Energy and Climate Change 6 (2025) 100223

Contents lists available at ScienceDirect

Energy and Climate Change

journal homepage: www.sciencedirect.com/journal/energy-and-climate-change

JMIP2 Part 3: The pace of hydrogen and electricity adoption in Japan's demand-side decarbonization

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ARTICLE INFO

Keywords:
Model intercomparison project
Final energy
Hydrogen
Electrification
Net-zero scenario

ABSTRACT

Reaching net-zero emissions in Japan depends on technological advancements in energy efficiency and cost-effectiveness across both energy supply and demand sectors. Previous model comparison studies in Japan did not adequately address uncertainties from technological development under the latest net-zero commitment, potentially hindering effective stakeholder decision-making. This study coordinates multiple integrated assessment and energy systems models to analyze consistent policy and technology scenarios, focusing on energy transition pathways in end-use sectors. The results show that, to meet the net-zero requirement, all models exhibit a similar trend of declining total final energy demand, with a reduction of approximately 30% by 2050 relative to 2020. Meanwhile, electricity may account for around 50% or more of the total final energy in 2050 while hydrogen could grow to approximately 13%, with growth accelerating after 2040. Hydrogen is effective in achieving deep reductions in industrial emissions, and its necessity increases as emission targets become more stringent. The government has set ambitious targets for the utilization of hydrogen, but its deployment in end-use sectors requires further policy guidance to facilitate investment. The study emphasizes that end-use energy technology transformations should align with trends in both imported clean energy costs and domestic renewable energy costs.

1. Introduction

Global climate change has compelled all countries to reconsider their energy strategies and pursue green development. Scenario analysis can serve to identify optimal pathways leading to low overall costs and deep carbon emission reductions. Global net-zero scenario analysis is inevitably based on a series of simplified assumptions, and the derived cost-optimal solution may lack practicality by overlooking regional characteristics. Japan is an island nation far from continental landmasses, with limited renewable energy resources, mountainous terrain, and high population density. These traits are similar to the challenges faced by some other countries that struggle to achieve carbon neutrality. Therefore, an investigation into net-zero scenario analysis for Japan can serve as a reference for other countries with similar limitations, helping to refine and adjust global pathways.

Japan, as the 8th largest greenhouse gas (GHG) emitting economy

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https://doi.org/10.1016/j.egycc.2025.100223

Available online 16 November 2025

[1], has committed to reducing its emissions by 46 % in fiscal year 2030 compared to fiscal year 2013 levels, setting an ambitious target that aligns with the long-term goal of achieving net-zero emissions by 2050 [2]. However, the net-zero GHG commitment faces challenges in some aspects. For example, Japan is an export-intensive industrial country with potentially substantial residual emissions from sectors that are difficult to decarbonize [3]. Further, factors such as high population density, mountainous terrain, limitations in grid infrastructure, and limited social acceptance hinder the extensive expansion of renewable energy, increase reliance on highly uncertain carbon dioxide removal or negative emission technologies, and could pose obstacles to Japan's future net-zero commitments.

Over the past decades, Japan has introduced a series of sector-specific policies under the framework of the Act on Promotion of Global Warming Countermeasures [4]. Before the Paris Agreement, Japan's climate policy primarily focused on energy efficiency initiatives within large businesses, such as the Top Runner Programs, building codes and labeling, and voluntary actions by industry [5]. Following the announcement of net-zero GHG commitment, innovation promotion became another emphasis for deep emission mitigation. For example, Green Transformation (abbreviated as GX), as the latest industrial policy package, plans to allocate 20 trillion yen through the issuance of government bonds to stimulate low-carbon technology innovation and the green transformation of industrial sectors and invoke an additional 130 trillion yen from the private sector [6]. Under the guidance of these policies, the policy direction on the energy supply side has become increasingly clear, specifically focusing on decarbonizing the power system and expanding clean energy supply represented by hydrogen energy. On the demand side, a representative policy is Japan's Act on Rationalizing Energy Use (Energy Conservation Act) [7]. It was first enacted in 1970, and was revised in 2023, aiming to regulate big corporations that meet certain annual operational criteria to report on their energy consumption and conservation plans. Due to significant sectoral heterogeneity, the policy stimulus for promoting energy efficiency, electrification, and the introduction of clean energy varies greatly across different energy-consuming sectors.

To accelerate electrification on the energy demand side, firstly taking passenger vehicle in transportation sector as an example, Japan implemented the Subsidies to Promote the Introduction of Clean Energy Vehicles (a.k.a. CEV Subsidies), increasing subsidies for electrified vehicles, promoting not only electric vehicles (EVs), but also hybrid EVs (HEVs), plug-in hybrid EVs (PHEVs) and fuel cell vehicles (FCVs) [8]. The country has set a goal for all sales of new passenger vehicles to be "electrified" by 2035 [9]. However, since the subsidy targets also include HEVs, there could be residual emissions from gasoline or diesel, and this necessitates the commercialization of synthetic fuel (e-fuels) to reach full decarbonization.

In the building sector, enhancing energy efficiency remains the primary objective. Approximately 90 % of houses in Japan do not meet the current energy conservation standards because the energy conservation standards for houses established in 1980 were voluntary rather than mandatory [10], although there will be mandates. Regarding the electrification of buildings, energy consumption in both residential and non-residential buildings in Japan has achieved an electrification rate exceeding 50 %, with the remaining non-electrified consumption primarily concentrated on water and space heating [10]. The adoption of heat pump water heaters in housing is a direction for transition. The current challenges are how to promote the introduction of heat pumps (for space heating and cooling as well as water heating/hot bath, which occupies a large proportion of household energy consumption) in the existing housing stock and to increase residents' willingness to adopt novel technology.

In the industrial sector, options for electrification include electric and plasma arc furnaces alongside high-temperature heat pumps. Currently, industrial heat pumps are a feasible solution for processes requiring temperatures between 90 to 140 °C, including many steam-based processes, and are most efficient when maintaining a temperature difference of 50 to 60 °C. However, to the best of our knowledge, policies concerning the introduction of industrial heat pumps remain inadequate. Additionally, electric arc furnaces (EAF) are widely employed in secondary steel production; however, in Japan EAF usage rate is only ~25 %, due to the lack of scrap and the large demand for primary steel production [11]. All in all, electrification in steel sector has huge potential to cut down industrial emissions; however, Japan's steel decarbonization has put much emphasis on Carbon dioxide Capture, Utilization and Storage (CCUS) technology and retrofitting current coal-based furnaces.

Alternative fuels other than electricity, like hydrogen, also attract policy concerns. In 2020, Japan set a goal of achieving carbon neutrality by 2050, targeting the use of hydrogen and ammonia for 1 % of electricity production by 2030. Also in 2020, Japan announced plans for a 2 trillion yen ($12.5 billion) Green Innovation Fund, and around 800 billion yen of the sum was allocated for supporting development of hydrogen-related technologies [12]. More recently, the Hydrogen Society Promotion Act came into effect from Oct 2024, which is the first law regulating businesses relating to hydrogen and its derivatives in Japan. The primary objective is to provide support to approved businesses specifically through the "Support Focusing on the Price Gap" (Contracts for difference, namely CfD) Scheme and the "Support for the Development of Hubs" (Hub Support) Scheme [13]. The current mainstream studies on hydrogen penetration in future scenarios have some divergences, which further adds uncertainty for policymakers and investors. Some researchers found a high hydrogen penetration in the long-term scenarios, for example, an assessment by Oshiro and Fujimori [14] using the AIM-Tech model found that by midcentury hydrogen and hydrogen-derived energy carriers could provide up to ~9 % of global industrial final energy demand and up to ~50 % of global transportation energy needs in scenarios that limited warming to 1.5–2 °C. However, another study gave a smaller number [15], i.e., hydrogen provides a smaller share of total final energy at midcentury (2–4 %), with a similar share in transportation (2–6 %) and industry (2–4 %).This number is also aligned with the median value in IPCC AR6 scenario database [16]. The global level of discrepancies on hydrogen use is not a single example, and in Japan the debate also exists [17]. In the revised Basic Hydrogen Strategy [18], one of the goals is to increase domestic consumption of hydrogen to 3 million tons by 2030 (~0.36 EJ), to 12 million tons by 2040 (~1.44 EJ), and to 20 million tons by 2050 (~2.4 EJ). However, it is not clear whether the target can be achieved under varying policy stringency and technology innovations.

In summary, past policies on the demand side have primarily targeted big businesses, and focused on enhancing energy use efficiency, while there is a relative scarcity of policies aimed at promoting the expansion of clean energy consumption. The uncertainty of future clean energy markets may, to some extent, impede the investment enthusiasm of enterprises.

