forest wood as 385 PJ yr^{-1} listed from cheaper to expensive options. These limits in 2050 are applied to the extended periods until 2070.

Fossil energy import prices are assumed to follow the Sustainable Development Scenario (SDS) of World Energy Outlook 2017 of the International Energy Agency (IEA 2017). Import of liquified hydrogen is assumed to be available from 2030, and the price is set 37 USD/GJ constantly until 2070 that is slightly higher than the anticipated price in 2030 of Japan's Basic Hydrogen Strategy (METI 2017). We assume the upper-bound of nuclear power capacity from 2040 to 2070 with approximately 40 GW as a standard setting, that corresponds to the capacity before the 2011 Tohoku earthquake. This relatively conservative assumption (i.e. no large expansion) is set because of the corresponding nuclear safety concerns to earthquakes and the current strategy of the Japanese government toward 2050 to reduce its dependency on nuclear power as much as possible (METI 2018).

We assume off-shore geological CO_2 storage available from 2020, with 0.1 $MtCO_2$ yr^{-1} as an upper limit at 2020 expanding to 50 $MtCO_2$ yr^{-1} in 2050 following the setting of TIEMS-Japan 3.1 in EMF 35 JMIP. In this study, we set the maximum capacity of the geological storage in 2070 as 200 $MtCO_2$ yr^{-1}. The annual capacity in 2070 is slightly larger than the assumption of "CCS expansion case" of 182 Mt CO_2 yr^{-1} in 2050 in Akimoto and Sano (2017), however, the upper limit of the cumulative storage assumed in this study is far lower than the reported cumulative potential of 146.1 $GtCO_2$ for Japan (Nakanishi et al. 2009).

Assumptions of demand-side decarbonization technologies

Decarbonization of industry sectors toward the mid-twenty-first century is generally considered hard (Davis et al. 2018) and the difficulty is shown in our previous study on Japan's energy systems (Sugiyama et al. 2019). To cope with the issue, we added further options of decarbonization technologies in the representation of industry sectors of TIMES-Japan in this study and the EMF 35 JMIP in this special issue. We implemented a direct reduction of iron ore using hydrogen (H-DR) technology in the iron and steel sector, assuming its availability from 2030 using parameters from Otto et al. (2017) and Vogl et al. (2018). In addition, a high-temperature heat pump is assumed as alternatives for boilers in non-energy intensive industry and chemical industry with their share limit to 64% and 8% based on a scenario from Heat Pump & Thermal Storage Technology Center of Japan (HPTCJ 2017).

For the transportation sector, which is another hard-to-decarbonize energy sector (Davis et al. 2018), we considered the same set of technological options of TIMES-Japan 3.1 in EMF 35 JMIP. EV and FCV, and methanol fuel are available for light-duty vehicles, buses, and trucks. For aviation, hydrogen fuel is considered as a carbon-free alternative fuel. For shipping, we considered LNG and methanol as alternative fuels.

Negative Emissions technologies (NETs)

As in our preliminary study on the role of BECCS in the deep decarbonization for Japan's energy system in 2050 (Kato and Kurosawa 2019), we considered biomass power generation combined with CCS specifically as a NETs in the power sector in this study, which is not enabled in the standard setting of TIMES-Japan. We considered the supply of the domestic biomass with an upper limit of sustainable criteria described in the section "Resource assumptions".

Post-combustion capture rate of CO_2 from flue gas is assumed to be 90%. CAPEX of biomass power plant is set from EIA (2016), and the capture cost of CO_2 is set from Rubin et al. (2015).

In addition to BECCS, we implemented a DAC system using a liquid solvent in TIMES-Japan because of the availability of the technological details and supposed advantages in scale-up (Keith et al. 2018). We employed an assumption of input of 5.25 GJ natural gas and 366 kWh electricity to capture 1 tCO_2 from the atmosphere. CAPEX and O&M cost value is also employed from the same systems from Keith et al. (2018). CO_2 emissions generated during heat production in the calcination kiln are also captured (de Jong et al. 2019) in the analysis. Electricity supply for the DAC is delivered from the grid calculated endogenously within the model.

Scenario setup

To analyze the range of possible options achieving the net-zero CO_2 emissions in the early part of the second half of this century, we set up scenarios on key uncertain items; energy service demands (4 cases), nuclear power generation capacities (2 cases), and combination of availability on the NETs and CO_2 utilization using DAC (6 cases) as described below.

We set constraints on the CO_2 emissions from the domestic energy system until 2050 according to the default policy scenario used in EMF 35 JMIP; 26% emissions reduction by NDC at 2030, 80% emissions reduction by 2050. To analyze the implication of achieving net-zero CO_2 emissions at the early period of the latter half of this century, we constraints the total CO_2 emissions in 2070 to zero, with an assumption of anthropogenic land-sink from managed forests and croplands in Japan as 40 $MtCO_2$, which roughly corresponds to the threshold of forest-sink in the first commitment period of the Kyoto protocol (47.7 $MtCO_2\ yr^{-1}$). The assumptions of 40 $MtCO_2\ yr^{-1}$ land-sink is derived from the estimates of forest sink (~ 34 $MtCO_2\ yr^{-1}$), that is reduced from the forest sink of 47.7 $MtCO_2\ yr^{-1}$ by 28% caused from the assumed maximum utilization of forest biomass for energy (400 PJ yr^{-1}), in addition to the targeted cropland sink (~ 8 $MtCO_2\ yr^{-1}$) of the NDC of Japan. Namely, the residual fossil CO_2 emissions from the energy system including international transportation are constrained 40 $MtCO_2$ in 2070.

Energy service demand

We followed the energy service demands scenarios of JMIP round4 (Sugiyama et al. 2021) until 2050, based on GDP growth rate of the reference demand scenario (Ref) and SSP2-based low demand scenario (SSP2). From 2050 to 2070, we set two cases, high (H) and low (L) cases, for each energy service demand until 2050, which leads to four energy service demands in 2070 (RefH, RefL, SSPH, and SSP2L hereafter) shown in Fig. 1. For RefH and SSP2H scenarios, we keep the total energy service demands from 2050 until 2070, that means per-capita demands increase during the period due to the projected decline of the national population of Japan (IPSS 2017). For RefL and SSP2L scenarios, we set energy service demand declining according to the population projection, that keeps per-capita energy service demand at the same level from 2050 to 2070.

