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Enabling energy system transition toward decarbonization in Japan through energy service demand reduction

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ABSTRACT

Japan's mid-century strategy for reducing greenhouse gas emissions by 80% in 2050 would require large-scale energy system transformation and associated increases in mitigation costs. Nevertheless, the role of energy demand reduction, especially reductions related to energy services such as behavioral changes and material use efficiency improvements, have not been sufficiently evaluated. This study aims to identify key challenges and opportunities of the decarbonization goal when considering the role of energy service demand reduction. To this end, we used a detailed bottom-up energy system model in conjunction with an energy service demand model to explore energy system changes and their cost implications. The results indicate that final energy demand in 2050 can be cut by 37% relative to the no-policy case through energy service demand reduction measures. Although the lack of carbon capture and storage would cause mitigation costs to double or more, these economic impacts can be offset by energy service demand reduction. Among energy demand sectors, the impact of industrial service demand reduction is largest, as it contributes to reducing residual emissions from the industry sector. These findings highlight the importance of energy service demand reduction measures for meeting national climate goals in addition to technological options.

1. Introduction

The Paris Agreement requires each party to submit a Nationally Determined Contribution (NDC) and formulate a Mid-Century Strategy (MCS), which include emission reduction target around 2030 and 2050, respectively. Japan has submitted its NDC and MCS with the aims of reducing greenhouse gas emissions by 26.0% by 2030 with respect to the 2013 level and by 80% by 2050. Several studies have explored the challenges and opportunities related to these mitigation goals and their technological and economic implications using integrated assessment models (IAMs) and energy system models [1,2]. Recently, Sugiyama et al. [3] compiled six models for Japan and assessed the 2030 and 2050 mitigation goals described in the NDC and MCS. Oshiro et al. [4] assessed national emission pathways in Japan that are consistent with the global 2 °C goal based on two national models and seven global models. Given the national mitigation target, several multi-model studies have been carried out which explored the low-emission development pathways in the major economies including Japan, employing the several national IAMs for each country [5–7].

These studies generally consider the technological challenges facing energy supply sectors, such as uncertainty in the availability of nuclear and carbon capture and storage (CCS) technologies, for both the national and global studies [8,9]. Specifically, given Japan's national contexts, large-scale penetration of renewable energy faces several challenges associated with limited potential for solar and wind power, low capacity factor and the integration of variable renewable energies (VREs) [10–12]. Among energy demand sectors, although Japan already has advantages in the penetration of energy-efficient technologies [13], additional efficiency improvement is required to meet the long-term mitigation goal. Previous scenario studies have clarified the potential of electrification, especially for buildings and transport [3,14]. Nevertheless, a large portion of heavy industries, such as steel and cement, will generate residual emissions unless CCS is implemented at a large scale [3]. Given these challenges to deep decarbonization in Japan, previous

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studies have highlighted an increase in carbon prices, reaching approximately US$1,000/t-$CO_2$ or more in 2050. These challenges would be exacerbated by uncertainties related to energy supply options for decarbonization, especially nuclear, CCS and VREs [15–18]. Given these challenges to energy system transformation, Japan's mid-century strategy should be informed by scenario analyses that consider the broad range of options available for decarbonization in terms of technological and economic feasibility.

Among existing mitigation options, the effectiveness of energy demand reduction, which involves changes to behavior and economic structures as well as technological options such as energy efficiency improvement and shifting to low-carbon carriers, has been evaluated in several studies. At the global scale, several investigations have explored the role of energy demand reduction using global IAMs [19–24]. Grubler et al. (2018) provided perspectives on the low energy demand scenario and quantified changes in activity levels and energy intensity in the Global North and South in the context of the Paris Agreement climate goals and Sustainable Development Goals [20]. In addition, van Vuuren et al. (2018) explored alternative pathways that do not depend on carbon dioxide removal technologies to meet the Paris Agreement climate goals, accounting for the effect of lifestyle changes [21]. These studies have generally suggested that energy demand reduction would contribute greatly to fulfilling decarbonization goals and alleviating the economic impacts associated with climate change mitigation. Whereas some have focused on stringent mitigation goals such as 1.5 °C scenarios, few studies have explored the role of energy demand reduction in scenarios of drastic energy system transformation wherein the carbon price reaches US$1,000/t-$CO_2$ or more. At the national scale for Japan, several studies have assessed the implications of the MCS scenarios in attaining the 80% reduction goal in 2050 [17,18,25,26], but findings on the effectiveness of energy demand reduction, especially those focused on energy service demand, remain scarce. A few studies present two representative socio-economic scenarios as basic assumptions for achieving low-carbon societies by 2050 in Japan [27–29], but do not cover more stringent mitigation scenarios, such as 80% reduction with constraints on the availability of nuclear and CCS. Against this background, the effectiveness of substantial energy demand reduction within the context of non-linear energy system transition remains unclear.

The objective of this study was to identify key challenges and opportunities facing Japan in the context of the MCS while considering the effectiveness of energy service demand reduction. To this end, we developed a model for estimating energy service demand based on socio-economic conditions, as well as for quantifying the impact of measures to reduce energy service demand. Finally, we assess the effectiveness of service demand reduction measures for attaining the MCS in Japan using the energy system model.

2. Methods

2.1. Model framework

In this study, two models were compiled to assess the impact of energy demand reduction measures on energy system transformation in Japan. In addition to the partial equilibrium energy system model where energy service demands are given as exogenous fixed parameters, the energy service demand model are used which estimate the service demands in energy sectors based on the socio-economic indicators. While the energy service demand was mostly estimated based on the historical trends, energy system model can explicitly consider dynamic technological changes to meet the decarbonization targets. This section provides an overview of these models and the basic assumptions used for scenario analysis.

2.1.1. Energy system model (AIM/Enduse [Japan])

The energy system model AIM/Enduse [Japan], quantifies key indicators of energy consumption, energy-related CO_2 emissions, and cost, such as carbon price and energy system costs [30]. This model is a bottom-up energy system model with recursive dynamic simulations of mid-to long-term climate policy assessments for Japan. AIM/Enduse [Japan] models various energy efficiency and low-carbon technology options, in which energy service demand needs to be given exogenously. In this model, the introduction of energy technologies is based on linear programming to minimize total energy system cost, which comprises the annualized initial cost of technologies and energy costs subject to the efficiency of the technology, energy service demand, and emission constraints. The power sector considers the balance of electricity supply and demand at 1-h intervals to account for the impacts of VREs and measures used to integrate VREs into the power grid, such as batteries, pumped hydro storage, demand response using battery electric vehicles and heat pump devices, and grid expansions. CCS can be implemented in the power and industry sectors. The full definition, equations, and assumptions of this model are presented in Appendix B.