One way to better explore the uncertainty in policy formulation is to compare the results of energy system models and draw robust conclusions. Comparative modeling studies in Japan have progressed through the phases of JMIP 0 [19] and Stanford Energy Modeling Forum (EMF) 35 JMIP 1 [5,20]. To our knowledge, we are among the few groups conducting academic model comparisons in Japan, and previous efforts mainly focused on 80 % reduction scenarios. Given this, our study extends it to net-zero and includes multiple technology assumptions, addressing a clear gap in existing literature. As for the contribution to the MIPs, while many model comparison studies exist for other regions and countries, it is essential to consider Japan's specific context and constraints. The impact of technological innovations on total final energy consumption and the adoption of clean energy remains unclear, particularly concerning low-cost renewable energy technologies, affordable clean energy imports, and the electrification of end-use energy technologies. Additionally, the extent to which unlimited carbon dioxide removal (CDR) usage would impact the remaining fossil fuels in final energy consumption is still uncertain. This study aims to address the aforementioned gaps and share insights to identify further research priorities. Specifically, it will examine the role of clean energy carriers—such as electricity, hydrogen, and bioenergy [21]—under net-zero scenarios for the transportation, residential and commercial, and industrial sectors, while exploring the differences and similarities in technology pathways.

The structure of the paper is as follows: 1) The Methods section briefly introduces the participating models and scenarios. For more detailed descriptions of the model itself and the scenarios, refer to the attached Supplementary Information (SI). 2) The Results section presents the composition of final energy consumption under net-zero scenarios, the path of clean energy adoption, the decomposition analysis of the primary factors driving emission reductions in each sector and introduces the emission reduction effectiveness of hydrogen and electricity across various sectors. Finally, we conduct a sensitivity analysis for the final energy composition under various emission constraints and technological innovations. 4) The Discussion section combines the study's results with Japan's industrial policies to discuss the potential and directions for deploying clean energy in each sector. 5) The Conclusion section summarizes the core findings of the paper and outlines prospects for future model development.

2. Methods

Energy systems analysis and integrated assessment are essential for examining the assumptions of policies and technologies that support sustainable energy pathways compatible with net-zero emissions [16]. This study examines results from the Japan Model Intercomparison Project (JMIP) 2 Net Zero scenario database. To understand the role of clean energy carriers (hydrogen, electricity, etc.) in transforming energy systems, a comprehensive set of scenarios was analyzed among participating models, encompassing different climate targets and technology portfolios.

2.1. Model descriptions

AIM-Hub-Japan is a general equilibrium (GE) model, whereas the other models are partial equilibrium (PE) models. In the GE model, service demands are price-elastic, meaning they respond to changes in prices. In contrast, the PE models assume exogenous service demands, which do not change in response to price variations. Table 1 presents, for each model, the applictaion of hydrogen and bioenergy by three major end-use sectors. It should be noted that in the subsequent analysis, if the value of a given energy carrier in the final energy mix is zero, this may reflect the absence of a corresponding technological option in the model rather than an actual modelled outcome of zero. More information about models can be found in Section 1.1 in the SI and Sugiyama et al. [22].

2.2. Scenario design

These technology scenarios were designed to explore the possibility of clean energy pathways in light of the availability and economics of other key abatement options.

Initially, various emission scenarios with differing levels of climate policy stringency, namely 100 %, 105 %, and 110 % reduction of CO_2 emission in 2050, were utilized to examine its impact on the final energy mix. Additionally, multiple technology availability scenarios were evaluated to investigate the end-use energy transition amidst uncertainties regarding the availability and cost of other decarbonization technologies, which influence the complexity of mitigation efforts. The technology scenarios include higher CDR availability (XX_cdr), more affordable electricity end-use technologies (XX_electech), more affordable clean energy imports (XX_import), and lower renewable energy costs (XX_re). By analyzing the model's output of these scenarios, we gain deeper insights into the implications of these scenarios. Scenario names are structured as AAbyBB_CC, indicating an AA % CO_2 emission reduction by year BB under the CC technology scenario, with the baseline scenario included for comparison.

The net-zero equivalent (NZE) scenario uses 105 % CO_2 emission reduction constraints, while technology costs, complementary policies, and consumer preferences are decided by each model's default assumptions, and the maximum deployment of CDR is limited to 100 Mt-CO_2/yr throughout [3].

2.2.1. Baseline

This scenario models the continuation of current policies without stringent emission constraints or aggressive carbon pricing policies (neither cap-and-trade nor carbon tax). Note that the model includes the economic impact of COVID-19 (reflected in economic contraction in 2020 and 2021 and subsequent rebound). Specific technical parameters are determined by each model.

2.2.2. Policy dimension

We designed targets to achieve 100 %, 105 %, and 110 % CO_2 emission reductions by 2050. These varying targets test the dependence on various low-carbon technologies under uncertain future emission pathways. Additionally, since Japan's official goal is to achieve 100 % GHG reduction, and most studies in the literature so far considered 100 % CO_2 reduction, different CO_2 reduction stringency targets can also inform strategies for reducing other GHGs. As estimated, 105 % reduction of CO_2 emissions is roughly equivalent to 100 % of greenhouse gases, thus we also define target of 105 % CO_2 reduction as net-zero equivalent scenario (NZE).

2.2.3. Technology dimension

The technology assumptions are shown in Table 2. This set of technology sensitivity scenarios cover variations in renewables, end-use electrification technologies, CDR and clean energy imports. More details about the consideration and uncertainty can be found in Section 1.2 in the SI and Sugiyama et al. [22].

2.3. LMDI analysis

This study employs the LMDI decomposition method to analyze the factors influencing the change in CO_2 emissions from 2020 to 2050. LMDI is a widely recognized technique in energy economics and environmental studies for its ability to decompose complex changes in aggregate indicators into meaningful contributing factors [23]. Its additive property ensures that the sum of individual contributions

Table 1
Hydrogen and Bioenergy application in sectors in each model.

Sectors	Energy carriers	AIM-Hub-Japan	AIM-Technology-Japan	D-TIMES	IEEJ-NE_Japan	TIMES-Japan
Industry	Hydrogen	Not applicable	√	√	√	√
Industry	Bioenergy	√	√	Not applicable	√	Not applicable
Residential and Commercial	Hydrogen	Not applicable	√	Not applicable	√	√
Residential and Commercial	Bioenergy	√	√	Not applicable	Not applicable	Not applicable
Transportation	Hydrogen	Not applicable	√	√	√	√
Transportation	Bioenergy	√	√	Not applicable	√	Not applicable

Note: Electricity has been reported by all models, so it is not shown in the table.

Table 2
Abbreviation and description of various technological assumptions.

Technology assumptions	Short definition	Description
deftech	Default technology	Default assumptions for technology costs and performance (including a 100MtCO_2/yr CDR constraint)
cdr	Increased availability of CDR	CDR constraint is set to model's usual setting, rather than the upper limit set in deftech
import	Cheaper imported clean energy	Halves the price of imported carbon-neutral fuels like hydrogen and ammonia (excl. biofuels) by 2050, on a linear scale starting in 2030.
re	Cheaper renewables cost	Halves the capital and operational costs of variable renewable technologies (i.e. solar PV, onshore wind, and offshore wind) by 2050, on a linear scale starting in 2030.
eletech	Cheaper electricity end-use technologies	Halves the cost of electricity technologies in end-use sectors
Innov	Combination of all above	Integration of all above innovations

precisely accounts for the total change, providing clear insights into the driving forces behind emissions trends. The details of calculation can be found in Section 1.3 in SI.

3. Results

3.1. Overall final energy demand in 2050

Fig. 1 illustrates the trends in total final energy demand under the Baseline and NZE scenario. Under the latter, all models show a decreasing trend in total energy demand, with the TIMES-J model indicating the lowest final demand in 2050 and the D-TIMES model exhibiting the fastest rate of decline. The results show the necessity of declining final energy use to achieve net zero targets, though the speed and path of reduction volume differs somewhat. For example, the TIMES-J model provides an optimistic estimate of the rapid decrease in final energy demand; even under the Baseline scenario, its results show that the 2050 demand is lower than the final demand in most models' NZE scenarios. In contrast, the AIM-Hub results are more conservative, projecting that under the Baseline scenario, final energy demand will remain relatively stable until 2050, while under the NZE scenario, the demand decline is gradual, and by 2050, it shows the highest final energy demand compared to other models.