Nuclear power generation

We set two scenarios on the upper limit of nuclear power capacities according to EMF 35 JMIP. RefNuc scenario uses the default options of TIMES-Japan (approximately 40 GW upper limit throughout 2050–2070). Nuclear phaseout scenarios (LimNuc) is also analyzed based on the assumption of limited new capacity additions with extended life (60 years) of existing plants.

NETs and CO_2 utilization options

On the technological availability of NETs and CO_2 utilization using DAC, we considered four options regarding NETs; both BECCS in the power generation and DACCS available (FullNETs), only DACCS available (noBECCS), only BECCS available (noDAC), and no NETs available (noNETs). For the scenarios with DACCS as NETs (FullNETs and noBECCS scenarios), the availability of synthetic fuel production using DAC (DACU and noDACU) is also considered. In total, six technological scenarios are analyzed (FullNETs-DACU, FullNETs-noDACU, noBECCS-DACU, noBECCS-noDACU, noDAC, and noNETs).

Supplementary scenarios

In addition to the 48 scenarios described above, we conducted three supplementary scenarios derived from SSP2L-RefNuc-noNETs to diagnose our assumptions on the nuclear capacity and the energy service demands to get net-zero CO_2 emissions by 2070. The first scenario is SSP2L-HighNuc-noNETs that has a higher upper limit of nuclear capacity up to 80 GW throughout 2040 to 2070. The second scenario is SSP2L-LoIndDem-RefNuc-noNETs that has lower service demands for industry sectors by halving SSP2L's industrial demands from 2030 to 2070. The third scenario, SSP2L-LoIndDem-HighNuc-noNETs, is the combination of the higher nuclear capacity and the lower industrial service demands.

Results

Feasibility of achieving net-zero CO_2 emissions

Among the 48 scenarios analyzed in this study, half of the scenarios show infeasible solutions (Table 1). There are no feasible solutions for noNETs scenarios, even in the scenario with the lowest energy service demands in 2070 (SSP2L), showing the essential importance of utilization of NETs to achieve the net-zero CO_2 emissions target. In addition, there are no feasible solutions in the scenarios with the highest energy service demands (RefH) even when both full NETs and DACU technologies are available.

In the scenarios with middle-level energy service demands in 2070 (SSP2H, RefL), there are no feasible solutions when DACCS is not available. In addition, even when DACCS is available, we cannot find feasible solutions if neither BECCS nor synthetic fuel production with DAC is available when the energy service demands are relatively high (SSP2H). Interestingly, the SSP2H demand scenario only shows the importance of the availability of DAC with CO_2 utilization. Only the lowest service demand scenarios (SSP2L) show the feasibility without DACCS.

There are no differences in the feasibility between the setting of the capacity of nuclear power generation (RefNuc vs. LimNuc).

Furthermore, in the supplementary scenarios for noNETs, we cannot find feasible solutions for all three scenarios (SSP2L-HighNuc-noNETs, SSP2L-LoIndDem-RefNuc-noNETs, and SSP2L-LoIndDem-HighNuc-noNETs).

Primary energy supply and final energy consumption

The share of fossil fuels (coal, oil, and gas) significantly drops from 95% at 2015 to 42% on average (ranging from 39 to 45%) in 2050 for all scenarios with feasible solutions available. The share further drops to 33% in 2070 (ranging from 27 to 38%). The details of the primary energy supply in 2050 and 2070 for the feasible scenarios are available in Supplementary Figure S1.

Because TIMES-Japan shows the maximum use of VRE capacity in 2050 for the default scenario of EMF 35 JMIP (Shiraki et al. 2021), biomass and hydrogen supplies are two important factors achieving net-zero CO_2 emissions from 2050 toward 2070. From 2050 to 2070, there are large increases in domestic biomass supplies among the scenarios with BECCS technology available (Fig. 2a). Domestic biomass supplies reach the assumed limitation (1500 PJ yr^{-1}) in 2070 for those scenarios with BECCS enabled. In contrast, scenarios without BECCS generally do not employ much of the biomass, ranging from 10 PJ yr^{-1} for SSP2L-RefNuc-noBECCS-DACU scenario to 521 PJ yr^{-1} for RefL-LimNuc-noBECCS-DACU scenario in 2070. Supplies of imported hydrogen in 2050 range from 454 PJ yr^{-1} in SSP2L-RefNuc-noDAC to 1768 PJ yr^{-1} in RefL-LimNuc-noBECCS-noDACU. The supplies in 2070 range from 61 PJ yr^{-1} in RefL-RefNuc-FullNETs-DACU to 3572 PJ yr^{-1} in SSP2H-LimNuc-noBECCS-DACU, showing high sensitivity largely depending on the level of energy service demands (Fig. 2b).

In the final energy consumption by sources (Supplementary Figure S2), the share of electricity is expanded from

Table 1 Feasibility of net-zero CO_2 emissions in 2070

	RefH-RefNuc	RefH-LimNuc	RefL-RefNuc	RefL-LimNuc
a				
FullNETs-DACU	No	No	Yes	Yes
FullNETs-noDACU	No	No	Yes	Yes
noBECCS-DACU	No	No	Yes	Yes
noBECCS-noDACU	No	No	Yes	Yes
noDAC	No	No	No	No
noNETs	No	No	No	No

	SSP2H-RefNuc	SSP2H-LimNuc	SSP2L-RefNuc	SSP2L-LimNuc
b				
FullNETs-DACU	Yes	Yes	Yes	Yes
FullNETs-noDACU	Yes	Yes	Yes	Yes
noBECCS-DACU	Yes	Yes	Yes	Yes
noBECCS-noDACU	No	No	Yes	Yes
noDAC	No	No	Yes	Yes
noNETs	No	No	No	No

"Yes" in the cells indicates feasible scenarios, and "No" for the infeasible scenarios. **a** RefH and RefL demand scenarios. **b** SSP2H and SSP2L demand scenarios