2.1.2. Energy service demand model

Fig. 1 provides an overview of the energy service demand model. The details of each module, the equations, and parameter settings can be found in the appendices. Gross domestic product (GDP) and population are the basic input parameters of the energy service demand model. First, the sectoral value added and the number of households are estimated with the macroeconomy and population/household modules [31,32]. Second, sectoral energy service demand indicators are estimated using the sectoral modules.

Industrial service demands are represented as material production or indices of industrial production in the following subsectors: steel, cement, petrochemical, pulp and paper, non-ferrous metals, other non-metallic minerals, other chemicals, machinery, textiles, food, other products, construction, agriculture, and fisheries. These energy service demand indicators are estimated primarily through regression analysis based on historical time-series data of sectoral value-added and GDP, which were also used in the existing studies [33,34]. As steel production is strongly influenced by global steel demand, it is estimated based on a global steel demand and production model [31]. The transport demand module originated from the Transport Demand Model [32], which estimates passenger and freight transport demand for the modes of road, rail, ship, and air. In addition to population and economic drivers, freight transport demand includes industrial production, as estimated by the industry service demand module. The service demands for the buildings sector are estimated through regression analysis to cover several energy services, including space heating and cooling, water heating, cooking, lighting, and other appliances. Household and commercial floor space are also considered as service demand drivers for the buildings sector.

2.2. Scenarios

2.2.1. Energy service demand

We assumed two cases of energy service demand. First, the DefDem scenario is the default case, in which no specific energy service demand reduction measures are implemented. Energy service demands in 2050 were estimated using the energy service demand model with population and GDP growth according to SSP2 of the Shared Socioeconomic Pathways (SSPs) [35]. Second, the

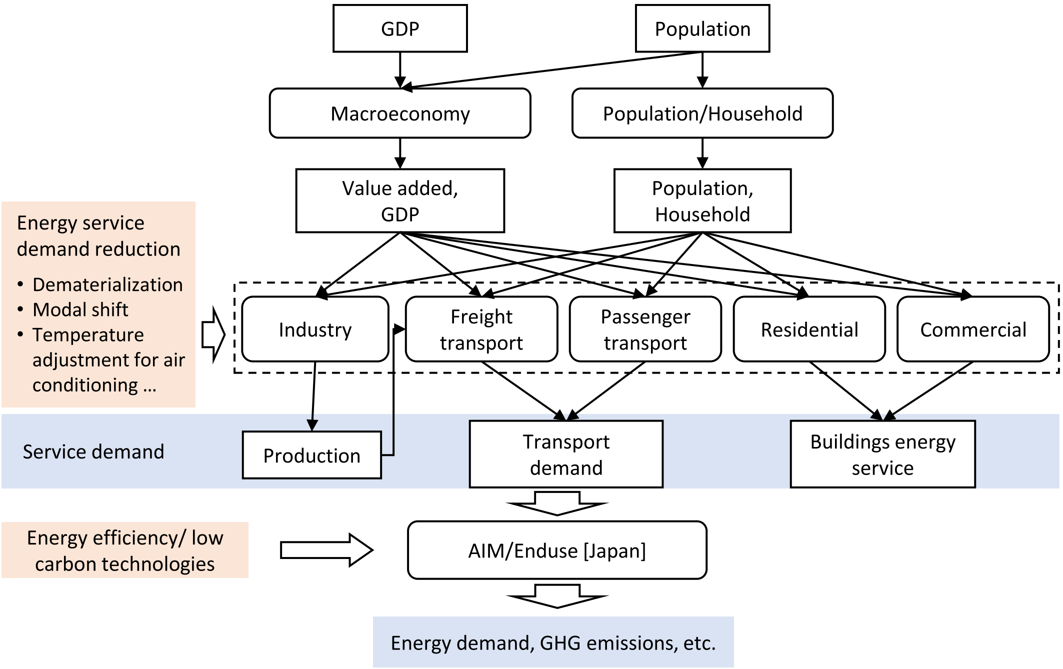

Fig. 1. Schematic framework of this study. Rectangles represent indicators. Rounded rectangles represent models and modules.

LoDem scenario incorporates several energy service demand reduction measures, including material efficiency and behavioral changes, which are described in the literature [20,21]. In addition, the LoInd, LoBui, and LoTra scenarios were used to distinguish the contributions of energy service demand reductions in specific sectors, namely industry, buildings, and transport, respectively. For example, industrial energy service demand reduction measures are included in the LoInd scenario, whereas related to the buildings and transport sectors are ignored.

Table 1 summarizes the parameter assumptions in the energy service demand model for the LoDem scenario. In the industry sector, reductions in industrial production due to dematerialization and material efficiency are considered, with these factors derived from Grubler et al. [20]. In the steel sector, dematerialization and material efficiency are related to several measures, including sharing, lifetime extension, and light-weighting of goods. Based on global steel production, the level in Japan was estimated using a global steel production model (see appendices for more details). For other industrial sectors, the improvements related to dematerialization and material use efficiency mainly arise from the demand-side measures, such as lifetime extension, re-use, and digitalization; these factors are generally applicable to Japan, and we therefore used the reduction rate of Grubler et al. [20].

The buildings sector accounts for service demand reduction related to the use of multifunctional home appliances, temperature changes for air conditioning, and reducing hot water use. The effect of room temperature adjustment for space heating and cooling was estimated by changing base temperature by 1 °C when calculating heating and cooling degree days. Hot water demand reduction is based on reduced shower time of 2 min [22]. Reduced use of consumer goods is due to the use of multifunctional devices, goods sharing, and efficient lighting based on previous research [20] that can be considered applicable to Japan.

For the transport sector, the effects of modal shifts, application of virtual reality, reduced trip frequency, decentralization and localization of the supply chain, and reduction of freight transport due to decreased industrial production were estimated by the transport demand module. As Kainuma et al. [36] considered the

Table 1
Service demand reduction measures considered in the LoDem scenario.