Overall, the median total final energy demand for Japan nationwide in 2050 is approximately 8.5 EJ, representing a decrease of about 30 % compared to 2020 (11–13 EJ). Compared to the latest 7th Strategic Energy Plan, which projects a 15 % reduction in final energy consumption between 2022 and 2040, the median value from model comparison shows a larger potential reduction of approximately 20 %. This gap highlights the need to strengthen the policy support in end-use sectors beyond the targeted efficiency improvements.

In the previous round of JMIP studies [24], under an 80 % emission reduction target scenario by 2050 (shorten as 80by50_Def), the final demand in 2050 across multiple models ranged from 7 EJ to 12 EJ. Comparing the results of the two JMIP rounds, we find that the sensitivity of final energy demand to emission reduction constraints varies among models. Except for IEEJ-NE, all models show a decrease in final energy demand under NZE scenario in 2050 compared to the 80by50 scenario, whereas IEEJ-NE exhibits an increase (i.e., final energy demand is 9 EJ under the 105 % reduction target and 7 EJ under the 80 % scenario). It is noteworthy that the model versions vary across the two phases of JMIP, thus the discrepancy might be due to model updates.

The total amount and rate of change in final energy demand under the NZE scenario are related to the models' assumptions regarding energy supply and demand technologies as well as energy service demand. However, comparison across multiple models indicates that to achieve net-zero emission targets, final energy demand may decrease by approximately 30 %.

In Fig. 2, we present the composition and changes in energy carriers under the NZE scenarios for 2020 and 2050. The figure clearly shows an increase in the use of electricity and hydrogen, as well as a consistent phasing out of fossil fuels across models in the NZE scenario. In terms of electricity penetration growth, most models project an increase of approximately 0.5–0.8 EJ from 2020 to 2050, i.e. the electrification rate reaches around or over 50 %. Among them, AIM-Hub shows a higher growth, i.e. an increase of around 5.2 EJ in electricity use, reaching to around 90 % of final energy. Compared to the NZE scenario, Sakamoto

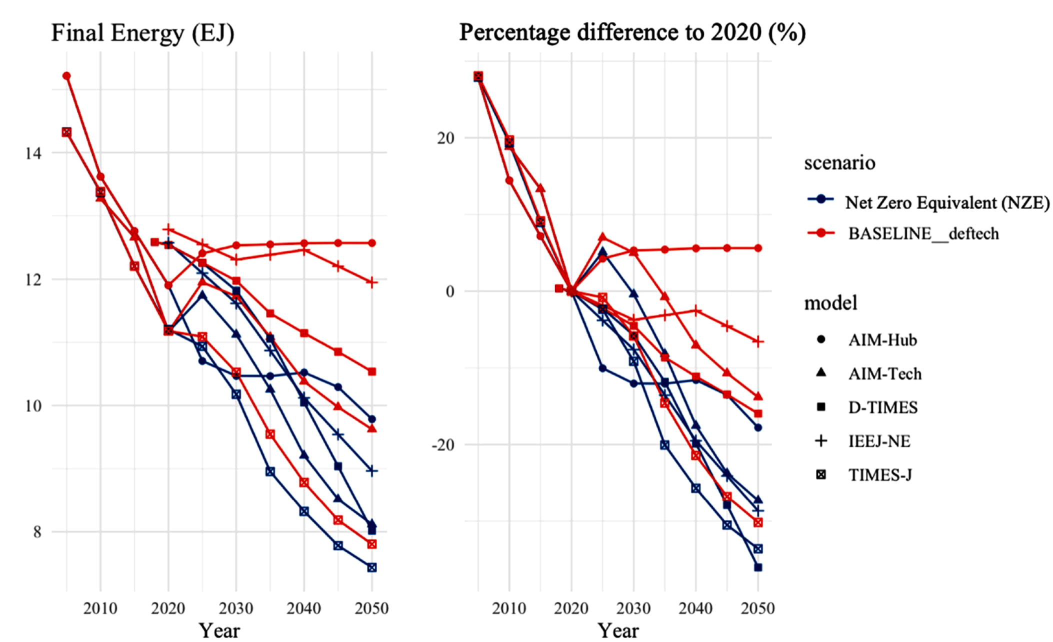

Fig. 1. Trends in final energy demand under the baseline and NZE scenarios. (a) shows the total demand volume, and (b) represents the percentage difference from 2020.

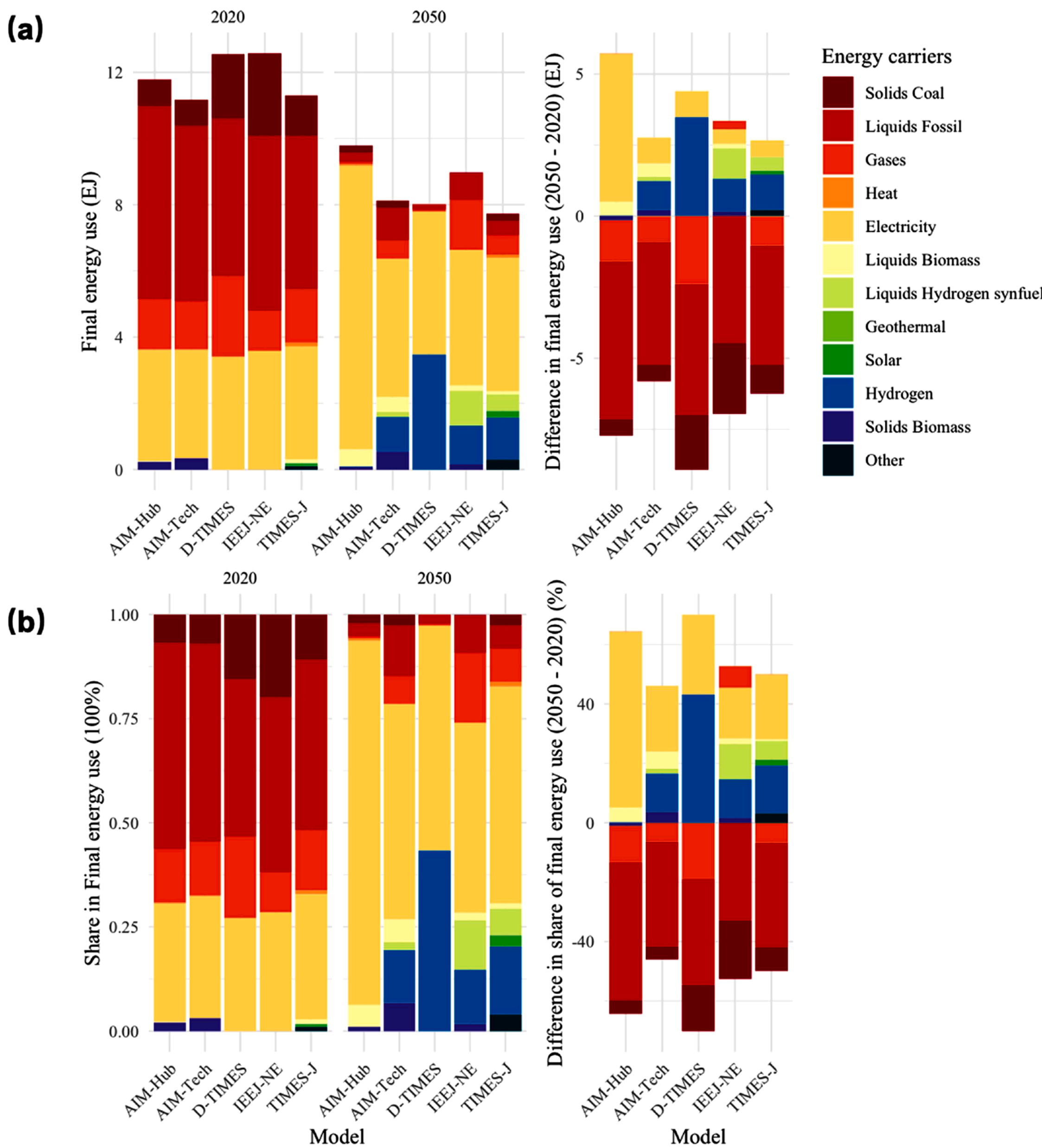

Fig. 2. Final energy demand in 2020 and 2050 under NZE scenario, differentiated by energy carriers. Panel (a) presents the total energy demand, and (b) shows the percentage share of each energy carrier. In both (a) and (b), the left panel represents the total amounts or percentages, while the right panel displays the difference between 2050 and 2020.

et al. [24] found that under a scenario targeting 80 % emission reduction by 2050, the electrification rate needs to reach around 40 %. A stricter emission reduction target leads to the requirement for a higher rate of electrification, indicating the effectiveness of electrification in driving deep decarbonization.