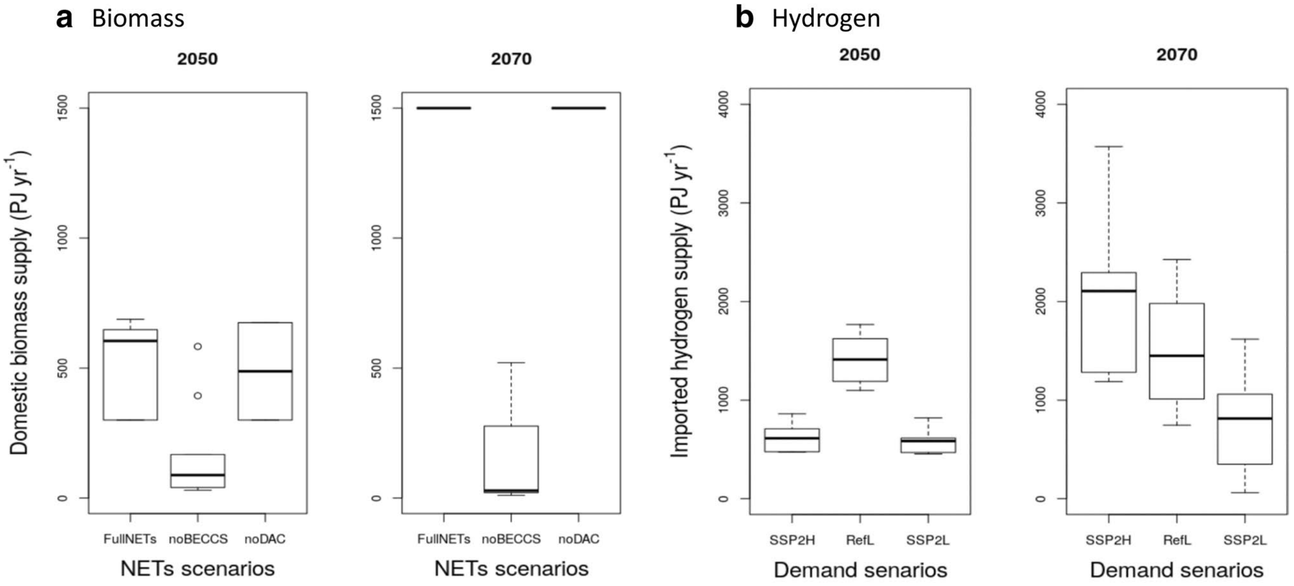


Fig. 2 Primary energy supply in 2050 and 2070 by **a** domestic biomass categorized by scenarios of the availability of NETs, and **b** imported hydrogen categorized by scenarios of the energy service demands. Categories used in the x-axis of each plot are selected by the factor with the largest variances explained to the total variance of the supplies

about 25% at 2015 to 41% on average in 2050 (ranging from 38 to 42%). Then, the share reaches up to 50% in 2070 (ranging from 40% in SSP2H-LimNuc-FullNETs-DACU to 49% in SSP2L-RefNuc/LimNuc-noDAC), depending mainly on the level of energy service demands and availability of nuclear power capacity (Fig. 3). Share of hydrogen in the final energy consumptions is 9% on average in 2050 (ranging from 6% in SSP2H-RefNuc-FullNETs-DACU, SSP2L-RefNuc-FullNETs-DACU, SSP2L-LimNuc-FullNETs-noDACU, and SSP2L-LimNuc-noDAC to 16% in

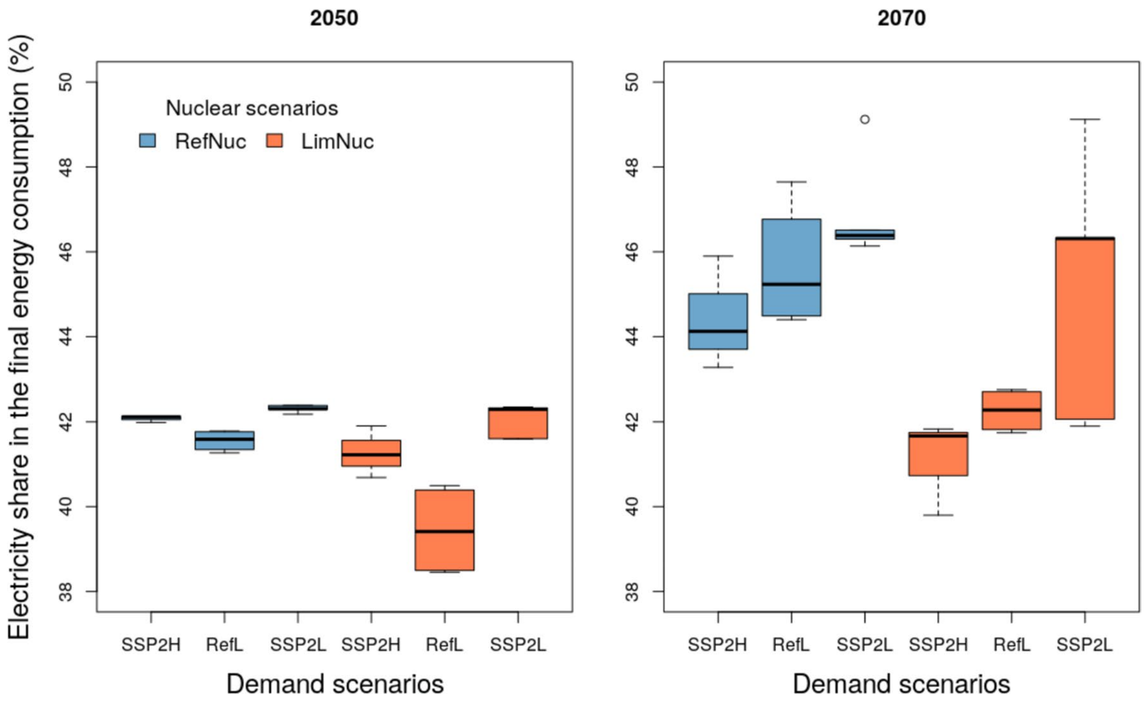


Fig. 3 Share of electricity in the final energy consumptions in 2050 and 2070

RefL-LimNuc-noBECCS-DACU/noDACU), showing dependency on the level of energy service demands, and availability of nuclear generation and BECCS. The share increases to 15% in 2070, ranging from 9% in SSP2L-RefNuc-FullNETs-DACU to 20% in SSP2H-LimNuc-FullNETs-DACU and SSP2H-LimNuc-noBECCS-DACU.

Primary energy supplies in all SSP2H scenarios increase in 2070 compared to that of 2050 by about 12% on average, even the energy service demands for industries, transportations, and buildings are the same level (Supplementary Figure S1). Similar to the increases of primary energy supplies, electricity generation in 2070 is higher than those in 2050 for all SSH2H scenarios (Supplementary Figure S4).