Sector	Measure	Description	Source
Industry	Dematerialization	Industrial production reduction based on dematerialization factors. The factors are 0.9, 1, 0.5, and 0.75 for the steel, cement, paper, and chemical sectors, respectively.	[20]
	Material efficiency	Industrial production reduction based on the material efficiency factors. The factors are 0.27, 0.8, 1, and 1 for the steel, cement, paper, and chemical sectors, respectively.	[20]
Buildings	Air conditioning temperature adjustment	Space cooling and heating temperatures adjusted by 1 °C. Cooling and heating degree days are reduced accordingly.	[21,22]
	Hot water use reduction	Residential water heating demand reduction of 25%.	[21,22]
	Reduced use of consumer goods	Appliance and lighting demand decrease of 17–22%.	[20]
Transport	Modal shift to public transport	20% of road passenger transport shifting to rail in urban areas.	[20,36]
	Modal shift to non-motorized transport	20% of road passenger transport shifting to walking and biking in urban areas.	[20,36]
	Virtual-reality technologies	Trip frequency of commuting is cut by 20%.	[20,36]
	Decentralization and localization of the supply chain	Average freight transport distance decrease of 20%	[20,36]
	Freight transport demand reduction due to reduced industrial production	Dematerialization and material efficiency in the industry sector affect freight transport demand by reducing industry sector production.	[20]

effect of transport demand reduction to be 10–20% in Japan, we assumed that 20% of road transport would be replaced or reduced with the implementation of transport demand reduction measures. The numbers shown in Table 1 represent parameters for 2050. Values for years between 2020 and 2050 were estimated through linear interpolation.

Notably, the starting point or reference level for the energy service demand calculation in this study was not identical the literatures. For example, Grubler et al. [20] used the Global Energy Assessment (GEA) Efficiency Scenario, wherein some demand reduction measures were already considered, as a reference scenario, whereas energy service demand in the present study was calculated based on the SSP2 assumptions. This difference means that the effect of energy service demand reduction in this study will be more moderate than that in Grubler et al. [20].

2.2.2. Technology dimensions

In terms of the availability of low-carbon technologies, four different scenarios were investigated to consider technological uncertainties and identify their impacts on the challenges to energy system transformation. First, FullTech is the default scenario, with no stringent constraints on nuclear or CCS. The assumption of nuclear power plant capacity was taken from a previous study that considered the government energy plan, as outlined in the NDC [14]. Annual CCS capacity was set to 250 Mt-CO_2/yr in 2050 based on previous research [18]. In the NoNUC (no nuclear) scenario, restarting and new construction of nuclear power are excluded. The NoCCS scenario assumes that CCS is unavailable during the period of calculation. NoNUC + NoCCS is a combination of the NoNUC and NoCCS scenarios, wherein both nuclear and CCS are unavailable by 2050.

2.2.3. Climate policy

Two scenarios regarding national climate policies were explored. First, in the BaU scenario, there are no constraints on emissions, although some energy efficiency measures can be introduced based on cost optimization in AIM/Enduse [Japan]. Second, in the MCS scenario, the effects of both the NDC and MCS on CO_2 emissions from energy production and industrial processes are considered. As the base year for the 2050 emission reduction goal, which was not stated in the MCS, we used 2010, in accordance with previous studies [1,14]. The emission pathways between 2030 and 2050 in the MCS scenario were linearly interpolated.

2.3. Cost indicators

Two cost indicators associated with the mitigation challenges are estimated. First, carbon prices are estimated as marginal costs of CO_2 emission based on the linear programming in the energy system model, as these two indicators are equivalent in case of no other policy interventions, such as subsidy for low-carbon technologies [37] (see Supplementary Note 1 for more detail on carbon price estimation). Second, as an indicator of policy cost, total energy system costs were calculated as the sum of the energy investment, operation and management cost, and energy cost relative to the BaU scenario. The contribution of each sector's energy service demand reduction to the total reduction in energy system costs in the LoDem scenario was estimated as follows. First, $\Delta PolicyCost_i$ was calculated as the difference between energy system costs in the DefDem scenario and those in scenarios with energy service demand reductions for each sector using equation (1). As energy service demand reduction in a single sector would affect other energy-related sectors such as energy supply, the sum of policy cost reductions in the LoInd, LoBui, and LoTra cases did not always equal that of the LoDem scenario. Therefore, the residual energy system cost (Δe) was calculated with equation (2).

$$\Delta PolicyCost_i = PolicyCost_{DefDem} - PolicyCost_E, \quad i = \{LoInd,\ LoBui, LoTra\} \tag{1}$$

$$\Delta e = PolicyCost_{DefDem} - PolicyCost_{LoDem} - \sum_i \Delta PolicyCost_i \tag{2}$$

3. Results

3.1. Energy service demand

Energy service demand estimates for the DefDem and LoDem scenarios in 2050 are summarized in Figs. 2 and A. 5. For industry sectors, dematerialization and material efficiency in the LoDem scenario contribute to reductions in material production, especially in the steel sector, with crude steel production in the LoDem scenario approximately a third of that in the DefDem scenario. In the buildings sector, energy service demand in the DefDem scenario for space heating, cooling, and appliances increases toward 2050 due to economic growth, whereas demand for water heating decreases slightly due to decreasing population. In 2050, energy service demand for appliances is projected to be 50% higher than the 2010 level in the DefDem scenario. In the LoDem scenario, energy service demands for space heating and cooling, water heating, and other appliances decrease by approximately 8%, 25%, and 17% relative to the DefDem scenario, respectively. The energy service demand reduction for appliances in the LoDem scenario helps to offset demand increases after 2020. In the transport sector, several assumed measures in the LoDem scenario result in decreases of 27% and 26% by 2050 relative to the DefDem scenario in total passenger and freight transport demands, respectively. In addition, modal shifts from road to rail in passenger transport contribute to a reduction in road transport of 43% in 2050.

3.2. Energy system changes

Final energy demand estimates from the energy system model in the DefDem and LoDem scenarios are depicted in Fig. 3. In the BaU-DefDem scenario, total final energy decreases over time due to population decline and autonomous energy efficiency improvement, reaching approximately 10 EJ in 2050. Although the level of energy service demand in the MCS-DefDem scenarios is identical to that in the BaU scenario, the final energy demand is 12–23% lower than in the BaU scenario due to improved energy efficiency. Moreover, in the LoDem scenarios, energy service demand reduction measures facilitate additional decreases in energy demand in 2050, which is 34–37% lower than in the BaU scenarios. This difference corresponds to approximately half of the final energy demand in 2010. The right panels of Figs. 3 and A. 6 show final energy demands for the industrial, buildings, and transportation sectors in the MCS scenarios. Compared with DefDem, the decrease in industrial energy demand drives a reduction in total final energy demand, followed by effects of the transport sector, due to a reduction in material production. In the transport sector, the energy demand reduction is derived from a modal shift from road usage to public transport, as well as decreasing total transport demand. Due to changes in sectoral final energy demand profiles, the sectoral composition of residual CO_2 emissions also varies between the DefDem and LoDem scenarios (Figs. A. 7 and A. 8). Although the share of residual emissions related to the industry sector in 2050 is critical in the DefDem scenario, in accordance with