Similarly, hydrogen shows significant growth, with its consumption increasing from nearly zero in 2020 to approximately 1.0 EJ (median), i. e. approx. 13 % of total final energy demand in 2050. Japan's newly revised Basic Hydrogen Strategy in 2023 envisions annual hydrogen consumption of approximately 2.4 EJ (20 million tons) by 2050. Notably, both projected hydrogen usage (3.5 EJ in 2050) and import (~5.2 EJ, see in Section 1.4 in SI) in D-TIMES even exceeds Japan's demand target. Although domestic hydrogen production in Japan is generally considered costly and limited by available clean electricity for electrolysis, some studies suggest that the cost gap between domestically produced and imported hydrogen may not be significant in the future [25]. This largely depends on the prices and efficiencies of electrolyzers and assumptions about renewable energy prices. For a cross-model comparative analysis of hydrogen supply and its application in power systems, refer to Section 1.4 in SI and Frazer et al. (submitted).

Another common trend among the models is the significant reduction in fossil fuels. However, gaseous fossil fuels do not exhibit a consistent downward trend like solid and liquid fossil fuels. Solid and liquid fossil fuels show a substantial decline or even complete phase-out by 2050, whereas the reduction in gaseous fuels varies. In AIM-Hub and D-TIMES, gases are nearly completely substituted and phased out from the energy supply system, while IEEJ-NE maintains stable usage levels. This may be due to the relative cleanliness and cost advantages of gaseous fossils as well as its role of flexibility in the power sector.

3.2. Clean energy penetration toward 2050

Fig. 3 below illustrates the diffusion speed in the proportions of electricity, hydrogen, and bioenergy within final energy demand. From

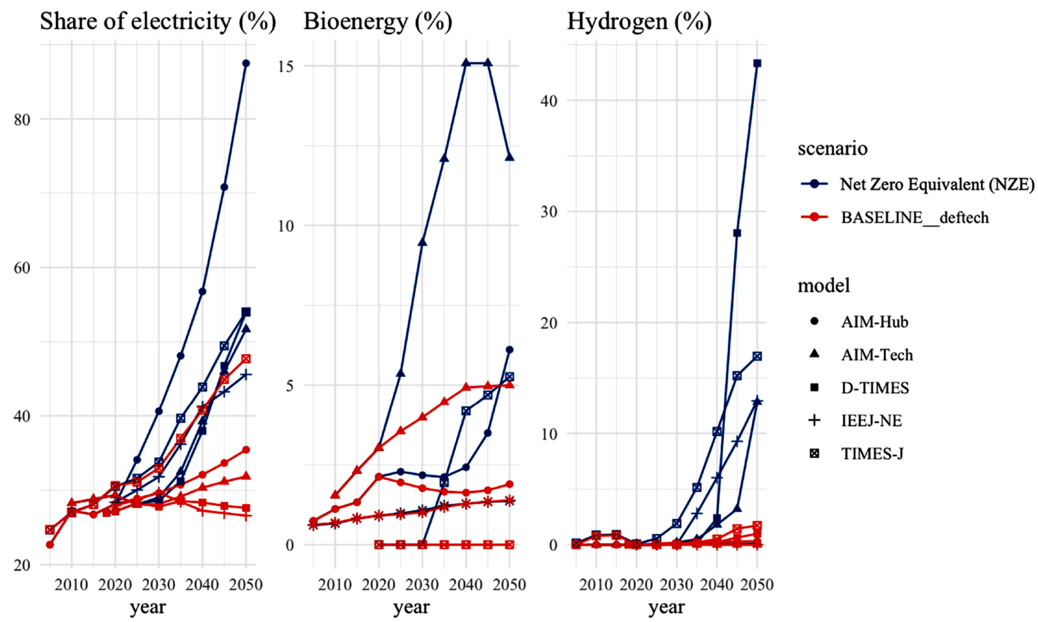

Fig. 3. Trends in the share of electricity, hydrogen, and biomass energy in final energy consumption from 2005 to 2050. Note, hydrogen classification here excludes e-fuels. Scales vary by panel.

the perspective of the rate of increase in each energy type's share, the results indicate that before 2030, most models maintain an electricity consumption growth rate similar to that of the baseline scenario, reaching METI's projected target of 29 % by 2030. The simulation results for the share of electricity demand in 2050 are largely consistent across models, approximately 52 %, except for AIM-Hub.

In terms of hydrogen usage, prior to 2030, most model results indicate low application, followed by a period of rapid growth between 2040 and 2050. Under the baseline scenario, except for D-TIMES and TIMES-J, other models do not incorporate hydrogen usage. The growth in hydrogen demand is characterized by currently limited applications and the necessity for rapid, large-scale deployment in the medium to long term, which poses greater challenges for fully realizing its emission reduction potential.

Regarding bioenergy, there is significant variation among models. Except for the D-TIMES model, which does not model bioenergy, other models' bioenergy ratio distributes around 5 %, with the AIM-Tech estimates being slightly higher and increasing rapidly, peaking in 2040 before declining.

Fig. 4 presents the final energy use by sector in 2050 under both the baseline scenario and the NZE scenario. From this chart, we can clearly observe the shifts in the largest energy-consuming sectors and the changes in the dominant energy types within each sector. In terms of energy types, fossil fuels' share of final energy consumption decreases from 61.5 % to 18 %, while electricity's share rises from 33.9 % to 56.4 %, alongside increases in hydrogen and biomass. From a sectoral perspective, the final energy consumption shares for the industry, building, and transportation sectors see relatively small changes between the baseline and NZE scenarios, shifting from ~47 %, 36 %, and 17 % to ~50 %, 32 %, and 14 %, respectively. This consistency in sector-level consumption structure is similar to conclusions found in other studies [16,26].

The prevailing limiting factors for greater electrification vary by model but include the lack of electric alternatives for certain modes of transport or industrial processes and deployment limits. The NZE scenario especially shows added electrification in the building sector, leading to almost full electrification in many models. While results for the transportation and industrial sectors also show increased electrification, the increase is less pronounced compared to the building sector.

3.3. Decomposition analysis of emission reduction

Understanding which factors significantly impact emission reductions can aid in adjusting emission reduction strategies across various sectors. We primarily considered energy service demand intensity, per capita energy service demand, fuel emission intensity, and population change. Due to the inconsistency in the units of energy services across sectors, simple aggregation is not feasible. Therefore, we conducted an analysis for each sector individually. Given the steel sector accounting for ~40 % of emissions in the industry sector and 14 % of total in 2020, we take it as an example. The decomposition results of other sectors' results can be found in Section 1.4.1 in SI.

As illustrated in Fig. 5, the emission intensity is generally recognized across models as the factor with the greatest emission reduction potential. This validates the importance of power system emission reductions and clean energy deployment for achieving net-zero emissions. The factor of per-capita energy service demand (specifically product output in the industrial sector) slightly increases CO_2 emissions in multiple models. This indicates that reducing per-capita output still holds certain potential for achieving zero-carbon goals, for instance, by decreasing the demand for high-emission-intensive products through material efficiency improvement, material substitution and extending the lifespan of housing and transportation vehicles.

3.4. Sensitivity analysis

3.4.1. Stringency of emission constrains

Fig. 6 illustrates the total amount and composition of final energy use by energy type in 2050 under different levels of carbon emissions constraints. The scenarios include the baseline scenario, as well as 100 % and 105 % CO_2 emissions constraints. We also tested the 110 % emissions reduction target, but the 110 % reduction scenario is not shown in the figure since not all models were able to find feasible solutions. Infeasible solutions mean that, given the models' assumptions about economic growth, techno-economics, technology deployment dynamics, and model-solving algorithms, some models were unable to generate feasible emissions pathways that met the emissions budget constraints. For details on model solution feasibility, refer to Section 1.2.2 in SI and Sugiyama et al. [22].