CO_2 emissions

CO_2 emissions from industry sectors dominate in 2050, as we showed in the previous study and this special feature (Sugiyama et al. 2019, 2021), averaging 183 $MtCO_2$ yr^{-1}. The share of industry is 72% of the total positive emissions on average, ranging from 63% in SSP2L-LimNuc-noBECCS-DACU/noDACU to 82% in RefL-LimNuc-FullNETs-DACU (Fig. 4). The emissions from the power sector in 2050 become net-negative if BECCS is available for the scenarios with higher energy service demands in 2050 (RefL), and/or for the scenarios with limited nuclear capacity (Fig. 4a). DACCS is also deployed in 2050 if BECCS is not available, showing maximal negative emissions about -10 $MtCO_2$ yr^{-1} in SSP2H/L-RefNuc-noBECCS scenarios.

In 2070, the average emissions reductions rate from 2050 is 35% in industry, 86% in transportation, and 44% in buildings. Even with the reductions, industry emissions are still the largest part of the positive emissions in 2070, ranging from 98 to 132 $MtCO_2$ $yr^{-1}$and the share of industry increases to 80% on average of total positive emissions (Fig. 4b). To compensate these positive emissions, there is large scale deployment of negative emissions around -84 $MtCO_2$ yr^{-1} from the power sector in all scenarios with BECCS available (FullNETs and/or noDAC). In contrast, deployment levels of DACCS in 2070 depend on the

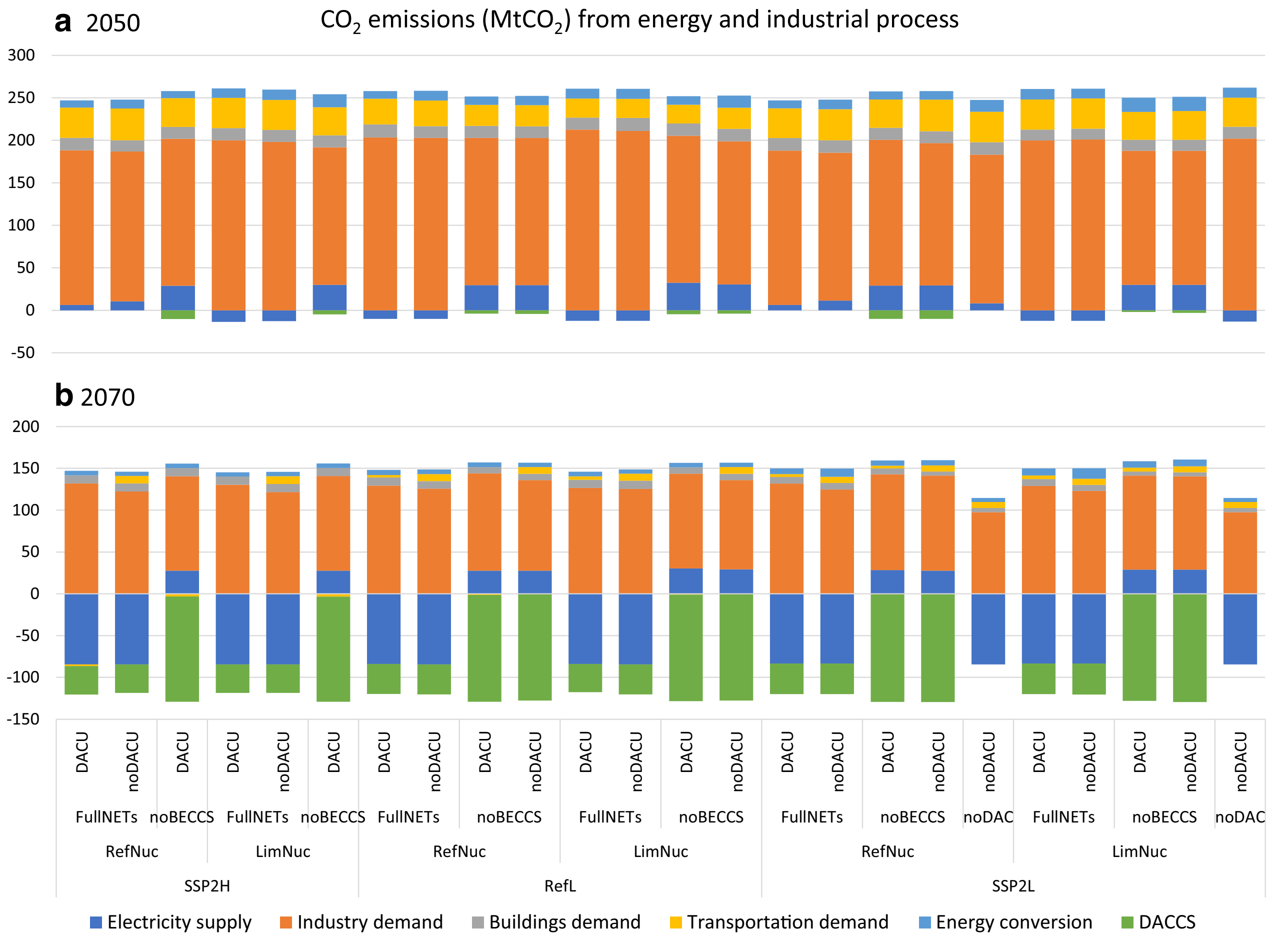


Fig. 4 Domestic CO_2 emissions from energy and industry process by sectors in **a** 2050, and **b** in 2070. Emissions from international transportation are not included

availability of BECCS. When BECCS is available, about -35 $MtCO_2$ yr^{-1} of negative emissions are produced by DACCS in 2070, however, the deployment increases to about -130 $MtCO_2$ yr^{-1} of negative emissions for the scenarios without BECCS (noBECCS).

CCUS

In 2050, assumed geological storage is maximally utilized in all scenarios, indicating about 50 $MtCO_2$ yr^{-1} of net CO_2 sequestration throughout the whole CCS systems (capture, transportation, and geological storage). In 2070, assumed constraint of 200 $MtCO_2$ yr^{-1} is maximally utilized except for noDAC scenarios (SSP2L-RefNuc/LimNuc-noDAC; Fig. 5). The limit to the noDAC scenarios in 2070 is imposed from the capacity of BECCS by the domestic biomass supply (see “Primary energy supply and final energy consumption”).