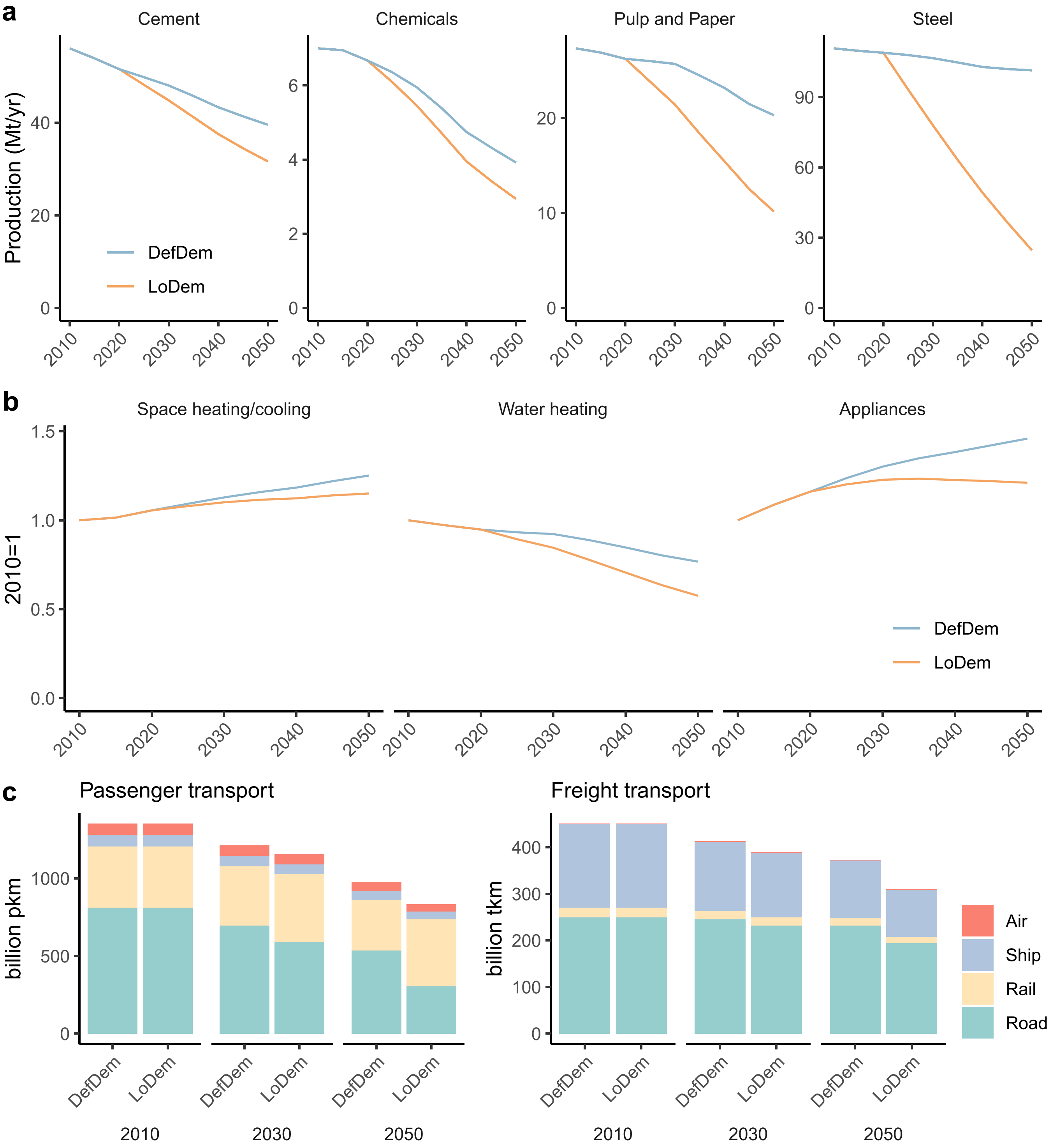

Fig. 2. Energy service demands of the a) industry, b) residential, and c) transport sectors by mode. The "Chemicals" graph in (a) includes ethylene production. Residential service demands are normalized to the energy service level in 2010.

previous research [3], industrial CO_2 emissions in the LoDem scenario are almost halved relative to the DefDem scenario due to the reduction in energy service demand.

In terms of energy system changes, the volume of carbon sequestration, power generation, share of VREs in electricity generation, and electrification rate in final energy demand are summarized in Fig. 4a–d. In the DefDem scenarios, CCS plays a critical role in decarbonization, reaching 250 Mt-CO_2/yr by 2050 in the FullTech and NoNUC cases. Moreover, if CCS utilization were limited in the DefDem scenarios, a drastic change in the energy system would be required especially in the power sector (Fig. 4b). As shown in Fig. 4c and d, it is necessary in the NoCCS scenarios to increase the share of VREs in electricity generation by 60% or more, and to increase the electrification rate in the end-use sectors by

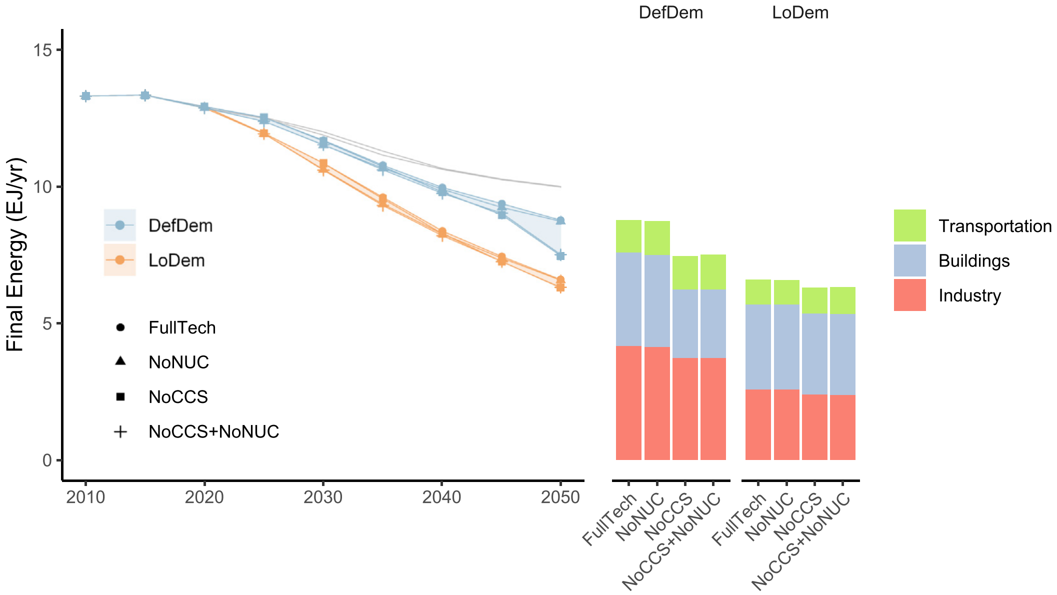

Fig. 3. Final energy demand over time (left) and its sectoral composition in 2050 in the MCS scenarios (right). Grey lines indicate the BaU-DefDem scenarios.