Stricter emission constraints do not always shrink the final energy

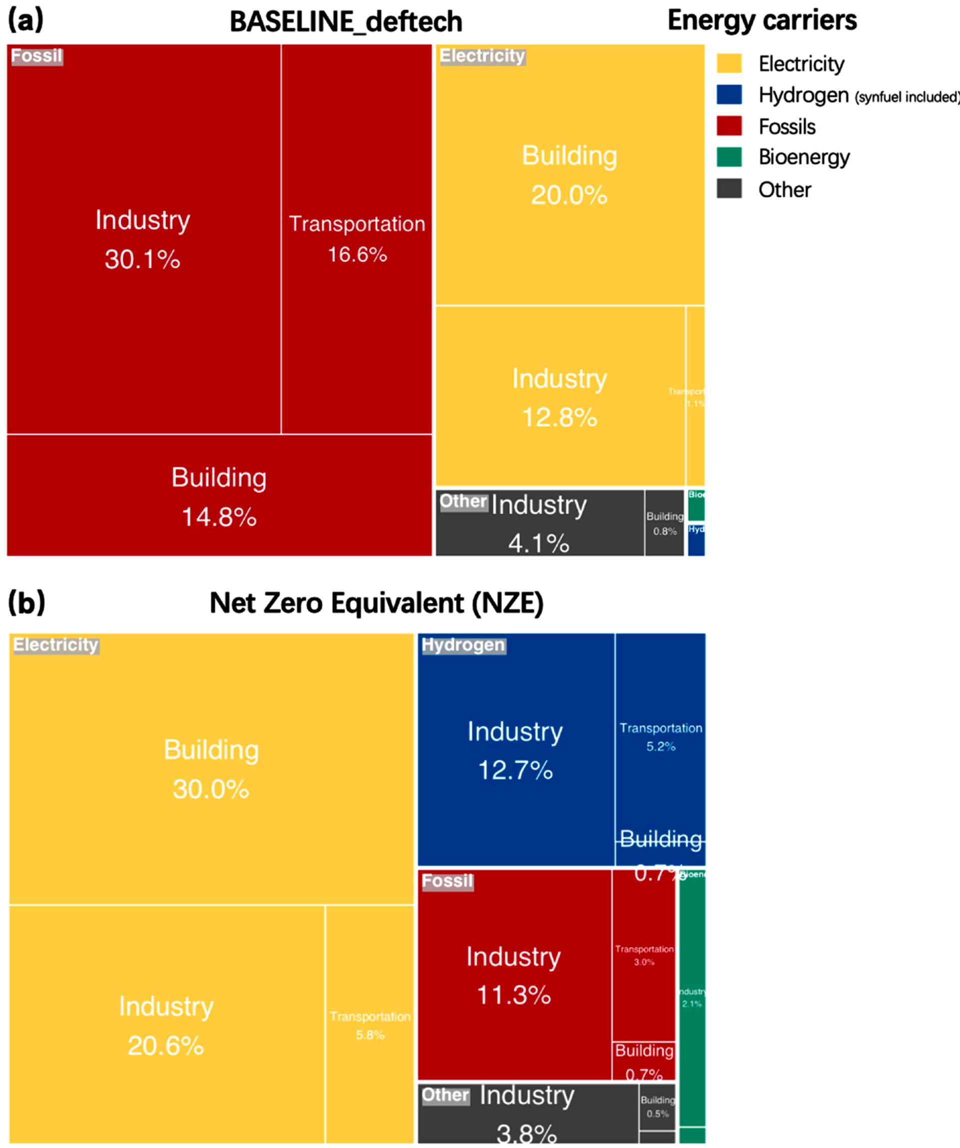

Fig. 4. Final energy shares by sector and energy carrier. This figure presents the median composition of final energy demand in 2050 by energy carriers and sector for the Baseline and NZE scenarios. Panel (a) is the Baseline Scenario, and (b) is the NZE Scenario (105BY50_deftech). Note that "Other" here includes "Geothermal," "Heat," "Solar," etc. Additionally, the "Hydrogen" category includes hydrogen as well as hydrogen synfuel. Portions less than 0.5 % are not labeled. "Building" sector includes residential and commercial sectors.

demand. In the building and transportation sectors, stricter emissions reduction targets tend to lead to lower final energy demand. However, this trend is more mixed in the industrial sector. In particular, only AIM-Hub shows that stricter emissions reduction measures lead to a decrease in total final energy use in industry. In contrast, results from AIM-Tech, IEEJ-NE, and TIMES-J indicate that strengthening the emissions reduction target from 100 % to 105 % results in a slight increase in final energy use, which is primarily driven by the additional introduction of hydrogen or biomass energy.

3.4.2. *Technological aspects*

Under each specific technology scenario, the difference in the final energy consumption mix compared to the default technology (deftech) scenario varies between models and sectors. In the scenario with higher CDR deployment availability (i.e., the cdr scenario, which permits over 100 Mt/year while adhering to the models' default cap settings), fossil fuel usage is expected to increase significantly compared to the deftech scenario, accompanied by a certain degree of displacement of electricity use. This substitution is particularly evident in the building and transportation sectors, and such characteristics underscore the importance of coordinating CDR policies with sectoral decarbonization strategies. Reliance on CDR technologies would keep remaining of fossil fuels with permit ongoing residual emissions from fossil fuel use, while at the same time, it might postpone the promotion and use of electrification and other clean energy sources. Residual emissions led by remaining fossil use are especially pronounced in the building and transportation sectors.

In the scenario assuming cheap clean energy imports (import scenario), the AIM-Tech, IEEJ-NE and TIMES-J models show an increase in hydrogen use, primarily in the transportation sector. Meanwhile, due to the enhanced competitiveness of hydrogen as an alternative energy source, electricity demand is expected to decrease, particularly in the industrial sector.

There is some divergence about energy carrier usage change under the re scenario, in which domestic renewable energy price is halved. On the supply side, the robust result is that the re scenario brings an increase in electricity generation, but models did not witness a consistent increase in electricity consumption under the re scenario compared to the

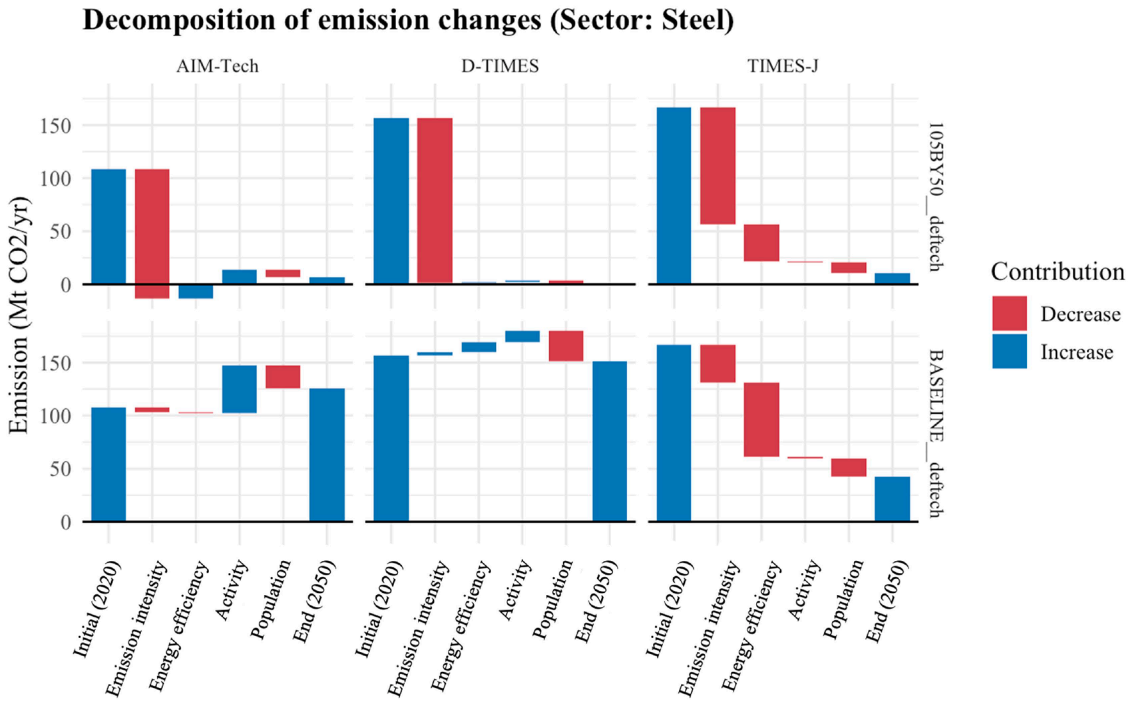

Fig. 5. Decomposition of emission changes in the steel sector between 2020 and 2050. Note: Emission intensity denotes emission per unit of final energy use; energy efficiency represents final energy demand per energy service provision, and activity means energy service demand per capita. Except in the initial and end bar, blue means this factor raises emissions while red shows a reducing effect.