BECCS dominates with almost 100% share of CCS in 2050 if the energy service demands are high (RefL) in 2050 and/or the capacity of nuclear power is limited combined with lower service demands (SSP2H/SSP2L-LimNuc). CCS from the cement industry is deployed in 2050 if these BECCS’ dominating conditions are relaxed. The cement CCS is also used when BECCS is not available. In 2050, DACCS is deployed only in the scenarios without BECCS, and the share to the total CCS is relatively small (5–28%; 2.5–13.5 $MtCO_2$ yr^{-1}). CCS with LNG Combined Cycle (LNGCC) and fossil fuel conversion processes (coal gasification, gas reforming, and CO shift conversion) are used in some scenarios, but the amount and share are generally limited. In 2070, the share of BECCS, cement, and DACCS to the total net geological storage is 62%, 12–14%, and 23–25%, respectively, for all FullNETs scenarios, indicating 120 $MtCO_2$ yr^{-1} is stored with BECCS. In contrast, the share of DACCS becomes 86–88%, and the rest of the share is used by cement CCS for the noBECCS scenarios, indicating 165–169 $MtCO_2$ yr^{-1} are stored through DACCS.

The amount of CO_2 utilized in synthetic fuel production is generally small compared to the amount of CO_2 for the geological storage (Fig. 6). 0–4.5 $MtCO_2$ yr^{-1} are utilized by DACU if the technology is available, and 0–5 $MtCO_2$ yr^{-1} are utilized from fossil fuel conversion processes in 2050. The amount CO_2 with DACU process expands to 4–22 $MtCO_2$ yr^{-1} in 2070, depending largely on the final energy demands and availability of BECCS. However, CO_2 utilization with fossil processes in 2070 keeps the same level of 2050 (0–4.5 $MtCO_2$ yr^{-1}), and they are not very sensitive to the energy service demands nor technological options.

Even the amount of CO_2 captured by DAC for the synthetic fuel productions is small, the timing of deploying DAC systems starts earlier than that for DACCS among FullNETs scenarios (Fig. 7). Furthermore, shifting earlier deployment of DACU is shown in the scenarios with high

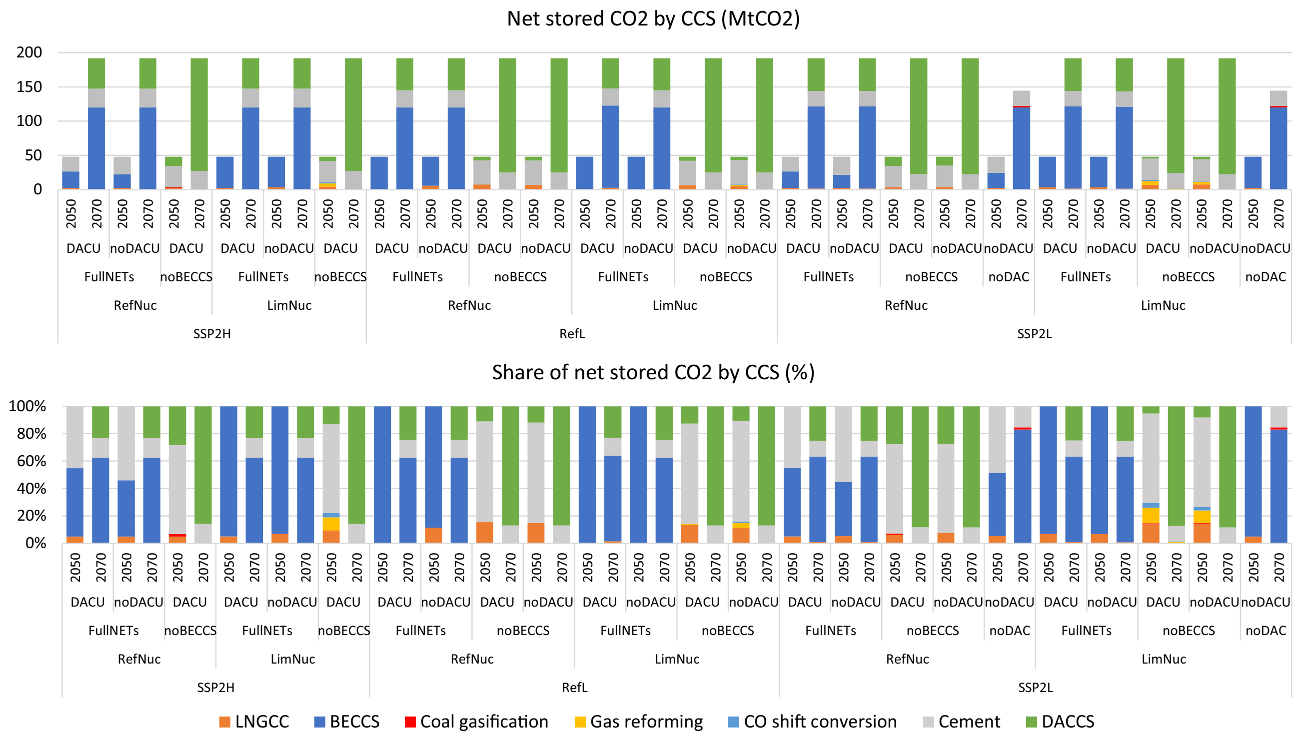


Fig. 5 Net CO_2 stored in the geological storage by CCS technologies in 2050 and 2070 (upper), and their share to the total (lower)