50%.

A decrease in energy service demand would also cause challenges for energy system transformation in the energy supply sectors. Notably, as shown in Fig. 4a, the volume of carbon sequestration in the LoDem scenario would be dramatically reduced, falling to almost half that in the DefDem scenario under FullTech. Because CCS becomes more important as a low-carbon energy source in the NoNUC scenarios, the CO_2 captured in 2050 accounts for less than 200 Mt-CO_2, which is approximately 20% lower than in the DefDem scenario. Although the reduction in carbon sequestration in LoDem is primarily derived from decreased production of steel and cement, carbon sequestration in energy supply sectors also falls sharply, especially in the FullTech scenario. This decrease is mainly because dependence on CCS in power generation is avoided due to the decrease in electricity demand (Figs. A. 9–A. 12).

In contrast to CCS, upscaling of VREs remains a key mitigation option in the LoDem scenario as well as the DefDem scenario (Fig. 4b and Fig. A. 9). In 2050, VREs in the LoDem scenarios account for approximately 20–60% of total power generation, which is approximately 10% points lower than that in the DefDem scenario (30–70%), suggesting that increasing VREs could be a key option for decarbonization, especially in scenarios with nuclear and CCS constraints (see Supplementary Note 2 for more detail). In addition, electrification of end use is a key pillar for decarbonization in both the DefDem and LoDem scenarios. As shown in Fig. 4c, the contribution of electricity use to total final energy demand is approximately 40–50% in 2050.

3.3. Impact of reduced energy service demand on mitigation costs

First, carbon price trajectories are depicted in Fig. 5a, as the most existing studies have focused on the level of carbon prices as cost indicators [3,4]. In the DefDem scenarios, carbon prices in the FullTech and NoNUC cases are approximately US\$1,100/t-CO_2 in 2050. By contrast, that in the NoCCS scenario is almost quadrupled, reaching approximately US\$4,000/t-CO_2 or more, similar to the findings from the existing studies that unavailability of CCS causes increase of mitigation cost drastically [38]. These carbon price hike comes from the investments for additional mitigation options, such as removal of residual emission in the energy demand sectors without CCS, additional introduction of VREs in power generation and their associated integration costs, and the removal of existing fossil fuel infrastructures earlier than their expected lifetime [39] (see Supplementary Note 1 and 2 for more detail). By contrast, carbon prices in the LoDem scenarios fall to less than US\$500/t-CO_2 in the FullTech and NoNUC cases and remain at US\$1,100/t-CO_2 even in the NoCCS + NoNUC scenario. Similar to the carbon price implications, technological constraints on CCS cause an increase in the total energy system cost in the DefDem scenarios, with that in the NoCCS + NoNUC scenario double that in the FullTech scenario, reaching more than US\$200 billion/yr by 2050 (Fig. 5b). Nevertheless, the LoDem scenarios result in drastic reductions in energy system costs, equaling approximately US\$100 billion. Based on these mitigation cost results, we suggest that reducing energy service demand has the potential to offset the increase in carbon prices and energy system costs related to constraints on low-carbon measures in the energy supply sectors.

The contribution of each sector's service demand reduction to reducing cumulative energy system costs by 2050, which was estimated using equations (1) and (2), is summarized in Fig. 5c. According to our sectoral analysis, the industry sector is the largest contributor to halving energy system costs through energy service demand reduction, followed by the buildings and transport sectors. In particular, the contribution of the industrial sector increases in the NoCCS cases. The relationships between annual final energy demand reduction and the reductions in carbon price and energy system cost by 2050 are depicted in Fig. 5d and e, respectively. Although the level of energy demand and economic indicators are generally linearly correlated, the slopes in the NoCCS scenarios are substantially steeper than those in the FullTech and NoNUC scenarios for both carbon price and energy system cost. This result emphasizes the effectiveness of energy service demand reduction in the industrial sector, which contributes not only to reducing energy demand but also to avoiding dependence on CCS for decarbonizing the industrial sector.