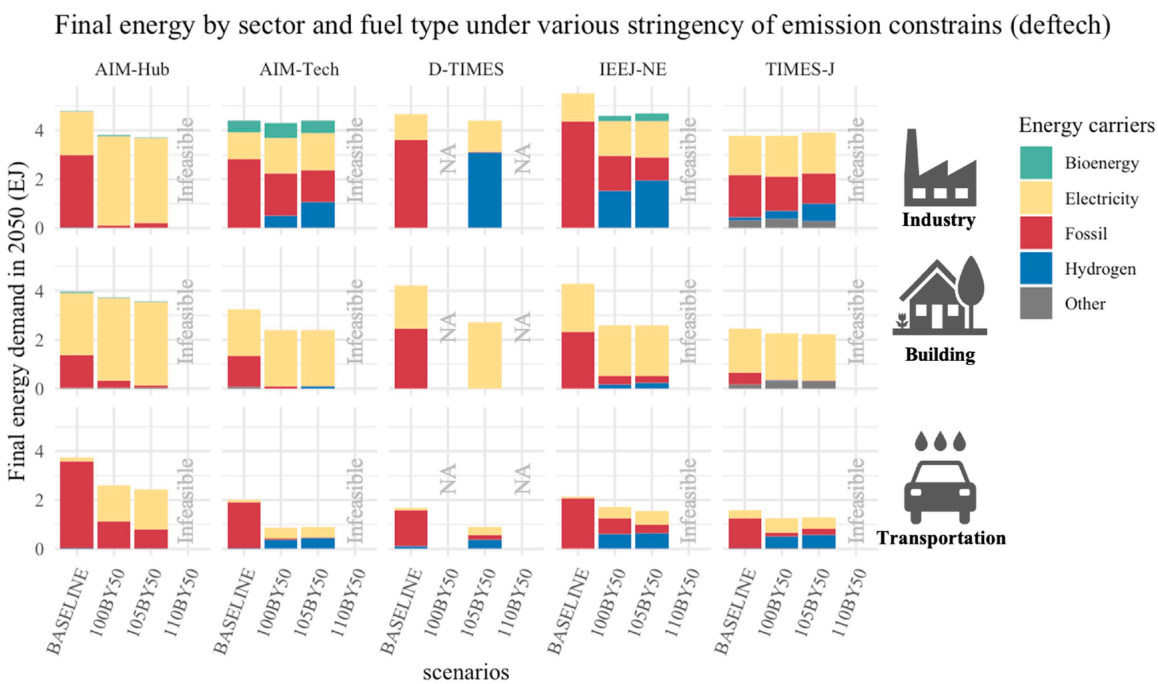

Fig. 6. Final energy demand composition by sector under scenarios with varying carbon emission constraint. The technological assumption is based on the deftech scenario. "NA" denotes the lack of submission, while "Infeasible" means no solution under this constraint.

default one. Indeed, some models see an increased use of electricity while some see hydrogen use enhancement. The latter is likely brought about by increased electricity-based (electrolysis) hydrogen production due to cheaper electricity, which is sometimes considered indirect electrification.

Under the eletech scenario, the increased uptake of electrified end-use devices increases electricity consumption and reduces the use of other competing energy sources, such as fossil fuels and hydrogen. As for sectoral impacts, the additional electrification in industry and building sectors is subtle, while in contrast, it is more evident in the transportation sector. This indicates the potential of electrification in the former sectors might have already reached the plateau under the deftech scenario. As a result, this suggests that cost-based incentives alone may be insufficient, and additional enabling policies—such as regulatory support, infrastructure development, or risk-sharing mechanisms—are likely necessary to unlock electrification potential in the industrial sector.

In the innov scenario, changes in the use of various energy sources across most models and sectors seem to be an aggregation of the changes caused by each individual scenario. However, there are exceptions, such as the industrial sector in AIM-Tech and the transportation sector in IEEJ-NE. In the industrial sector of AIM-Tech, the increase in fossil fuel use under the innov scenario is not entirely driven by the significant increase seen in the CDR scenario but shows only a slight rise. Similarly, in the transportation sector of IEEJ-NE, fossil fuel use in the innov scenario does not follow a positive additive trend but instead shows a decline. This characteristic shows that the simultaneous imposition of multiple policies may not be a simple additive effect on changes in final energy use, but rather a more complex dynamic interaction.

3.5. Contribution of clean energy demand in CO_2 abatement

Lastly, we examined the relationship between clean energy applications (mainly hydrogen and electricity) and the reduction ratios in various sectors. To do this, we visualized the relationship between the share of electricity/hydrogen in final energy use and the proportion of CO_2 emissions reduction, as shown in Fig. 8. We aggregated the results for all models across all scenarios for 2050 to observe the decarbonization effects of these two types of clean energy. In terms of electrification, there is a clear correlation between the increased use of electricity in the building and transportation sectors and the amount of CO_2 reduction. It is worth noting that there is saturation in the penetration of electricity in the industrial sector, even under scenarios that are conducive to the promotion of electricity.

As for hydrogen, the most notable positive correlation is in the industry sector, indicating that the higher the proportion of hydrogen

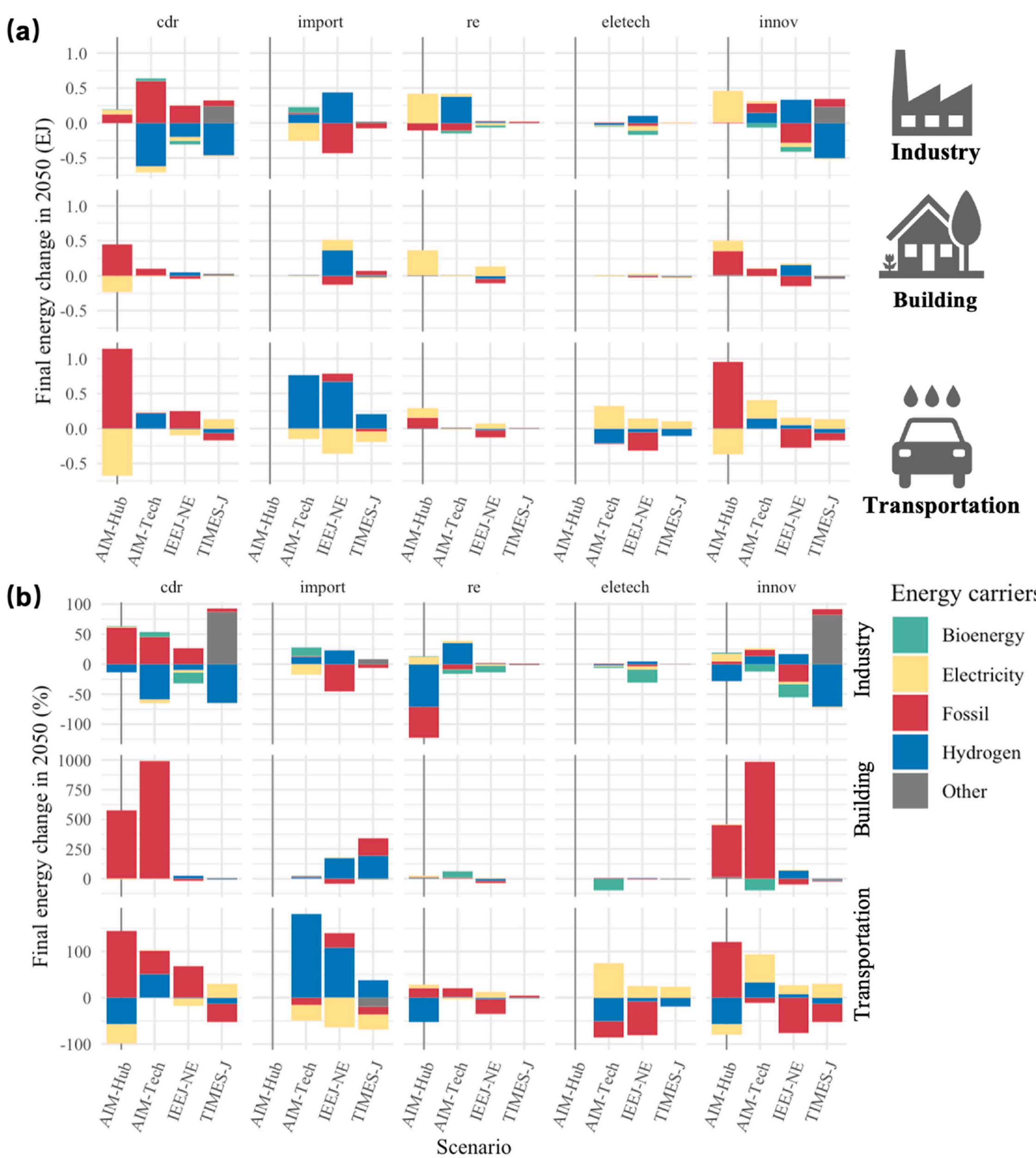

Fig. 7. Sensitivity analysis of final energy demand in 2050 under different technological scenarios. Panel (a) shows the volume change while (b) represents the percentage changes. The number is calculated by the gap between various technological scenarios and the default scenario, both under the net zero narrative in 2050 (105BY50_deftech). AIM-hub did not report the import and eletech scenario data given its model characteristics.

energy in final energy consumption, the greater the emission reduction in the industry sector. Although Japan is promoting the use of hydrogen fuel cell vehicles, some models (AIM-Tech) indicate that increased hydrogen usage does not lead to more significant emission reductions. Conversely, other models (IEEJ-NE) show that even without significant changes in hydrogen usage, more emission reductions can be achieved through other technological options. From the total volume of hydrogen in all sectors under the constraints of 100 % and 105 % CO_2 reduction, it is observed that there is no obvious relationship between the increase in hydrogen energy and the overall emission reduction. However, under stricter emission reduction constraints (110 %), the value of hydrogen energy becomes more prominent, showing a positive correlation between its usage and emission reductions.

