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IEEJ Outlook 2025 **BOX | Life cycle analysis of vehicles: Right selection of powertrain by country and region**

Box | Life cycle analysis of vehicles: Right selection of powertrain by country and region

Global sales of battery electric vehicles (BEVs) are expected to slow down in October 2024, compared to the rapid growth seen in previous years. In Europe, Germany, the largest EV market, suspended EV subsidies in December 2023 in response to spending cuts after its initial budget was ruled unconstitutional. France has also made Chinese-produced EVs ineligible for subsidies, causing BEV registrations in the European Union (EU) to fall by 43.9% from January to August 2024. The United States is expected to see a slowdown in sales in 2024, with a 20% year-on-year increase, compared to the approximately 40% growth recorded in 2023, as ‘Early Adopters’, who purchase new products at an initial stage, have apparently completed their purchases. In China, the world’s largest EV market, BEV/PHEV sales in 2024 are expected to grow 25% year on year—still expanding but at a slower pace—compared to the 82% growth in 2022 and 35% growth in 2023, with consumers’ tendency to save money being identified as an underlying factor.

In this context, discussions are also underway on making liquid fuels carbon neutral to reduce greenhouse gas (GHG) emissions from automobiles. Lower carbon emissions can be achieved by increasing the proportion of carbon-neutral (CN) fuels, such as biofuels and hydrogen-related synthetic fuels (e-fuels), in liquid fuels. Brazil has mandated a 27% bioethanol blend (E27) while E100 is also available. Indonesia plans to mandate the introduction of a 40% biodiesel blend (B40) and E10 by 2025, while Thailand and India have set targets of E10 or higher. Additionally, the India-led Global Biofuels Alliance was launched in 2023, focusing on securing the supply of biofuels and their sustainable production at reasonable prices. In May 2024, the leaders of Japan and Brazil agreed to launch the Initiative for Sustainable Fuels and Mobility (ISFM) to promote global decarbonisation on both supply and demand sides by combining sustainable fuels with highly efficient mobility equipment. Regarding e-fuels, projects are underway in South America, Northern Europe, the United States and elsewhere.

Although BEVs do not emit GHGs when driven, it is necessary to analyse their potential and limitations as a climate change countermeasure from a broader perspective. When estimating GHG emissions from automobiles, a comprehensive life cycle assessment (LCA) should be conducted that includes vehicle production and disposal, in addition to the supply (well to tank) and consumption (tank to wheel) of energy used in automobiles, known as the ‘well to wheel’ (WtW) approach. Furthermore, since the availability of carbon-neutral fuels, power generation mix, energy infrastructure and social conditions vary significantly by country and region, LCA analysis specific to each country and region is required.

LCA analysis of passenger cars by powertrain

In this Box analysis, the Carbon Neutral Fuel Promotion Case was developed by combining the Reference Scenario and the Advanced Technologies Scenario. GHG emissions per passenger car from well to tank, tank to wheel, production and disposal, were estimated in both the Carbon Neutral Fuel Promotion Case and the Advanced Technologies Scenario across Advanced Europe, the Association of Southeast Asian Nations (ASEAN), India, and Brazil.

Table 1 | Cases in Box analysis

	Carbon neutral fuel ratio (Biofuels + synthetic fuels)	Power generation mix and other energy transformation, fuel prices, fuel efficiency, etc.
Carbon Neutral Fuel Promotion Case	Equivalent to Advanced Technologies Scenario	Equivalent to Reference Scenario
Advanced Technologies Scenario	Advanced Technologies Scenario	Advanced Technologies Scenario

Note: For Brazil, the carbon neutral fuel ratio is assumed to be E100.

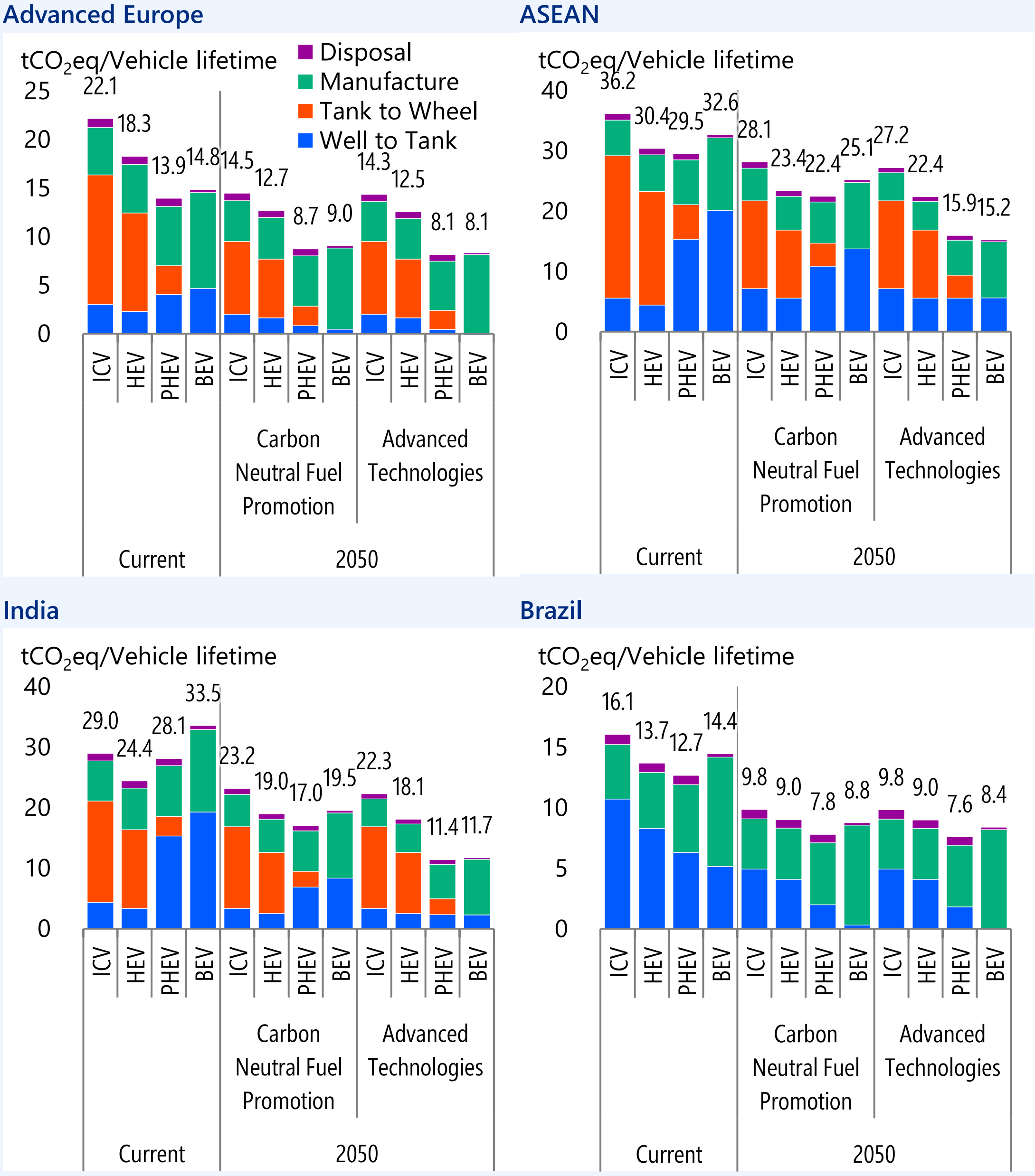
When examining LCA-based GHG emissions, the relative performance of HEVs, PHEVs and BEVs varies by country, region and timeframe. In Advanced Europe, PHEVs currently have the lowest GHG emissions, with BEVs at roughly equivalent levels. This relationship will remain unchanged in 2050 in both the Carbon Neutral Fuel Promotion Case and the Advanced Technologies Scenario. On the other hand, in ASEAN, where power generation decarbonisation has progressed relatively slowly, HEVs and PHEVs currently have comparable GHG emissions, which are lower than those of BEVs. In India, HEVs currently produce the lowest GHG emissions. In the Carbon Neutral Fuel Promotion Case, even by 2050, the combination of HEVs, PHEVs and carbon-neutral fuels will continue to have lower LCA-based GHG emissions than BEVs in both ASEAN and India. In the Advanced Technologies Scenario, where power sources also undergo significant decarbonisation, the LCA-based GHG emissions of PHEVs and BEVs will be roughly equivalent by 2050.