4. Discussion and conclusions

In this study, we identify the challenges to energy system

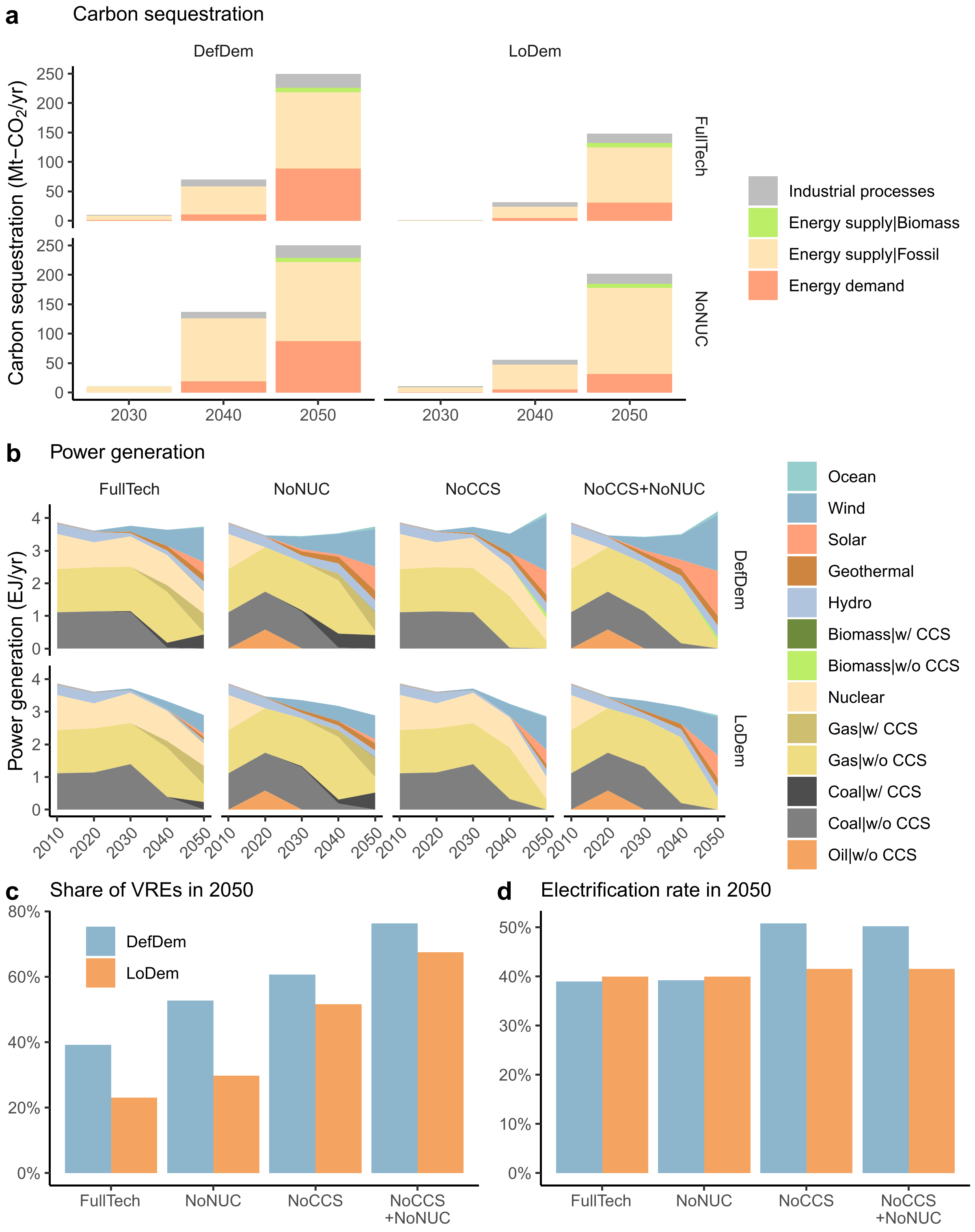

Fig. 4. Comparison of energy system transformations between the DefDem and LoDem MCS scenarios. a) Carbon sequestration in the FullTech and NoNUC scenarios, b) power generation in the DefDem and LoDem scenarios, c) share of power generation from VREs in 2050, and d) contribution of electricity to final energy demand in 2050.

transformation associated with the long-term decarbonization goal in Japan. Especially, the role of energy service demand reduction is explored, as their contribution to the decarbonization goals has not been sufficiently clarified in the existing studies. Based on scenario analysis through 2050, we reached the following conclusions. First, the importance of CCS is reconfirmed within the context of long-term low-emission scenarios. The absence of CCS would lead to massive mitigation cost increases, with carbon prices and energy system costs doubling or more, and associated rapid energy system changes including demand-side electrification. Second, we found

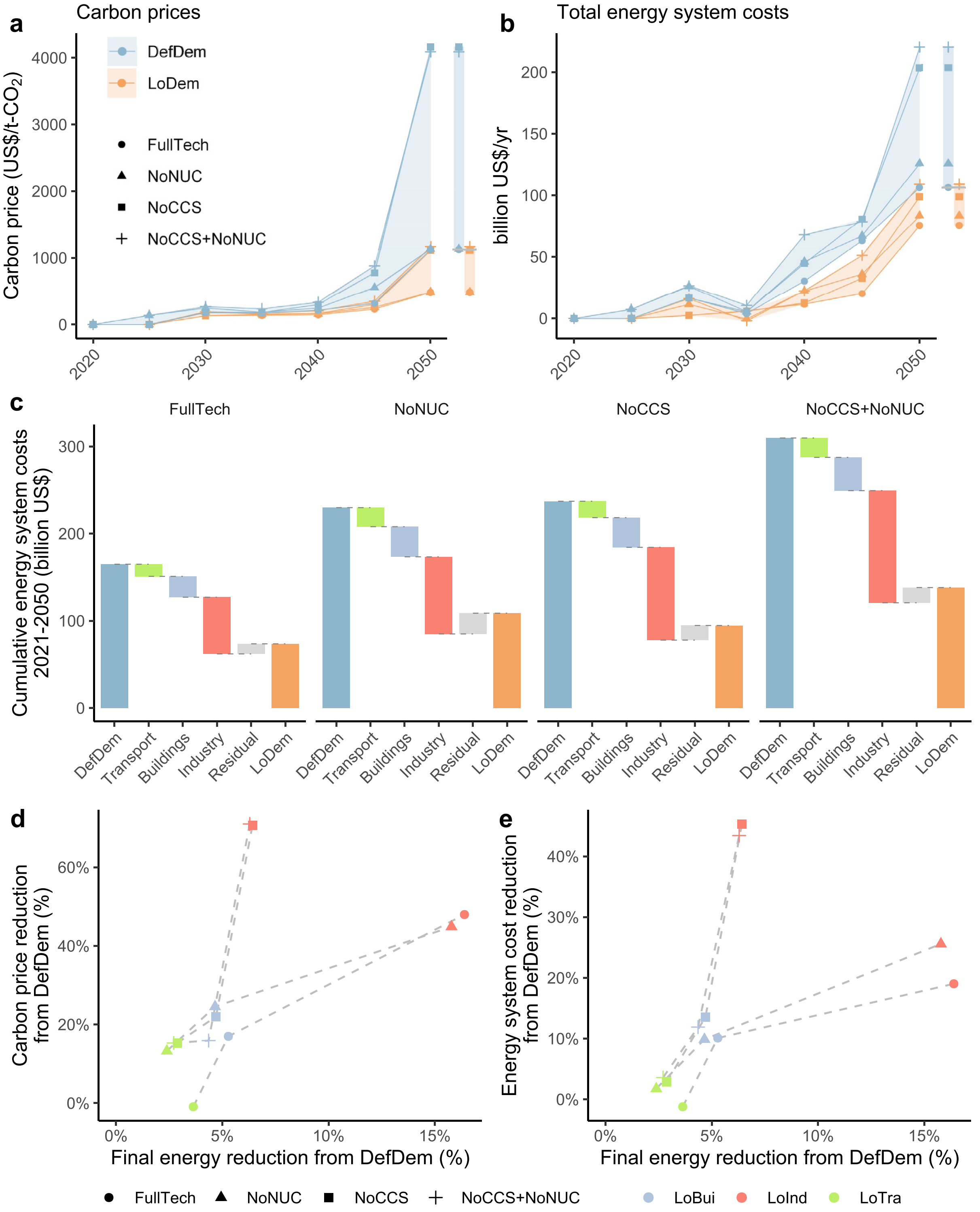

Fig. 5. Carbon prices (a) and total energy system costs (b) over time and their ranges in 2050 by level of energy service demand in the MCS scenarios. The grey horizontal line indicates carbon price in the DefDem-FullTech scenario in 2050. c) Cumulative energy system costs between 2021 and 2050 discounted using a 5% interest rate in the MCS scenarios. The first and sixth bars denote the energy system costs in the DefDem and LoDem scenarios, respectively. The second to fifth bars indicate the contributions of sectoral energy service demand reduction measures to reducing total energy system costs. (d) Relationship between final energy demand reduction and carbon price reduction under the DefDem scenario in 2050. (e) Relationship between final energy demand reduction and energy system cost reduction under the DefDem scenario in 2050.