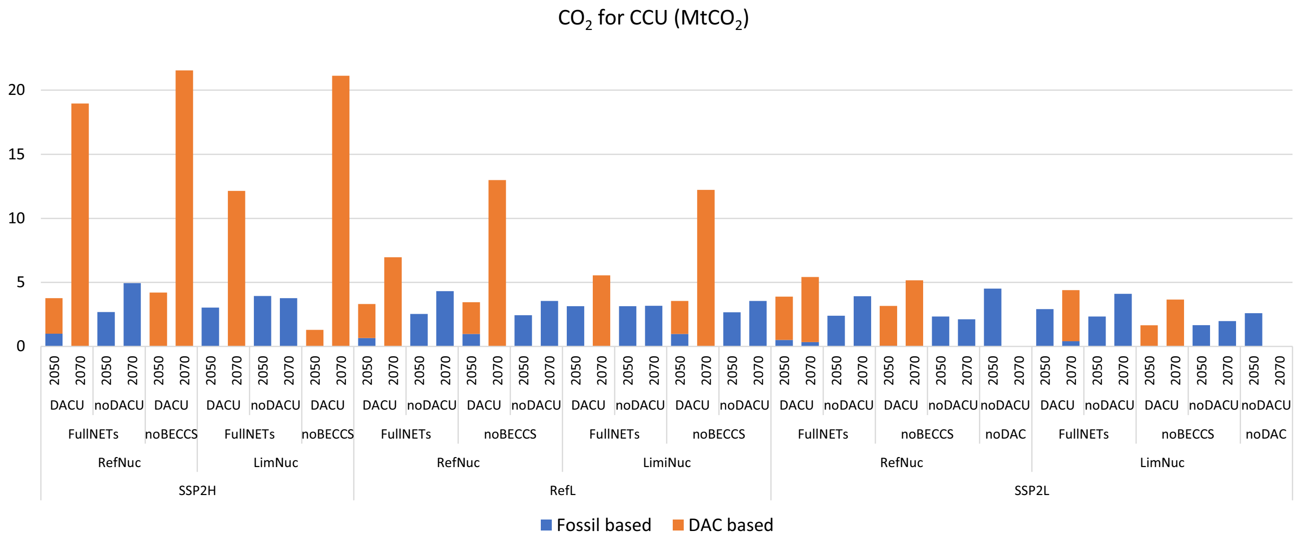
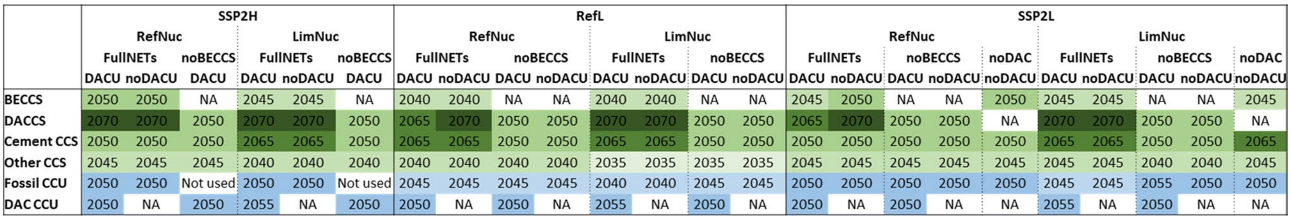


Fig. 6 Amount of CO_2 used in 2050 and 2070 for synthetic fuel productions by fossil fuel and DAC-based systems



	SSP2H						RefL								SSP2L									
	RefNuc			LimNuc			RefNuc				LimNuc				RefNuc					LimNuc				
	FullNETs		noBECCS	FullNETs		noBECCS	FullNETs		noBECCS		FullNETs		noBECCS		FullNETs		noBECCS		noDAC	FullNETs		noBECCS		noDAC
	DACU	noDACU	DACU	DACU	noDACU	DACU	DACU	noDACU	DACU	noDACU	DACU	noDACU	DACU	noDACU	DACU	noDACU	DACU	noDACU	noDACU	DACU	noDACU	DACU	noDACU	noDACU
BECCS	2050	2050	NA	2045	2045	NA	2040	2040	NA	NA	2040	2040	NA	NA	2045	2050	NA	NA	2050	2045	2045	NA	NA	2045
DACCS	2070	2070	2050	2070	2070	2050	2065	2070	2050	2050	2070	2070	2050	2050	2065	2070	2050	2050	NA	2070	2070	2050	2050	NA
Cement CCS	2050	2050	2050	2065	2065	2050	2065	2065	2050	2050	2065	2065	2050	2050	2050	2050	2050	2050	2050	2065	2065	2050	2050	2065
Other CCS	2045	2045	2045	2040	2040	2040	2040	2040	2040	2040	2035	2035	2035	2035	2045	2045	2045	2045	2045	2045	2045	2040	2040	2045
Fossil CCU	2050	2050	Not used	2050	2050	Not used	2045	2045	2045	2045	2040	2040	2045	2045	2050	2050	2050	2050	2050	2045	2045	2055	2050	2050
DAC CCU	2050	NA	2050	2055	NA	2050	2050	NA	2050	NA	2055	NA	2050	NA	2050	NA	2050	NA	NA	2055	NA	2050	NA	NA

Fig. 7 Start year of deployment of each CCUS system. NA denotes the system is not available in the scenarios. "Not used" means that the technology is available in the scenario but not deployed in the optimized solution. Cell with green color shows the CCS technologies, and blue color shows the CCU technologies. Cell with bright colors means the deployment of the technology starts earlier than a cell with darker colors

energy service demands in 2050, in particular scenarios with limited nuclear capacity. In contrast, the timing of deploying DACCS is not sensitive to the service demands nor nuclear capacity, beginning from 2065–2070 for scenarios with BECCS, and from 2050 for scenarios without BECCS.

Hydrogen supply and demand

Hydrogen is an important component of the transitions of energy systems toward net-zero CO_2 emissions (see "Primary energy supply and final energy consumption"). Hydrogen demands are 664–2054 PJ yr^{-1} in 2050 and 823–4071 PJ yr^{-1} in 2070, showing high sensitivity determined mainly by the level of energy service demands (45% of variances explained in 2070), and the combination of limited availability in both nuclear (21% of variances explained in 2070) and BECCS (23% of variances explained in 2070). In 2050, hydrogen demands by transportation sectors show the highest quantity (470–1050 PJ yr^{-1}), with their share ranging from 44 to 75% (60% on average) of total demands (Fig. 8). The demands for transportation in 2070 are at a similar level of 2050 (560–1160 PJ yr^{-1}) resulting in the decreased share for the transportation (47% on average, ranging from 29 to 68% of total hydrogen demands). The second-largest demands of hydrogen come from the power generation, having 53–422 PJ yr^{-1} in 2050 and 92–2058 PJ yr^{-1} in 2070. The demand for power generation in 2070 is exceptionally high in the SSP2H-LimNuc-noBECCS-DACU scenario. Hydrogen demands for the blending with natural gas, industrial use, and synthetic fuel production are relatively small compared to the above two demand sectors. Their average share is 12%, 8% and 6% in 2050, and 11%, 12%, and 8% in 2070, respectively. This shows the moderately growing demands for the industry mainly used for H-DR and synthetic fuel production toward 2070.