As such, there are significant differences in power generation mix decarbonisation between countries and regions. In countries and regions with a high proportion of low-carbon power sources, such as Advanced Europe, both the combination of carbon-neutral fuels with PHEVs and BEVs will result in lower LCA-based GHG emissions, making these approaches key to achieving carbon neutrality. Conversely, in ASEAN and India, where power source decarbonisation is progressing more slowly, the combination of carbon-neutral fuels and PHEVs represents a more promising option.

In Brazil, many vehicles are already capable of running on E100, and even now, the LCA-based GHG emissions of HEVs and PHEVs using E100 are lower than those of BEVs. Furthermore, even by 2050, when power sources are expected to be completely decarbonised, both HEVs and PHEVs are projected to have comparable LCA-based GHG emissions to BEVs. Therefore, in Brazil, which has substantial biofuel supply potential, the combination of carbon-neutral fuels with HEVs and PHEVs, alongside BEVs, will provide effective pathways towards achieving carbon neutrality.

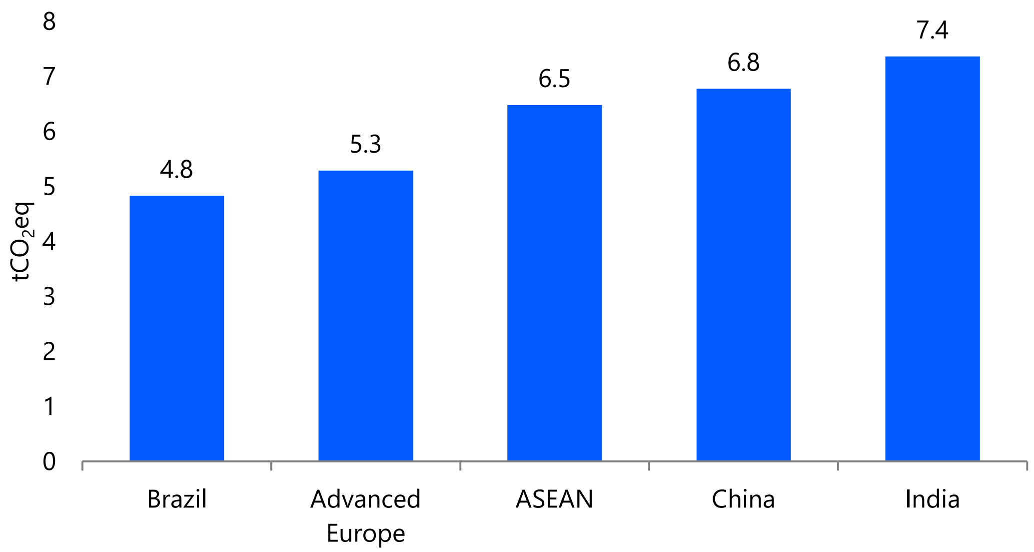
It should be noted, however, that when batteries, which generate higher emissions during manufacturing than other components, are produced in other countries and imported, the LCA-based GHG emissions may differ. Brazil, in particular, has already made significant progress in power source decarbonisation. If batteries were imported from China, where the electricity emission coefficient is relatively high, rather than being produced domestically in Brazil (as assumed in this analysis), emissions associated with battery manufacture would increase by 40% under current circumstances.

Figure 1 | GHG emissions per passenger car (LCA basis)



Note: As for well to tank, CO_2 emissions during fuel transport are excluded. As for the manufacture and disposal of vehicles, the Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) Model 2021 version issued by Argonne National Laboratory was used, assuming all such works are implemented within a country or region. Since the calculation was made under the assumption that the CO_2 capture effect (negative emissions) of e-fuel feedstock belongs to downstream users (vehicle users), emissions during e-fuel production (well to tank) were set at zero.

Figure 2 | GHG emissions from battery manufacture per BEV [current]

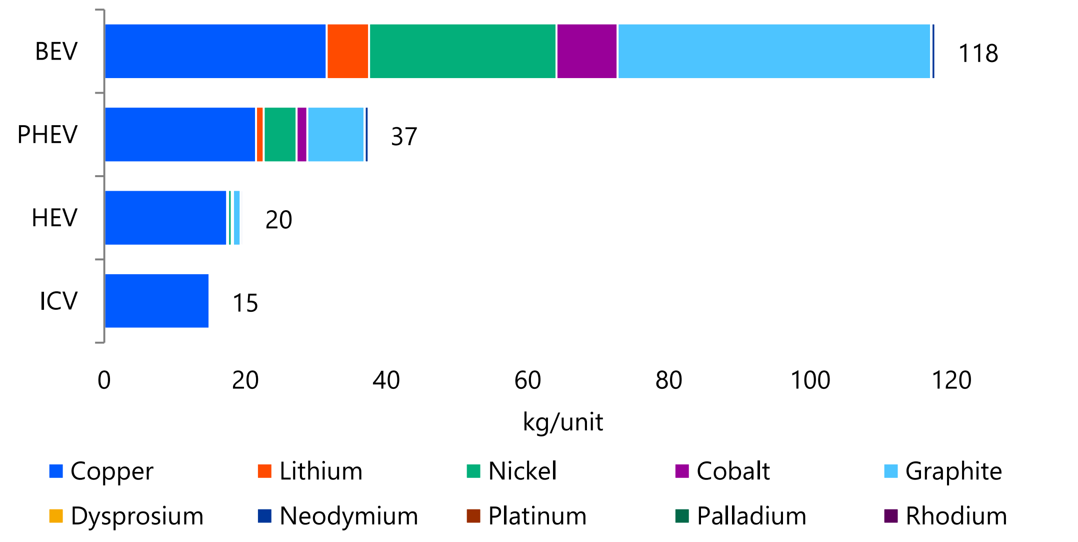


Note: Corresponding to manufacture in Figure 1

Critical mineral usage by passenger car powertrain

One advantage of combining HEVs and PHEVs with carbon-neutral fuels such as biofuels and e-fuels is the potential for reduced use of critical minerals compared to BEVs. BEVs contain large-capacity drive batteries that use critical minerals such as nickel and graphite as raw materials. The quantity of critical minerals used in BEVs is substantial: approximately six times higher than in HEVs and three times higher than in PHEVs (see IEEJ Outlook 2024 for details). In recent years, the capacity of on-board batteries has been increasing to extend the driving range per charge. If BEV numbers continue to rise significantly, the supply and demand balance of mineral resources may be disrupted, potentially increasing the manufacturing cost of BEVs.