that energy service demand reduction measures could contribute to reductions in final energy demand of up to 37% by 2050 relative to the BaU scenario, in conjunction with the application of several energy efficiency technologies. Such measures would help to avoid dependence on CCS, as demand for CCS was reduced by up to 50% relative to the default service demand case. In terms of mitigation costs, energy service demand reduction has the potential to offset the non-linear increase in costs due to lack of CCS availability.

Among energy demand sectors, the impact of the energy service demand reduction in the industrial sector is the greatest, as it contributes not only to cutting energy demand but also to avoiding dependence on CCS in energy demand sectors. Third, although our results highlight the roles of energy service demand reduction and CCS, these changes alone are insufficient to meet the long-term decarbonization goal of Japan. Transformation of the energy system beyond current trends would still be needed, especially the use of VREs in power sectors and promoting end-use electrification.

There are several limitations and caveats suggested by this study that should be considered when interpreting the role of energy demand reduction. First, the technological, economic and political feasibility of energy service demand reduction should be discussed further. As the options for energy service demand reduction are mostly based on global studies, exploration of their feasibility in Japan is needed. In particular, although this study stresses the importance of reducing industrial production, especially in the steel sector, domestic production of these materials would be influenced not only by domestic circumstances but also by global trends in demand for these commodities. This caveat emphasizes the importance of policy cooperation toward dematerialization and improved material use efficiency at the global scale, as well as that of domestic policies regarding resource use and recycling. Moreover, the level of steel production would affect the production of other commodities such as cars. While the economy-wide impacts of energy demand reduction are outside the scope of this study because we used a partial equilibrium model, further discussion of the economic feasibility of energy demand reduction is needed. In addition, it should also be noted that the uncertainty on baseline energy service demand estimation is remaining, as it is based on historical trends in Japan.

Second, the definition of the baseline is a key factor in interpreting the effects of energy demand reduction. In this study, we used a scenario with no additional climate policy as the baseline, as previous multi-model research indicated that the emission pathways in current policy scenarios are almost identical to historical trends and the no-policy scenario [7,40]. This finding indicates that the net effect on energy usage would be only moderate if some energy reduction measures and behavioral changes are implemented without broader climate policies. Nevertheless, energy demand reduction measures will be essential for avoiding the negative impacts of non-linear energy system transitions.

Third, research and development of new technologies will support some energy demand reduction measures, such as multifunctional home devices, virtual-reality technologies, and innovative low-carbon measures, which would help to reduce energy service demand in the buildings and transport sectors. Also, development of innovative technologies could provide additional energy and carbon intensity improvement opportunities, such as utilization of hydrogen-based energy carriers and application of heat-pump technologies in the high-temperature heat demand in the industry sectors.

Fourth, in terms of the cost implications of this study, the additional policy costs of energy service demand reduction were not considered during optimization of the energy system model and were thus excluded from the energy system cost results. As energy demand reduction, including the effect of reduced service demand, is generally a cost-effective option [41,42], the main findings of this study would not be influenced by the policy cost of energy service demand; nevertheless, quantification of the policy costs of energy service demand reduction and cost-benefit analysis are crucial topics for future research.

Finally, despite various challenges to realizing energy service demand reduction, the Japanese society has already implemented some measures to reduce energy usage. For example, the Cool biz and Warm biz campaigns help to facilitate energy savings in buildings by promoting room temperature changes for air conditioning, which is an energy service demand reduction considered in this study. National climate policy must be designed not only around technological solutions but also energy service demand reduction measures, including behavioral changes.

Author contributions

Ken Oshiro: Conceptualization, Methodology, Software, Visualization, Writing-Original Draft. **Shinichiro Fujimori:** Conceptualization, Writing-Review& Editing. **Yuki Ochi:** Data curation, Writing-Review& Editing. **Tomoki Ehara:** Data curation, 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 data

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References

[1] Fujimori S, Oshiro K, Shiraki H, Hasegawa T. Energy transformation cost for the Japanese mid-century strategy. Nat Commun 2019;10(1):4737.

[2] Silva Herran D, Fujimori S, Kainuma M. Implications of Japan's long term climate mitigation target and the relevance of uncertain nuclear policy. Clim Pol 2019;19(9):1117–31.

[3] Sugiyama M, Fujimori S, Wada K, Endo S, Fujii Y, Komiyama R, et al. Japan's long-term climate mitigation policy: multi-model assessment and sectoral challenges. Energy 2019;167:1120–31.

[4] Oshiro K, Gi K, Fujimori S, van Soest HL, Bertram C, Després J, et al. Mid-century emission pathways in Japan associated with the global 2 °C goal: national and global models' assessments based on carbon budgets. Climatic Change 2019;162(4):1913–27.

[5] Fragkos P, van Soest HL, Schaeffer R, Reedman L, Köberle AC, Macaluso N, et al. Energy system transitions and low-carbon pathways in Australia, Brazil, Canada, China, EU-28, India, Indonesia, Japan, Republic of Korea, Russia and the United States. Energy 2021;216:119385.

[6] Krey V, Guo F, Kolp P, Zhou W, Schaeffer R, Awasthy A, et al. Looking under the hood: a comparison of techno-economic assumptions across national and global integrated assessment models. Energy 2019;172:1254–67.

[7] Roelfsema M, van Soest HL, Harmsen M, van Vuuren DP, Bertram C, den Elzen M, et al. Taking stock of national climate policies to evaluate implementation of the Paris Agreement. Nat Commun 2020;11(1):2096.

[8] Giannousakis A, Hilaire J, Nemet GF, Luderer G, Pietzcker RC, Rodrigues R, et al. How uncertainty in technology costs and carbon dioxide removal availability affect climate mitigation pathways. Energy 2020:119253.

[9] Schreyer F, Luderer G, Rodrigues R, Pietzcker RC, Baumstark L, Sugiyama M, et al. Common but differentiated leadership: strategies and challenges for carbon neutrality by 2050 across industrialized economies. Environ Res Lett 2020;15(11):114016.