In the supply side, imported hydrogen dominates the supply of hydrogen through 2050–2070, except for three scenarios preferring the supply by electrolysis that is driven with the lowest energy service demands in 2070 having both nuclear generation and BECCS available

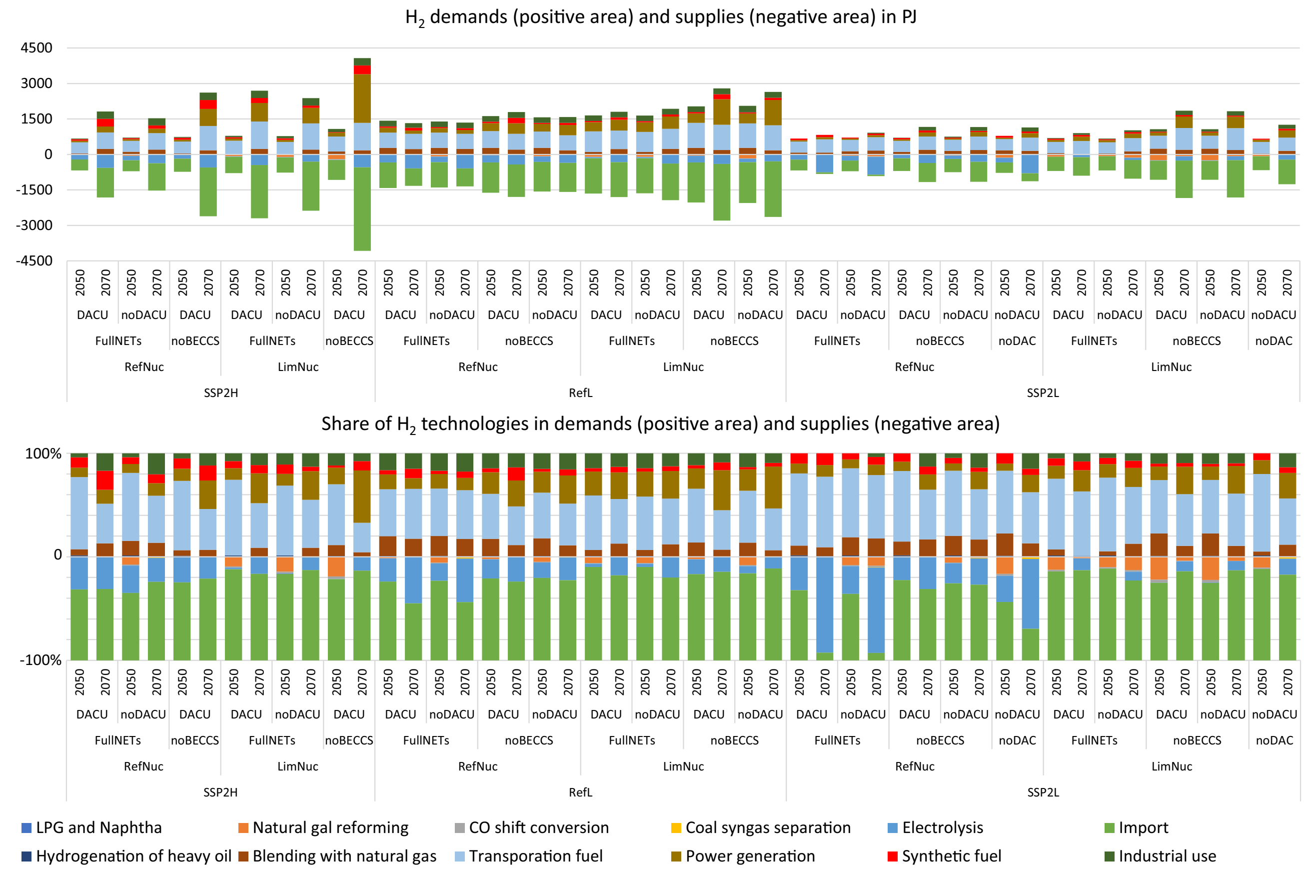


Fig. 8 Balances of hydrogen demands and supplies in 2050 and 2070 (upper), and the share of each component (lower). The positive area shows the demand side, and the negative area shows the supply side

(SSP2L-RefNuc-FullNETs-DACU/noDACU and SSP2L-RefNuc-noDAC). Hydrogen supply by the electrolysis is ranging from 0 to 316 PJ yr^{-1} in 2050, and the productions increase in 2070 ranging from 88 to 770 PJ yr^{-1}. Several scenarios show the production by natural gas reforming in 2050, but that production decreases toward 2070. While the level of hydrogen supply by import in 2070 is related to all three constraints (energy service demands, availability of BECCS, and availability of nuclear power generation), the supply of hydrogen by electrolysis is mainly controlled by the availability of nuclear power generation (Fig. 9).

Discussion and conclusions

This paper explores the role of innovative technologies including NETs to achieve the net-zero CO_2 emissions goal of Japan in the early period of the latter half of the twenty-first century. While many previous studies focus on the topics using aggregated global IAMs, this paper employs a detailed bottom-up model describing national energy systems. In addition, only a few recent studies analyze the role of both BECCS and DAC in the detailed energy modeling (e.g. Realmonte et al. 2019).

It is generally recognized that CO_2 capture and storage and negative emissions technologies (NETs) are vital to meeting the Paris agreement target (IPCC 2018). Likewise, our results show that there are no feasible solutions without any NETs available, even in the supplementary scenario with the lowest energy service demands assumed in this study (SSP2L-LoIndDem). This implies the huge importance of RD&D on NETs to achieve net-zero CO_2 emissions goal in Japan. However, with the assumption of the highest energy service demands, there are no feasible results even when both BECCS and DACCS are available, showing the importance of societal changes toward 2070, in addition to the mentioned technological development.