Figure 3 | Amount of minerals used per passenger car



Source: Japan Organization for Metals and Energy Security[1]

Usage cost analysis of passenger cars by powertrain

One current challenge is that the vehicle costs of PHEVs and BEVs exceed those of internal combustion engine vehicles (ICVs) and HEVs. To address this, we compared the total cost of ownership across different powertrains in passenger cars, projecting vehicle costs, and fuel and electricity prices through 2050, incorporating future battery price estimates.

In Advanced Europe, ICVs and HEVs currently offer lower running costs than PHEVs and BEVs. By 2050, however, BEVs will become the most economical option due to their reduced vehicle cost and the higher price of oil relative to electricity (electricity being cheaper than petrol). Similarly, in non-Organisation for Economic Co-operation and Development (OECD) countries such as ASEAN, India and Brazil, ICVs and HEVs are presently more affordable than PHEVs and BEVs. Even with projected cost reductions for PHEVs and BEVs by 2050, HEVs are likely to remain more economical than BEVs in the Carbon Neutral Fuel Promotion Case and comparable in cost in the Advanced Technologies Scenario in ASEAN and India, where oil prices are lower than in Advanced Europe. In Brazil, HEVs will maintain a cost advantage over BEVs due to cheaper biofuels. In essence, beyond vehicle costs, oil prices, carbon-neutral fuel prices and electricity prices will significantly influence consumers' powertrain choices[2].

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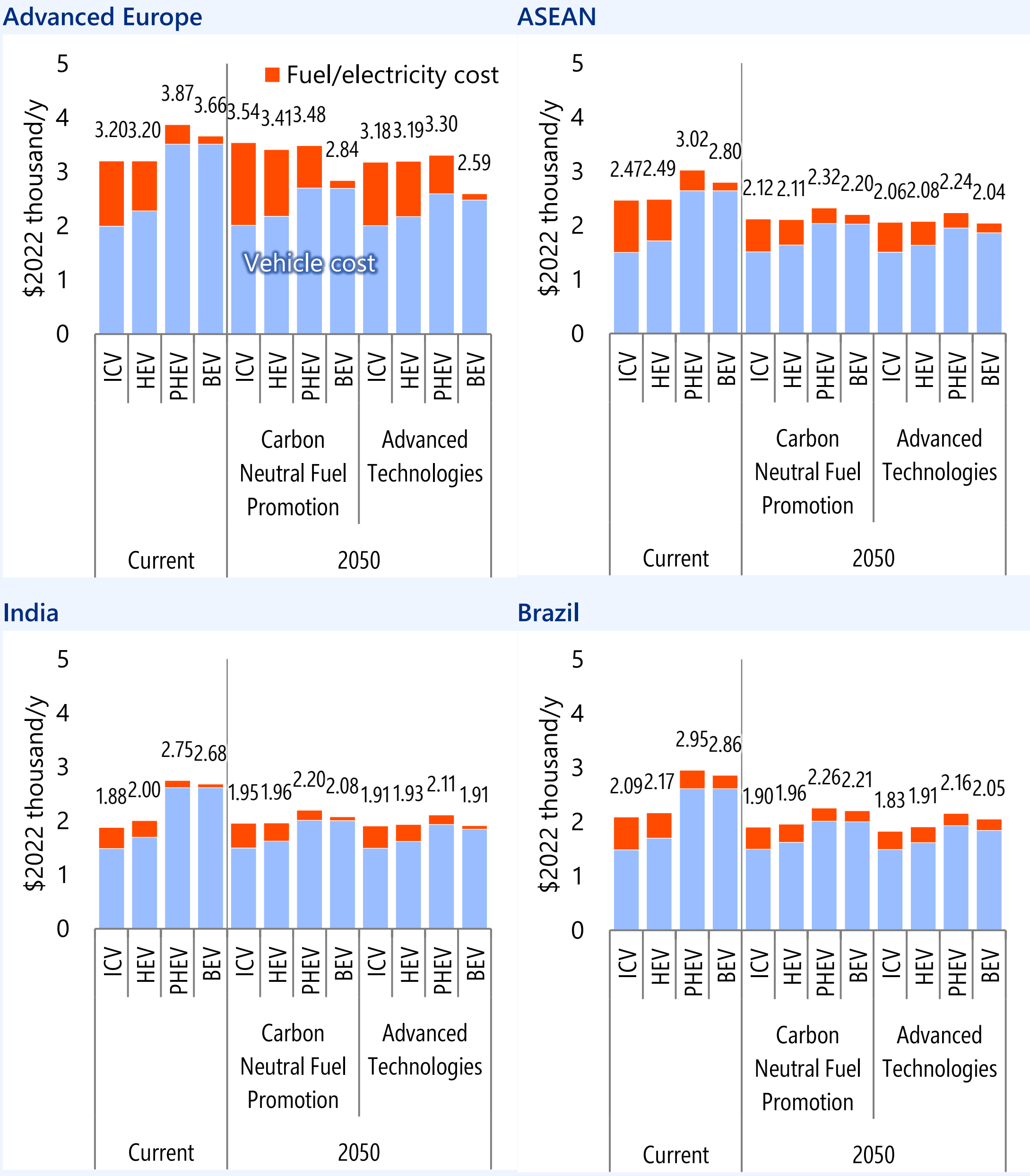
[1] Japan Organization for Metals and Energy Security, "FY2022 Mineral Resource Supply and Demand Survey Report for Achieving Carbon Neutrality" (2022)

[2] BEVs require battery replacement according to mileage and age, and this is especially true in cold climates. In addition, if the use of BEVs is expanded, it will be necessary to consider how to share the tax burden fairly among powertrains and how to cover road maintenance and other costs. In addition to the costs to consumers, it is also necessary to consider social burdens such as power generation capacity and the construction of transmission and distribution systems. This analysis assumes that battery prices are the same worldwide, however, it is estimated that the price of lithium iron phosphate batteries varies greatly depending on the country of production (around 10% higher in the United States and 20% higher in

Figure 4 | Usage cost per passenger car



Notes: Cost of vehicle is calculated by dividing the cost by the number of years of usage. For oil and electricity prices, it is assumed that taxes, subsidies, etc. do not change. Biofuels are assumed to have the same ratio to oil in 2023, and Brazil is assumed to continue its existing subsidies. The price of synthetic fuel is assumed to be ¥300/L in the case of Japan's overseas production in 2050, and the ratio with Japanese oil is applied to other countries as well.

Implication

Limiting the global temperature rise to 1.5°C requires a holistic and flexible approach. In doing so, the carbon neutrality of automobiles must take into account various regional factors,

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Europe than Chinese-made batteries). It should be noted that battery prices, which have a significant impact on the price of BEVs, also vary by country of production and there are other items to be considered besides this analysis that take into account future technological advances and other factors.

such as the availability of resources, the country's stage of development and consumer purchasing power, fuel and electricity prices related to automobile use and the decarbonisation of power sources.

As the LCA analysis results show, when considering GHG emissions not only during powertrain use, but also in the production of energy and in the manufacture and disposal of passenger cars, the assessment varies greatly depending on regional characteristics. When the proportion of low-carbon power sources is high, as in Advanced Europe, the combination of carbon-neutral fuels and PHEVs will have smaller GHG emissions, on par with BEVs. On the other hand, in ASEAN and India, where decarbonisation of power sources is relatively slow, the combination of carbon-neutral fuels and PHEVs is a promising option, whereas in Brazil, which has abundant biofuels, the combination of carbon-neutral fuels with HEVs and PHEVs is a viable option for carbon neutrality of automobiles.