4. Discussion

4.1. Possible alternatives for deep mitigation of hard-to-abate sectors

As the energy transition progresses, challenging trade-offs must be addressed among various objectives, including economic viability, reliability, industrial competitiveness, and energy security. Increasing the share of electricity and alleviating the dependency on fossil fuels are the mainstream decarbonization strategies. For the foreseeable future, fossil fuels are expected to meet the demand that renewable energy cannot satisfy due to deployment speed and to provide stability for renewable-based energy systems. The models in this study robustly agree that there would be some remaining fossil fuel use in 2050 (mainly natural gas), with usage mainly concentrated in the industrial sector, and this leads to inevitable residual emissions. This study pointed out that the electrification in industry may reach a plateau even when renewable energy or end-use electrification technology costs are halved. Deep mitigation of the industry sector is a huge challenge in Japan and other jurisdictions with similar characteristics [27].

As shown in Fig. 7, hydrogen use in industry is sensitive to both imported clean energy cost and renewable costs. Given the situation, the industry sector's deep mitigation can be fostered through cooperation with a region with cheap hydrogen and renewable costs, i.e. relocating certain high-energy industrial processes. For instance, relocating hydrogen production and hydrogen-based iron reduction processes in the hydrogen metallurgy sector abroad may enhance the cost competitiveness of steel products [28–30] while retaining approximately 75 % of jobs in the original country [31]. Despite the prospectives, such relocation strategies require more detailed assessments of their social, economic, and environmental impacts to determine their overall feasibility and alignment with long-term planning goals.

CDR is another recognized approach for reducing residual emissions. Though there is no clear quantitative target set in Japan so far, Sugiyama et al. [3] found the scale of CCS-based CDR deployment reaches an inter-model median of 132Mt-CO_2/yr in Japan in 2050. In this study, comparing the deftech (in which CDR is limited to 100 Mt-CO_2/yr) with CDR scenario (model default limits setting), we found there could be additional 0.5–1.5 EJ usage on fossils, while reducing ~0.25–0.5EJ hydrogen use. This reveals the high sensitivity of clean energy carriers upon the availability of CDR deployment. However, public perception may hinder deployment. In Japan, people are unfamiliar with CDR options and unsure of understanding such technologies [32], and this may hinder public acceptance. To increase public interest and awareness, there should be more public/private projects to spread knowledge through various media.

Demand-side solutions are increasingly attracting attention as additional measures to reduce industrial energy demand and related GHG emissions. Researchers have roughly estimated that around 15 % of industrial energy demand for consumer goods production in the Global North could be avoided, primarily through dematerialization and material efficiency improvements [33]. According to the latest Strategic Energy Plan (SEP) Energy Outlook [34], industrial product demand in Japan is projected to slightly increase; however, this trend runs counter to the model results under a net-zero pathway, which indicate a decline in industrial demand. To achieve deep emission reductions, Japan needs to reconsider its industrial production projections, their implications for energy demand and emissions, and the necessary countermeasures under net-zero constraints, particularly by adopting a systematic, cross-sectoral perspective. For instance, in the building sector, Pauliuk et al. [35] found that circular material efficiency strategies could reduce cumulative cement and primary steel demand by about two-thirds between 2020 and 2050. These strategies include lightweight design, extending building lifetimes, and related measures. Given the limited literature specifically addressing Japan's context, further research is needed to investigate demand-side solutions at the national level or to enhance Japan's regional representation within global analyses [36]. In addition to technological innovation, greater policy incentives should be directed toward demand-side management to effectively foster consumption behavior change

4.2. Challenges and measures for promoting clean energy penetration in Japan

This study pointed out the necessity of end-use energy efficiency improvement and energy transition to achieve a net zero target. According to Japan's 6th Strategic Energy plan, the policy efforts on the demand side include reviewing industrial efficiency benchmarks, strengthening the Top Runner equipment/building material standards, promoting electric vehicles (EV) and infrastructure, and so on. Given the huge discrepancy of energy-using technologies among sectors, the promotion strategy differs in terms of each type of energy carrier.

Electrification can be more emission-reduction effective in the building and transportation sector as shown in Fig. 8. In the building sector, as illustrated in Fig. 7, compared to the default scenario, reducing the costs of end-use electrification technologies leads to less additional electricity consumption than that resulting from scenarios that reduce renewable energy costs. This indicates that reducing the costs of end-use equipment in the building sector is less effective for advancing further electrification. Instead, greater efforts should be directed toward the energy supply side, such as lowering electricity costs for the building sector. In the transport sector, cheaper end-use electrification technologies can be effective in reducing the use of fossil fuels and hydrogen, while energy substitution is not that sensitive to renewable cost compared with the building sector. Overall, in order to promote electrification, more policy efforts should be put on renewable cost reduction in the building sector, such as subsidy for rooftop solar panel installation. However, in the transportation sector, the focus should be on technology and infrastructure cost reduction.

Regarding actions to promote hydrogen energy, although policies like promoting CfD and demonstration hubs were launched under the Hydrogen Society Promotion Act, the current lack of clarity in pricing mechanisms and future market developments may still limit the enthusiasm for long-term offtake agreements. Model results indicate that under the net-zero target by 2050, the demand for hydrogen energy will account for approximately 10–20 %, and some models project this expectation to increase to around 40 %. These numbers show the significance of hydrogen energy in a net-zero society to supplement energy demand that is difficult to electrify. To enhance the enthusiasm of production-side enterprises, more specific and direct promotion policies (e.g., public procurement) targeting end-use sectors such as industry, building, and transportation need to be introduced concurrently. As an example, the Tokyo Metropolitan Government [37] has proposed the Tokyo Hydrogen Vision, which includes direct intervention measures for the transportation sector, the introduction of green hydrogen in other public utilities, and even promotional activities to improve public awareness and acceptance of hydrogen energy.

Though Japanese government shows interest in hydrogen, there are still some uncertain factors that may dampen their enthusiasm. The first