[10] Komiyama R, Fujii Y. Optimal integration assessment of solar PV in Japan's electric power grid. Renew Energy 2019;139:1012–28.

[11] Luderer G, Pietzcker RC, Carrara S, de Boer HS, Fujimori S, Johnson N, et al. Assessment of wind and solar power in global low-carbon energy scenarios: an introduction. Energy Econ 2017;64:542–51.

[12] Shiraki H, Sugiyama M, Matsuo Y, Komiyama R, Fujimori S, Kato E, et al. The role of renewables in the Japanese power sector: implications from the EMF35 JMIP. Sustain Sci 2021;16:375–92.

[13] Oda J, Akimoto K, Tomoda T, Nagashima M, Wada K, Sano F. International

comparisons of energy efficiency in power, steel, and cement industries. Energy Pol 2012;44:118–29.
[14] Oshiro K, Kainuma M, Masui T. Implications of Japan's 2030 target for long-term low emission pathways. Energy Pol 2017;110:581–7.
[15] Homma T, Akimoto K. Analysis of Japan's energy and environment strategy after the Fukushima nuclear plant accident. Energy Pol 2013;62:1216–25.
[16] Oshiro K, Kainuma M, Masui T. Assessing decarbonization pathways and their implications for energy security policies in Japan. Clim Pol 2016;16(sup1):S63–77.
[17] Kato E, Kurosawa A. Evaluation of Japanese energy system toward 2050 with TIMES-Japan – deep decarbonization pathways. Energy Procedia 2019;158:4141–6.
[18] Oshiro K, Masui T, Kainuma M. Transformation of Japan's energy system to attain net-zero emission by 2050. Carbon Manag 2018;9(5):493–501.
[19] Fujimori S, Kainuma M, Masui T, Hasegawa T, Dai H. The effectiveness of energy service demand reduction: a scenario analysis of global climate change mitigation. Energy Pol 2014;75:379–91.
[20] Grubler A, Wilson C, Bento N, Boza-Kiss B, Krey V, McCollum DL, et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nature Energy 2018;3(6):515–27.
[21] van Vuuren DP, Stehfest E, Gernaat DEHJ, van den Berg M, Bijl DL, de Boer HS, et al. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. Nat Clim Change 2018;8(5):391–7.
[22] van Sluisveld MAE, Martínez SH, Daioglou V, van Vuuren DP. Exploring the implications of lifestyle change in 2°C mitigation scenarios using the IMAGE integrated assessment model. Technol Forecast Soc Change 2016;102:309–19.
[23] Levesque A, Pietzcker RC, Luderer G. Halving energy demand from buildings: the impact of low consumption practices. Technol Forecast Soc Change 2019;146:253–66.
[24] Wilson C, Pettifor H, Cassar E, Kerr L, Wilson M. The potential contribution of disruptive low-carbon innovations to 1.5 °C climate mitigation. Energy Efficiency 2019;12(2):423–40.
[25] Matsuo Y, Endo S, Nagatomi Y, Shibata Y, Komiyama R, Fujii Y. A quantitative analysis of Japan's optimal power generation mix in 2050 and the role of CO2-free hydrogen. Energy 2018;165:1200–19.
[26] Ozawa A, Kudoh Y, Murata A, Honda T, Saita I, Takagi H. Hydrogen in low-carbon energy systems in Japan by 2050: the uncertainties of technology development and implementation. Int J Hydrogen Energy 2018;43(39):18083–94.
[27] Fujino J, Hibino G, Ehara T, Matsuoka Y, Masui T, Kainuma M. Back-casting analysis for 70% emission reduction in Japan by 2050. Clim Pol 2008;8(sup1):S108–24.
[28] Ashina S, Fujino J, Masui T, Ehara T, Hibino G. A roadmap towards a low-carbon society in Japan using backcasting methodology: feasible pathways for achieving an 80% reduction in CO2 emissions by 2050. Energy Pol 2012;41:584–98.
[29] Matsuoka Y, Fujino J, Kainuma M. National implications of a 50% global reduction of greenhouse gases, and its feasibility in Japan. Sustainability Science 2008;3(1):135–43.
[30] Oshiro K, Masui T. Diffusion of low emission vehicles and their impact on CO2 emission reduction in Japan. Energy Pol 2015;81:215–25.
[31] Akashi O, Hanaoka T, Matsuoka Y, Kainuma M. A projection for global CO2 emissions from the industrial sector through 2030 based on activity level and technology changes. Energy 2011;36(4):1855–67.
[32] Akashi O, Ashina S, Ehara T, Fujino J, Fujiwara T, Hanaoka T, et al. Aligning climate change and sustainability -scenarios, modeling and policy analysis-. CGER-REPORT: center for global environmental research. National Institute for Environmental Studies; 2007.
[33] Kesicki F, Yanagisawa A. Modelling the potential for industrial energy efficiency in IEA's World Energy Outlook. Energy Efficiency 2015;8(1):155–69.
[34] Zhou S, Kyle GP, Yu S, Clarke LE, Eom J, Luckow P, et al. Energy use and CO2 emissions of China's industrial sector from a global perspective. Energy Pol 2013;58:284–94.
[35] Riahi K, van Vuuren DP, Kriegler E, Edmonds J, O'Neill BC, Fujimori S, et al. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Global Environ Change 2017;42:153–68.
[36] Kainuma M, Masui T, Oshiro K, Runsen Z. Pathways to deep decarbonization of passenger transport sector in Japan. IDDRI; 2017.
[37] Paltsev S, Capros P. Cost concepts for climate change mitigation. 04(supp01) Climate Change Economics 2013:1340003.
[38] Kriegler E, Weyant JP, Blanford GJ, Krey V, Clarke L, Edmonds J, et al. The role of technology for achieving climate policy objectives: overview of the EMF 27 study on global technology and climate policy strategies. Climatic Change 2014;123(3):353–67.
[39] Oshiro K, Fujimori S. Stranded investment associated with rapid energy system changes under the mid-century strategy in Japan. Sustain Sci 2020;16:477–87.
[40] Schaeffer R, Köberle AC, van Soest HL, Bertram C, Luderer G, Riahi K, et al. Comparing transformation pathways across major economies. Climatic Change 2020;162(4):1787–803.
[41] Krey V, Luderer G, Clarke L, Kriegler E. Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. Climatic Change 2014;123(3):369–82.
[42] Riahi K, Kriegler E, Johnson N, Bertram C, den Elzen M, Eom J, et al. Locked into Copenhagen pledges — implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technol Forecast Soc Change 2015;90:8–23.