In addition, as the LCA results show, in a country like Brazil where the power sector is already substantially decarbonised, importing batteries manufactured in countries with higher electricity carbon emission factors could increase battery-related emissions by up to 40% compared to domestic production. Therefore, a comprehensive LCA must evaluate GHG emissions by powertrain type, accounting for both domestic and international battery production.

The supply of critical minerals is currently dominated by certain countries, particularly China. An important implication of this is that combining carbon-neutral fuels with HEVs and PHEVs offers greater energy security benefits compared to BEVs, which depend more heavily on critical minerals.

When pursuing automobile carbon neutrality, it is crucial, especially in Emerging and Developing Economies, to determine whether proposed measures can be implemented in an 'affordable' manner regarding consumer costs. For example, as demonstrated in the analysis of ASEAN, India and Brazil, the use of HEVs powered by biofuels and other carbon-neutral fuels may remain an 'affordable' option even in 2050. Moving forward, in addition to forecasting vehicle costs based on the critical mineral resource supply-demand balance and the impact of technological developments on battery prices, detailed examination is needed of policy frameworks (tax systems, subsidies, etc.) that will influence the relative relationships between future oil prices, carbon-neutral fuel prices and electricity prices.

IEEJ Outlook 2025 BOX

| Solutions to issues arising from increased electricity demand at data centres, etc.

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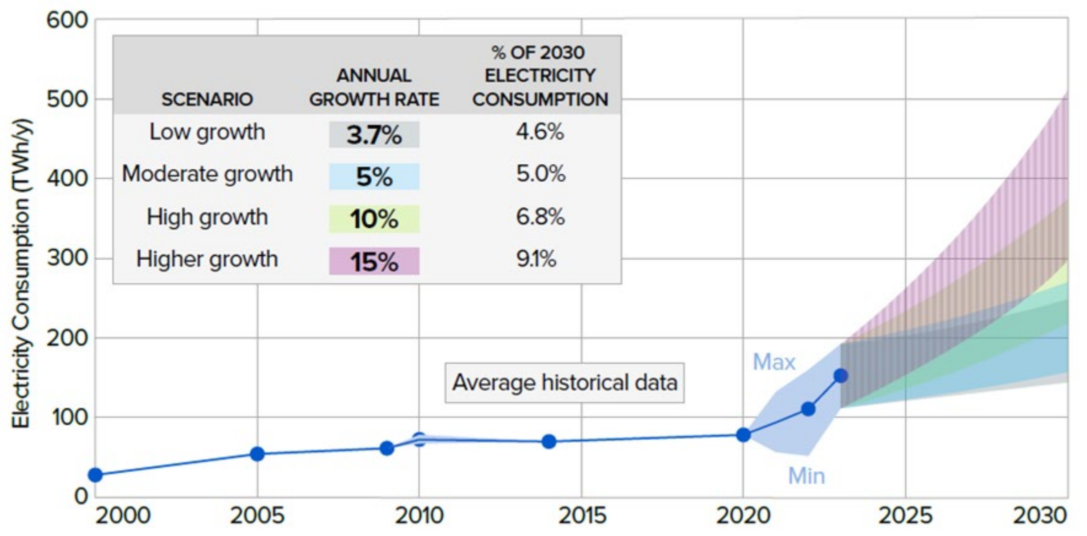
The electricity demand at data centres in the United States is expected to increase significantly in the future with the spread of generative artificial intelligence [AI] (AI that automatically generates content). In particular, with the release of OpenAI's ChatGPT in November 2022, the use of AI technology is expanding rapidly, which will greatly affect electricity consumption. For example, while a single Google search consumes 0.3 Wh of electricity, a single inquiry to ChatGPT consumes 2.9 Wh, about 10 times as much. Thus, the spread of AI-based services will cause electricity demand in data centres to continue to increase, but the extent of the increase remains uncertain.

In a report released in May 2024, the Electric Power Research Institute (EPRI) in the United States estimated the share of data centre electricity consumption in 2030 under four growth scenarios. The low growth scenario assumes an annual growth rate in data centre electricity consumption of 3.7%, the moderate growth scenario 5.0%, the high growth scenario 10% and the higher growth scenario 15%, with the share of electricity consumption under each scenario increasing to 4.6% for the low growth, 5.0% for the moderate growth, 6.8% for the high growth and 9.1% for the higher growth scenario. In addition, a January 2023 McKinsey & Company's report projected that annual electricity consumption growth in data centres in the United States will reach about 10% through 2030. As such, advances in AI technology are expected to accelerate electricity demand in data centres, which in the future will occupy an important position in overall energy consumption in the United States.

Data centre demand in the United States is concentrated in certain regions, and this uneven distribution has a significant impact on the amount of electricity consumed by each state. In particular, the proportion of electricity consumption by data centres varies widely from state to state. EPRI estimates that approximately 80% of the country's total data centre electricity consumption in 2030 will be concentrated in 15 specific states, including Virginia, Texas and California. In particular, Virginia's data centre consumption is prominent, reaching 33.9 TWh in 2023. This is significantly higher than the next largest state, Texas, at 21.8 TWh and the third largest, California, at 9.3 TWh. In 2030, Virginia's data centre electricity consumption is projected to account for 31% of the state's total electricity consumption, while Texas's is expected to reach about 6%.

Figure | Projection of data centre electricity consumption in the United States [2023–2030]



Source: Electric Power Research Institute (2024) "Powering Intelligence: Analyzing Artificial Intelligence and Data Center Energy Consumption". Retrieved on 2 September 2024, from https://restservice.epri.com/publicdownload/000000003002028905/0/Product

The concentration of data centres in Northern Virginia, particularly in the area known as 'Data Centre Alley', is attributed to several historical and geographic factors. First, the world's first network connection point, Metropolitan Area Exchange, East (MAE-East), was established there in the early 1990s. Through this point, internet traffic from around the world started flowing, leading to the concentration of data centres.

Another major factor was the development of fibre optic cables and electricity infrastructure when AOL, a major Internet service provider, established its base in Virginia in the 1990s. In addition, the introduction of tax incentives for data centres in Virginia in 2009 and lower electricity prices than the United States average also encouraged the concentration of data centres. The concentration of data centres in certain states, including Virginia, will continue to be a major factor affecting energy consumption in the United States.

The issue of increased electricity demand due to the deployment of data centres is extremely important in future energy policies and electricity infrastructure planning. In particular, the main issues that need to be considered to meet the increasing electricity demand include ensuring supply capacity, procuring thermal fuel/securing baseload power sources and optimising the electricity system.

IEEJ Outlook 2025 **BOX**

Achievability of 1.5°C target and progress towards NDC

Box | Achievability of 1.5°C target and progress towards NDC

The world is, on average, seeing a temperature rise of 1.5°C. According to observations by the European Union's Copernicus Climate Change Service, the global average temperature rose by more than 1.5°C above pre-industrial levels for 12 consecutive months from July 2023 to June 2024[1]. The El Niño phenomenon also contributed to the high temperatures in 2023, and while a temporary exceedance does not mean that the long-term 1.5°C target under the Paris Agreement will not be achieved, it is clear that stabilising global warming to 1.5°C is becoming increasingly difficult.