The infeasibility of “noNETs” scenarios is not affected by the availability of nuclear power generation (RefNuc vs. LimNuc) in our scenario space. Furthermore, even if we relax the conservative assumption of RefNuc’s capacity by doubling the upper limit as in the supplementary SSP2L-HighNuc-noNETs and SSP2L-LoIndDem-HighNuc-noNETs scenarios, we cannot find feasible solutions to get

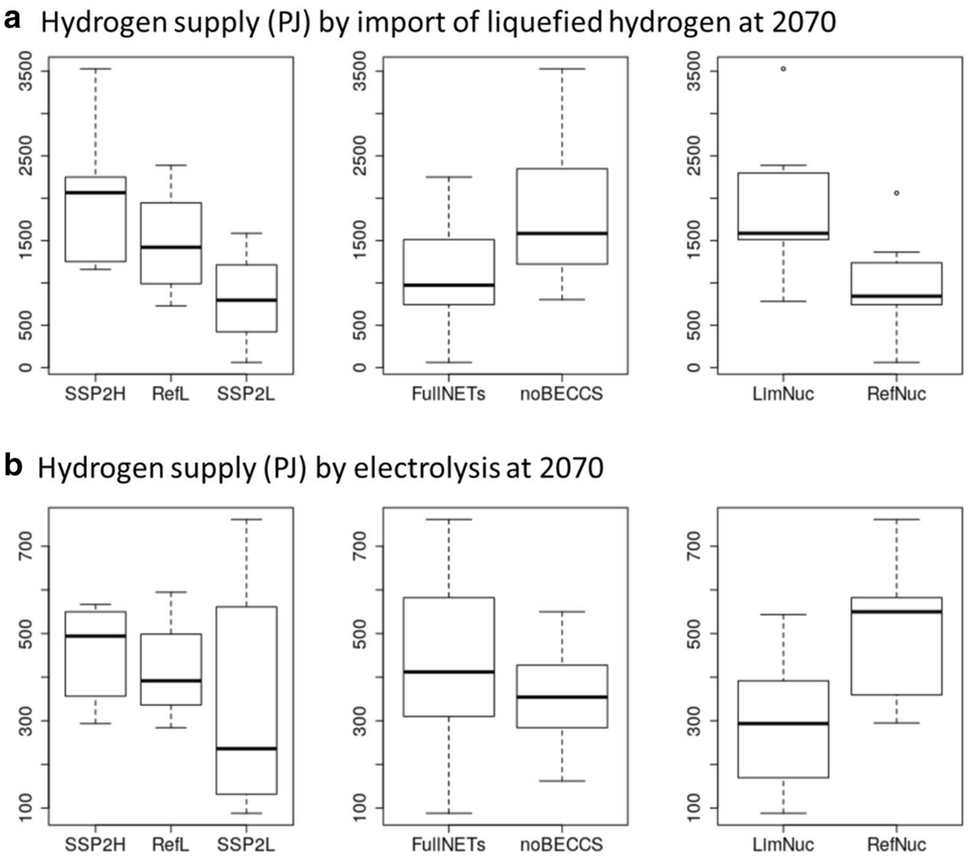


Fig. 9 Boxplots of hydrogen supplies in 2070 from **a** import of liquefied hydrogen and **b** electrolysis. “noDAC” scenarios are excluded in the plots because they are only available in SSP2L demands

net-zero CO_2 emissions by 2070. This implies that the residual emissions in 2070 mainly from energy-intensive industries and chemical industries of Japan would be unavoidable even when the large capacity of zero-emissions electricity is available within the current assumptions of the industry sector although technologies such as H-DR for steelmaking, high-temperature heat pumps, and use of synthetic methanol and hydrogen for heating in the industry sector are already modeled in this study. From the EMF 35 JMIP, we have recognized that there are research challenges to increase more modeling capability for the further end-use options and to integrate the analysis on how demands for industrial products and services change (Ju et al. 2021), but we can still conclude the necessity of the RD&D and scale-up of NETs to achieve net-zero emissions in additions to these challenges to reduce the residual emissions toward the goal.

In the feasibility solution space, earlier deployment of BECCS using domestic biomass can contributes cost-effectively to achieve the target with the additional support of DACCS in the end because of the possible limit to sustainable biomass availability. This results of the optimal sequence of NETs deployment pathways is consistent with a recent analysis by Realmonte et al. (2019). Furthermore, only the scenarios with the lowest service demands have feasible solutions without using DACCS. Therefore, the preparation of DACCS is the key component to achieve the long-term mitigation goal of Japan. The conclusion is also supported by the relative increases in carbon price (Figure S4). It shows the highest relative change of carbon price for the scenario without DACCS when the carbon price of scenarios is compared to the corresponding base scenario having both BECCS and DACCS within each demand case.

We also find that the DAC system is effective in terms of producing synthetic liquid fuels in the mitigation pathways. Even the scale of the utilization is one order of magnitude smaller than CO_2 captured for DACCS, DAC systems with utilization for the fuel productions can contribute the early scale-up of DAC systems in an effective manner as in our results showing the earlier deployment of DACU compared to the DACCS. This finding may contrast to Daggash et al. (2018), who found the advantage of DACCS over DACU in the UK energy systems.

If BECCS is not available for some reasons (e.g. difficulties in supplying enough domestic biomass due to the sustainability concerns), earlier deployment of DACCS and huge scale-up toward 2070 are required, that is, storing

CO_2 through DACCS needs to reach finally 170 $MtCO_2$ yr^{-1} level. In this case, averaged annual deployment rate of DAC system from 2050 to 2070 becomes 8.2–9.2 $MtCO_2$ yr^{-1}, requiring the higher scale-up rate compared to that of 2.3–3.1 $MtCO_2$ yr^{-1} during the same period in the scenarios with both BECCS and DACCS available. In terms of energy supply, this level of deployment of DACCS requires an electricity supply of 50 TWh yr^{-1} in 2070 with the DAC system considered in this study. It also involves the early and continued use of cement CCS, huge scale-up of infrastructure to import hydrogen for the demands for power generation, and material use for H-DR steelmaking, in addition to the use of DAC with synthetic fuel production up to 10 $MtCO_2$ yr^{-1} level toward 2070. Further studies on the trade-off among BECCS, hydrogen, and nuclear power generation are crucial to understand the effective mitigation pathways because this study only considered on/off options of BECCS availability.

Out results show that primary energy supplies in all SSP2H demand scenarios increase toward 2070 compared to that of 2050 while the energy service demands for industries, transportations, and building are the same level between 2050 and 2070. Thus, reducing energy consumptions (heat and electricity input) particularly for DAC system is crucial RD&D issues in the scale-up. Fasihi et al. (2019) reviewed the high-temperature aqueous solutions (HT DAC) and low-temperature solid sorbent (LT DAC) systems, concluding LT DAC systems are favorable due to lower heat supply costs and the possibility of using waste heat from other systems. Our study only considered HT DAC because of the considered advantage in scale-up (Keith et al. 2018), however, the integration of both systems and their cost estimates into Japan's energy system would be the next step to find effective mitigation pathways toward net-zero emissions.

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