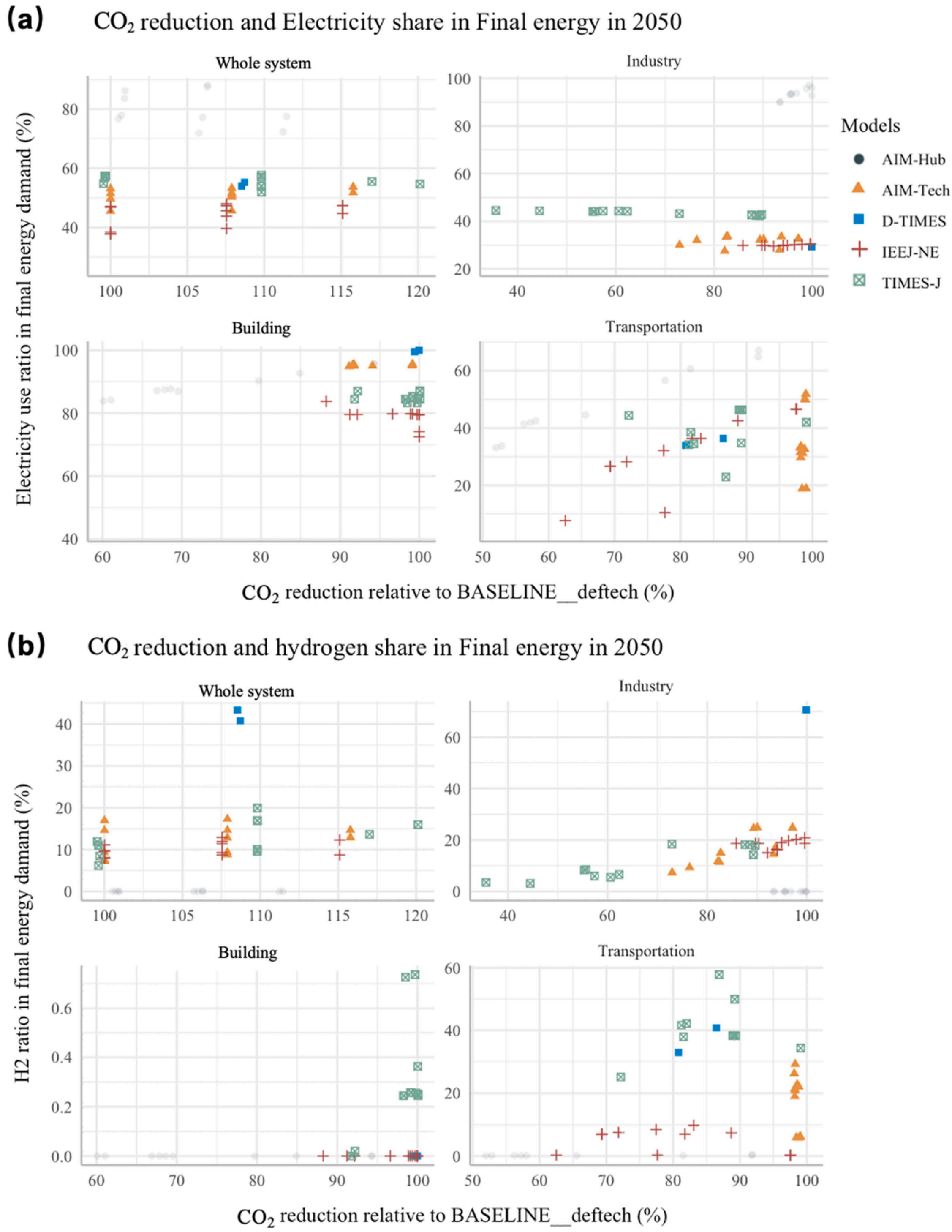

Fig. 8. Relationship between emission reduction ratios and the proportion of low-carbon energy applications across sectors. (a) reflects electricity, and (b) represents hydrogen. The figure includes results from all total emission constraint scenarios and technological scenarios. The percentages of CO_2 emission reductions are calculated relative to the BASLINE_deftech scenario. Note that since AIM-Hub did not represent hydrogen use due to its' model structure, we dimmed its dots here.

factor is that the clean hydrogen standard is still confronted with challenges from academia and society [17]. Another policy uncertainty is on the policy stringency. As shown in Fig. 6, overall hydrogen deployment is sensitive to increased climate policy stringency. Japan has pledged the net-zero target but the coordinated policy stimulus mechanism is still in a vague stage. For example, the carbon price is deemed essential to stimulate the penetration of green technologies, shown in SI and Sugiyama et al. [22]. Nevertheless, Japan has only recently launched its voluntary carbon credit mechanism, while a compliance market is still under development. This mechanism remains controversial among stakeholders, which limits the effectiveness of carbon pricing in driving progress towards net-zero emissions.

Bioenergy, as a complementary energy carrier to hydrogen and electricity, currently has stable applications and can be fully utilized and adapted to existing infrastructure and end-use energy equipment, making the scale-up of its applications relatively easier compared to hydrogen energy. Although bioenergy possesses certain advantages, its widespread adoption in models is constrained due to the uncertainty of its supply and the potential land use risks it may pose to production areas, such as land use competition, loss of biodiversity, impacts on food security, and effects on other environmental services. Rose et al. [38] conducted a multi-model comparison through EMF33 and found that the extent of bioenergy usage primarily depends on the combined effects of several factors, including feedstock costs, the availability and costs of alternative mitigation options for different end-uses, the availability of carbon dioxide removal (CDR) and potential payments, the speed at which large-scale changes in the composition of energy conversion facilities and integration can occur, and the relative demand for different energy services.

Lastly, the rising prominence of data centers have increasingly drawn attention to their potential for high electricity consumption [39]. While some studies have raised concerns about potential demand increases, recent developments such as energy-efficient model architectures and the growing focus on smaller, task-specific language models suggest that the energy impact may not grow linearly with AI proliferation. These uncertain points deserve more investigation in future energy modeling work.

5. Conclusions

Our study examines the final energy consumption under NZE scenarios and explores the sensitivity of total end-use energy changes and fuel type transitions across various sectors under technological advancement scenarios. The study provides important value as a rigorous and methodologically transparent replication analysis and helps validate and reinforce key insights from prior work under technology uncertainty for Japan's net-zero goal. When models do not fully agree, this suggests that flexible and adaptive policy instruments may be needed. This approach is consistent with findings from previous international multi-model studies, such as the EMF 37 study on U.S. climate policy [26], which demonstrated that large uncertainties do not preclude meaningful policy discussion but rather point to the importance of designing strategies that can perform well under a range of plausible futures.

Through model intercomparisons, we have identified robust change trends exhibited on the demand side. For instance, to achieve net-zero emissions by 2050, the total final energy consumption is projected to decrease by over ~30 % compared to 2020 levels. In terms of energy types, electricity is estimated to account for approximately 50 % of the total final energy demand, while hydrogen is expected to increase from near 0 % to 13 %, with this rise primarily occurring after 2040. Sensitivity analysis reveals that higher emission constraints may lead the industrial sector to consume more final energy, primarily due to the increased adoption of hydrogen. Additionally, under stricter emission constraints, the emission reduction potential of hydrogen is enhanced. Furthermore, in scenarios without limitations on the use of carbon dioxide removal (CDR), the system may retain approximately 0.5–1 EJ of fossil fuel consumption. When the price of imported clean energy is lower, the transportation sector exhibits greater sensitivity in energy carrier transitions compared to the industrial and building sectors, shifting from reliance on electricity to greater dependence on hydrogen. Overall, the abovementioned pathways for electricity and hydrogen deployment also offer valuable inputs for policy design in future SEPs.

Apart from consistent conclusions, there are some uncertainties among models regarding the specific use of energy types. These discrepancies reflect optional future development pathways and provide multiple perspectives for policymakers to design net-zero pathways [40]. Decarbonization of the power system and electrification of end-use sectors are recognized directions by most models. However, there are varying progress levels among models in considering diversified energy service demands. Examples include the rise of the sharing economy (shared offices, shared mobility), the emergence of artificial intelligence, and the growth of data centers etc. Economic and social systems are evolving rapidly, with new production technologies and novel demand patterns continuously emerging. Balancing the trade-off between increasing the fidelity of models' representations of reality and maintaining computational efficiency remains an issue worthy of further research.

Declaration of use of generative AI and AI-Assisted technologies

During the preparation of this study, the authors used DeepL and OpenAI ChatGPT to enhance the clarity of the English writing. All outputs were reviewed and edited as needed, and the authors take full responsibility for the final content. OpenAI ChatGPT was also used to support the coding process, but the final code was fully verified and tested by the authors.

Data availability

The data supporting the results of this study is publicly available at the following URL/DOI: https://doi.org/10.5281/zenodo.16559129.

CRediT authorship contribution statement

Tao Cao: Writing – review & editing, Writing – original draft, Visualization, Formal analysis. **Eamon Frazer:** Writing – review & editing. **Masahiro Sugiyama:** Supervision, Funding acquisition, Conceptualization. **Hiroto Shiraki:** Writing – review & editing, Conceptualization. **Shinichiro Fujimori:** Conceptualization. **Kenichi Wada:** Conceptualization. **Hiroshi Hamasaki:** Software, Formal analysis. **Etsushi Kato:** Software, Formal analysis. **Yuhji Matsuo:** Software, Formal analysis. **Osamu Nishiura:** Software, Formal analysis. **Tatsuya Okubo:** Software, Formal analysis. **Ken Oshiro:** Software, Formal analysis. **Takashi Otsuki:** Software, Formal analysis. **Fuminori Sano:** Software, Formal analysis.

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.

Acknowledgments

This research is supported by the Environment Research and Technology Development Fund (JPMEERF20212004) of the Environmental Restoration and Conservation Agency of Japan, JST Social scenario research program towards a carbon neutral society (JPMJCN2301 & JPMJCN2302) and JST SPRING (JPMJSP2108). This research is also partly supported the Energy Demand changes Induced by Technological and Social innovations (EDITS) project, which is part of the initiative coordinated by the Research Institute of Innovative Technology for the Earth (RITE) and International Institute for Applied Systems Analysis (IIASA) (and funded by Ministry of Economy, Trade, and Industry (METI), Japan). Lastly, the authors sincerely thank Dr. Shogo Sakamoto and Dr. Yu Nagai for their insightful comments.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2025.100223.

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