Furthermore, as noted in IEEJ Outlook 2024, the 1.5°C target is becoming more stringent, which is also evident from the decrease in the remaining carbon budget. A carbon budget represents the maximum amount of cumulative net anthropogenic CO_2 emissions that would limit global warming to a specific level with a certain probability, and the amount remaining after subtracting past emissions is called the remaining carbon budget. The Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) Working Group I (WG1) assessed the remaining carbon budget after 2020 to limit the temperature increase to 1.5°C with a 50% probability to be 500 $GtCO_2$.

Meanwhile, the latest research estimates of the remaining carbon budget from 2024 towards 1.5°C to be 200 $GtCO_2$ (Indicators of Global Climate Change [IGCC] 2023)[2] or 275 $GtCO_2$ (Global Carbon Budget [GCB] 2023)[3], which is roughly half the amount from IPCC AR6. The difference from the assessment at the time of IPCC AR6 comes from factors such as approximately 164 $GtCO_2$ emitted over the three-year period from 2020 to 2023 (estimated value for 2023), as well as an upward revision of the net greenhouse effect from non-CO_2 sources (updating a simplified climate model following updates to actual aerosol emissions[4]).

While there is significant uncertainty in estimating the remaining carbon budget[5], the 200 $GtCO_2$ figure represents only about five years' worth of CO_2 emissions at 2023 levels. As shown in Figure 5-4, if emissions are reduced linearly from 2024, the deadline for reaching net zero will be 2034, with an annual reduction of 9.4%. Even in 2020, a year hit by the COVID-19 pandemic, the reduction rate of energy-related CO_2 emissions was 5.7%.

Figure 1 also shows a group of CO_2 emission scenarios that are consistent with the 1.5°C target listed in the IPCC AR6 Working Group 3 (WG3) report. However, the scenario group with no or limited overshoot (C1)[6] corresponds to a remaining carbon budget of 500 $GtCO_2$, while the scenario group with high overshoot (C2)[7] is also depicted. Compared to C1, C2 is

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[1] Copernicus Climate Change Service, "June 2024 marks 12th month of global temperatures at 1.5°C above pre-industrial levels", 10 July 2024. https://climate.copernicus.eu/june-2024-marks-12th-month-global-temperatures-15degc-above-pre-industrial-levels.

[2] Forster et al., "Indicators of Global Climate Change 2023: annual update of key indicators of the state of the climate system and human influence", ESSD, 16, 2625–2658, 2024. https://essd.copernicus.org/articles/16/2625/2024/.

[3] Friedlingstein et al., "Global Carbon Budget 2023", ESSD, 15, 5301–5369, 2023. https://essd.copernicus.org/articles/15/5301/2023/.

[4] Lamboll et al., "Assessing the size and uncertainty of remaining carbon budgets", Nature Climate Change, 13, 1360–1367, 2023. https://www.nature.com/articles/s41558-023-01848-5.

[5] IPCC AR6 assessed the carbon budget to be ±220 $GtCO_2$ with uncertainty alone for non-CO_2 emission scenarios.

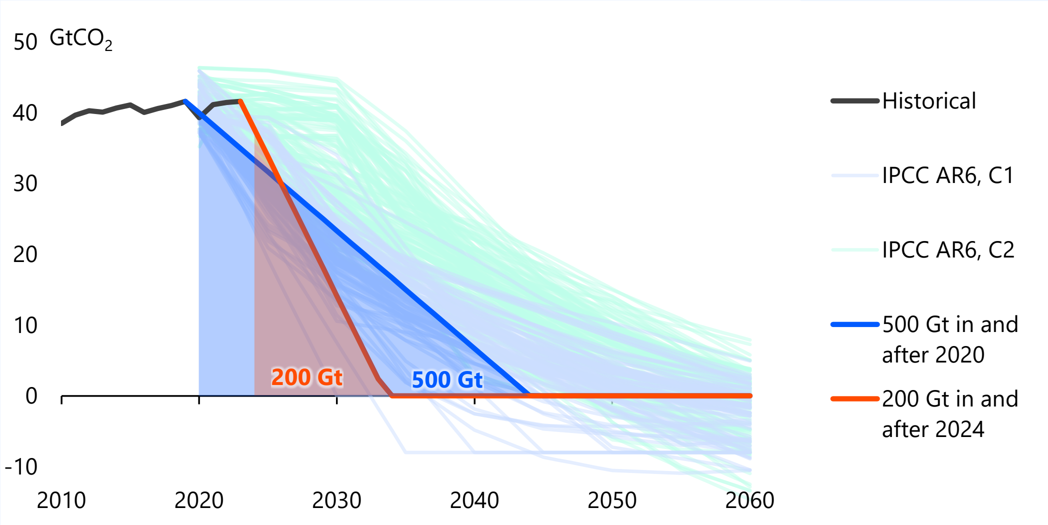
[6] Limited overshoot: 1.5°C exceeded by up to 0.1°C for up to several decades

[7] High overshoot: 1.5°C exceeded by 0.1°C–0.3°C for up to several decades

characterised by a slower pace of emission reductions in the short to medium-term, while CCS and CDR play a greater role in achieving significant reductions in the long-term.

Given the reduction in the remaining carbon budget, it may be difficult for the IPCC to present a scenario equivalent to C1 in the next assessment cycle (AR7), in which case the remaining path to 1.5°C would be a scenario equivalent to C2. At the recent COP28, a global stocktake was implemented for the first time to assess the world's overall progress towards the achievement of the goals of the Paris Agreement. The adopted decision document recognised the necessity of reducing GHG emissions by 43% by 2030 and 60% by 2035 relative to 2019 levels, and CO_2 emissions to net zero by 2050, in order to achieve the 1.5°C target. However, since these reduction targets are based on the C1 assessment at the time of IPCC AR6, under current circumstances, it is considered difficult to achieve 1.5°C with no or limited overshoot, even if these emission reductions are achieved.

Figure 1 | CO_2 emission path consistent with the 1.5°C target



Notes: 'Historical' was obtained from Global Carbon Budget 2023[8]. Including emissions from cement production processes, flaring, land use, land use change and forestry sector. 'IPCC AR6, C1' includes 97 scenarios that fall under 'C1: limiting warming to 1.5°C (>50%) with no or limited overshoot', while 'IPCC AR6 C2' includes 131 scenarios that fall under 'C2: returning to 1.5°C (>50%) after a high overshoot'[9].

Progress towards each country's 2030 targets (Nationally Determined Contributions: NDCs) has not been fully on track. Looking at advanced economies that have adopted absolute GHG emission targets, Japan's emissions result is roughly consistent with the target achievement path, while the United States and the European Union are above the target achievement path (Figure 2, left). Looking at the decomposition of energy-related CO_2 (the first item on the right of Figure 2), energy efficiency (including factors affecting changes in economic structure) has contributed the most to emission reductions since the base year in Japan, the United States and the European Union. It should also be noted that Japan's slower economic growth since the base year compared to the United States and the European Union (average annual GDP growth rate from the base year to 2022 was 1.7% for the United States and 1.6%

[8] Global Carbon Budget, "GCB 2023". https://globalcarbonbudget.org/carbonbudget2023/.

[9] Byers et al., "AR6 Scenarios Database hosted by IIASA", International Institute for Applied Systems Analysis, 2022. https://data.ene.iiasa.ac.at/ar6/#/login?redirect=%2Fworkspaces.

for the European Union, compared to 0.4% for Japan) has contributed significantly to emissions reductions.

For China and India, which have adopted targets for CO_2 or GHG emissions intensity per GDP, their performance changes are both on track to achieve their targets. However, the emissions figures on the left in Figure 2 are based on national inventories, and the latest years are somewhat outdated: 2018 for China and 2019 for India. Recently, both China and India have shown a slowdown in the improvement of primary energy and energy-related CO_2 emissions intensity per GDP[10]. In addition, the absolute value of emissions has increased significantly since the base year. Looking at energy-related CO_2 emissions, China has offset about half of the increase in emissions accompanying its economic growth through energy efficiency and new energy sources (renewables, hydrogen, synthetic fuels, etc.), but India saw limited contribution of emission reduction factors, including energy efficiency.

The achievement results of the 2030 target may also be divided (Figure 2, items 2 and 3 on the right). Compared with the scenarios in this outlook, China achieves its target even in the Reference Scenario, while the United States falls short of its target even in the Advanced Technologies Scenario. It should be noted, however, that the level of 'ambition' in each country's goals may differ. If the ambition level of the NDC goals is low, it will be easier to achieve the goals. In this regard, it is also necessary to evaluate each country's progress in achieving its goals relative to the ambition level.

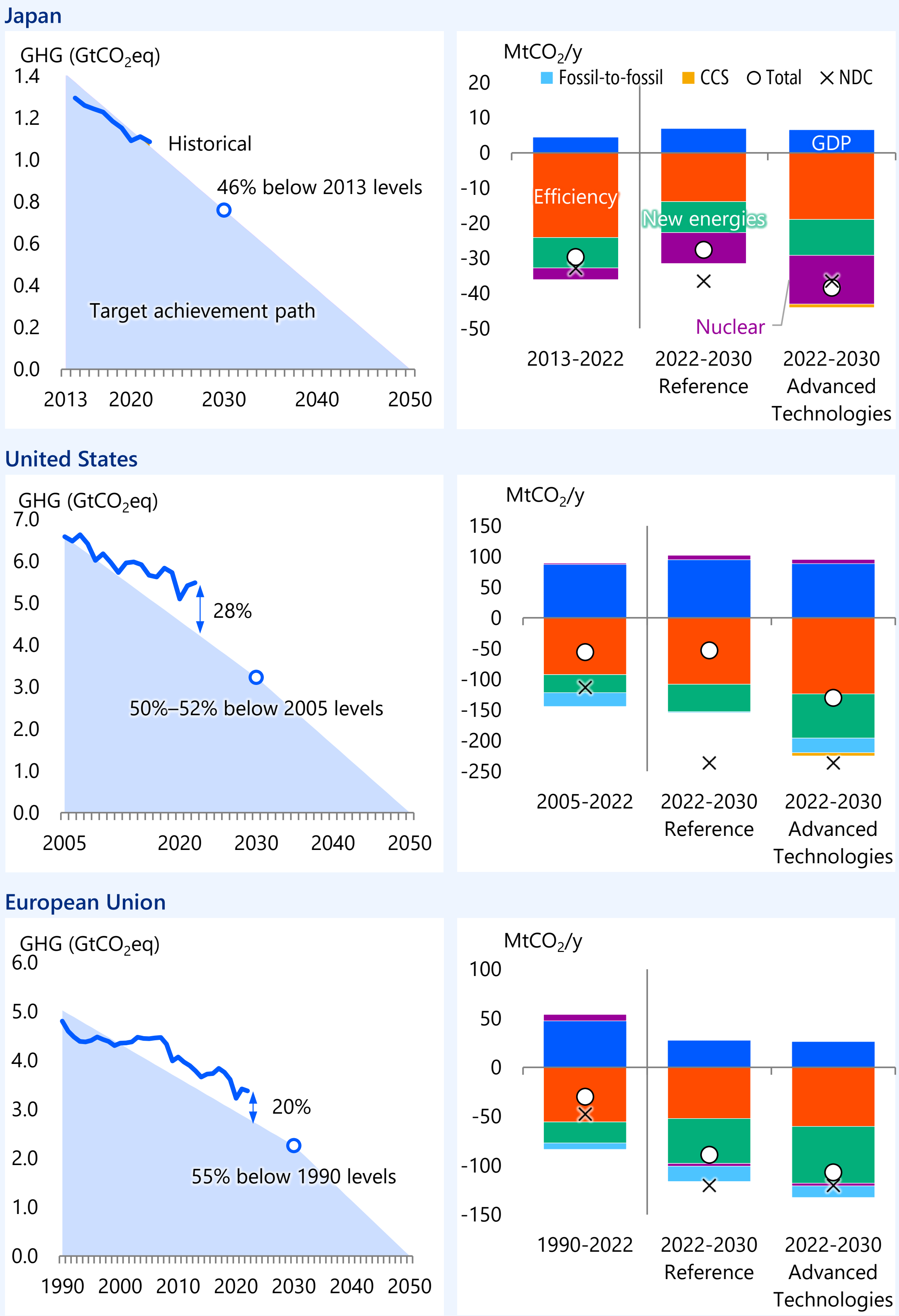
Japan, the European Union and India will not reach their targets in the Reference Scenario but achieve or come close to the goals in the Advanced Technologies Scenario. In all countries and regions, new energy sources will play a greater role in the future, but unless energy efficiency contributes at least as much as in the past, achievement of the 2030 goals will be in jeopardy. Furthermore, Japan would not be able to achieve its goal without the contribution of nuclear power.

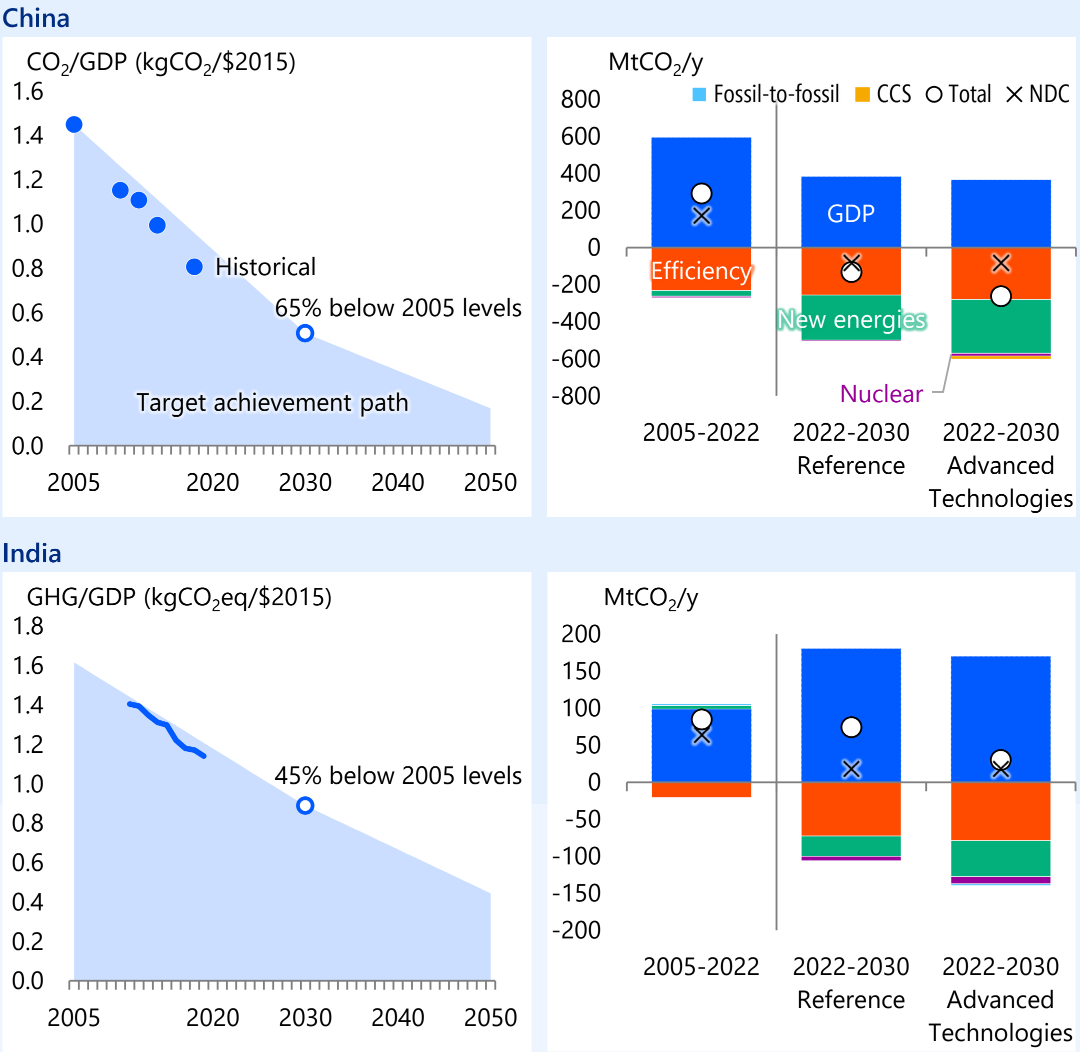
Governments' own projections assess that current policies are insufficient to achieve their medium- to long-term goals. The European Union's latest compilation of GHG emissions projections for its member states[11] assesses that current policies fall 15 percentage points short of the 2030 goal (55% below 1990 levels), and even if additional policies are taken into account, they will still fall 5% points short. These projections fall far short of net zero by 2050. The projections highlight challenges across the European Union, pointing out deep cuts still needed in the buildings and transport sectors, stagnation in emissions reductions in the agriculture sector, and backtracking against targets and declining removals in the land use, land-use change and the forestry (LULUCF) sector.

[10] China is not on track to achieve the intensity targets of its 14th Five-Year Plan (reducing energy consumption and CO_2 emissions per GDP by 13.5% and 18.0%, respectively, by 2025 compared to 2020). (According to the National Bureau of Statistics of China, the actual reduction in CO_2 intensity targets at the end of 2023 was approximately 4.6% below the 2020 level). Meanwhile, India's energy-related CO_2 emissions per GDP increased in 2021 and 2022 year on year.

[11] European Commission (2023), "Progress Report 2023 Climate Action", https://climate.ec.europa.eu/document/download/60a04592-cf1f-4e31-865b-2b5b51b9d09f_en.

Figure 2 | Progress towards NDCs of major advanced economies and decomposition of reduction factors of energy-related CO_2 emissions





Notes: The figure on the left is based on national inventories (emissions) and the World Bank (GDP). The latest year for emissions is 2018 for China, 2019 for India and 2022 for the rest countries. The base year emissions on which the targets in Japan and the European Union are based do not include LULUCF in accordance with the NDC. The United States' NDC is plotted at a position 51% lower than 2005. Emissions from China and India, which are not specified in their NDCs, do not include LULUCF emissions here. In the legend on the right, 'new energies' refers to renewable energy, hydrogen and synthetic fuels, etc., and 'Fossil-to-fossil' refers to substitution between fossil fuels. 'Efficiency' includes factors that affect changes in the economic structure. Decomposition covers energy-related CO_2 based on IEA (historical) and this outlook (projection), and NDCs are based on GHG or CO_2 reduction rates directly read as reduction rates for energy-related CO_2, except for Japan. China and India have emissions targets per GDP, but these were converted to absolute values based on the GDP assumptions in this outlook.

On 6 February 2024, the European Commission recommended a 90% reduction in GHG emissions in 2040 compared to 1990 levels, but the focus will be on ensuring the implementation of the Fit For 55 policy package aimed at achieving the 2030 target. The United States government has also announced its outlook[54] for GHG emissions under the

[12] United States of America (2023), "2023 Voluntary Supplement to the U.S. Fifth Biennial Report", https://unfccc.int/sites/default/files/resource/23-11-21%20BR_Supplemental_FINAL_clean%20OCEII_2_UST%20edits_clean.pdf.

Inflation Reduction Act and the Infrastructure Investment and Jobs Act in a document submitted to the United Nations. The analysis shows that under current policies, including these two laws, GHG emission reductions in 2030 will be 33%–41% below 2005 levels, showing the significant impact of current policies. However, to achieve the NDC (50%–52% below 2005 greenhouse gas emissions), additional policies by the federal government, state governments and the private sector are essential.

As we have seen, the latest scientific findings suggest that achieving the 1.5°C target with no or limited overshoot is becoming virtually impossible. Furthermore, while progress towards NDC is being made in major countries, advanced economies in particular are expected to find it difficult to achieve their NDCs unless they take additional policies. Under these circumstances, there is concern that NDCs after 2035 will sooner or later reach a dead end if the target is simply linearly connected to the 2050 net zero target, as shown on the left side of Figure 2. More ambitious reduction goals alone will not solve the problem. In addition to accelerating adaptation to climate change, mitigation needs to be based on a convex emission path that enables steady emission reductions in the medium-term through measures that each country can take, while at the same time accelerating emission reductions in the second half of the century through sufficient investments in technological innovation, including CDRs.

IEEJ Outlook 2025 **BOX**

Current energy conservation trends and future challenges: The importance of 'stock efficiency'

Box | Current energy conservation trends and future challenges: The importance of 'stock efficiency'

What does doubling the pace of energy efficiency improvements mean?

At the 28th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP28), an agreement was reached to strengthen the global commitment to doubling the current pace of energy efficiency improvements by 2030. Specific studies and policy formulation are under way in each country to strengthen domestic energy conservation measures and support by advanced economies to developing economies, while taking into account the burden on consumers.

The goal of doubling the pace[1] of energy efficiency improvements by 2030 is based on an analysis of the Net Zero Roadmap developed by the International Energy Agency (IEA) as a backcast to achieve net zero global CO_2 emissions by 2050. The analysis implies a worldwide improvement in primary energy intensity per unit of GDP per year[2] from now to 2030 at 4% annually, doubling from 2% in 2022.

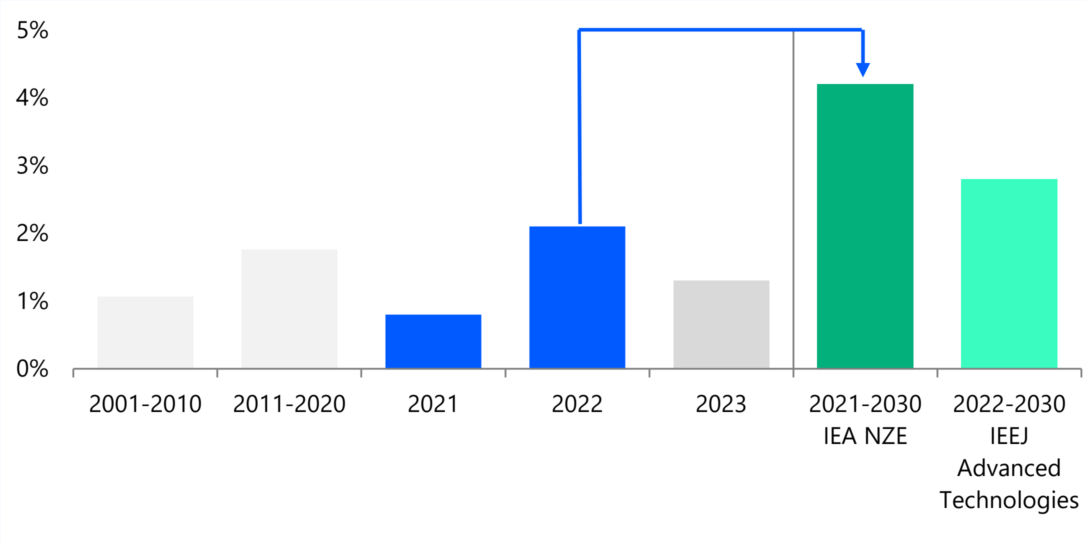
As shown in Figure 1, energy intensity improved more significantly in 2022 than in previous years, at a rate of 2% year on year. This improvement was driven by production

[1] Although the term 'energy efficiency improvements' in the COP28 agreement is not clearly defined, in the Box it refers to primary energy intensity per unit of GDP.

[2] The IEA utilises purchasing power parity-based GDP, but the IEEJ uses exchange rate-based GDP for its analysis.

adjustments in the industry sector due to the global rise in energy prices, progress in changing behaviour related to electricity and natural gas conservation in many countries and decreased demand for space heating in Europe due to the warm winter. The average improvement rate in energy intensity for the period 2010–2020 was 1.5%, slowing to 0.8% in 2021, then 1.3% in 2023, indicating a high pace of improvement in 2022.

Figure 1 | Improvement rate of global energy intensity



Sources: IEA (2024). Energy Balances., IEEJ, and IEA (2023). Net Zero Roadmap.

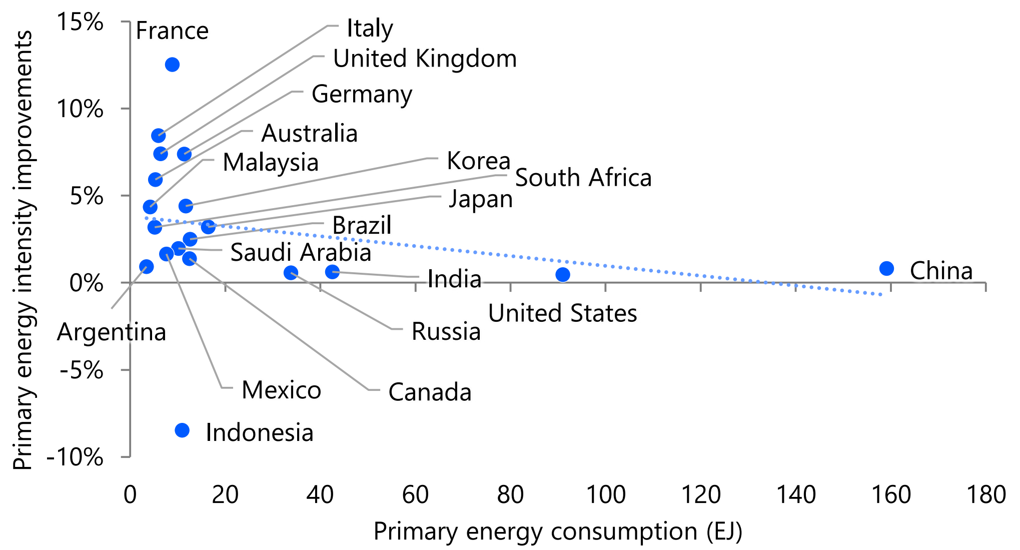
As shown in Figure 2, the energy intensity improvement rate in 2022 varied greatly from country to country among Group of 20 member states. Germany and the United Kingdom each saw a 7% improvement, Italy recorded 8% and France[3] demonstrated 13%.

In China, the United States, India and Russia, which are major energy consumers, year-to-year improvements in energy intensity in 2022 were much more modest, ranging between 0.5% and 0.8%. Compared to the high improvement rates in Europe and other regions, the rates were significantly lower in countries with large energy consumption, resulting in an average global improvement rate of 2%. China's energy intensity improvement rate slowed to 0.8% in 2022 compared to 3.2% in 2020–2021, primarily due to increased demand for oil as a feedstock for its expanding petrochemical industry, while China's economic growth rate decelerated to 3%. ASEAN has seen little improvement in energy intensity since 2015, with a 2% deterioration in 2022. This regression likely stems from increasing ownership of automobiles, air conditioners and other home appliances as living standards improve across the region.

The improvement in energy intensity in Europe was particularly remarkable in 2022, reaching 2%. However, in India and ASEAN, which will drive global energy demand in the future, as well as in other major countries (both advanced and developing economies), improvement rates are slowing down. This trend suggests that achieving the 4% target will be challenging, considering historical performance.

[3] The double-digit improvement in France is attributed to savings in energy input to the power generation sector, as the country relied on imports for electricity due to the shutdown of domestic nuclear power plants in the year.

Figure 2 | Relationship between GDP intensity improvement rate of primary energy and primary energy consumption [2022]



Source: Compiled from IEA (2024). Energy Balances

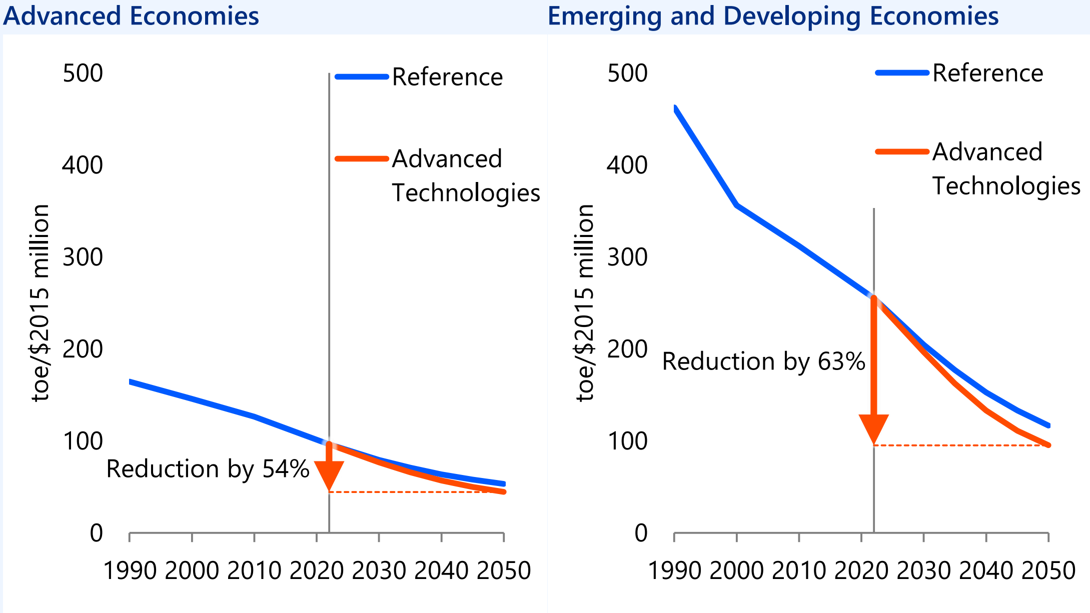
Outlook

Looking to the future, in the Advanced Technologies Scenario, which leads to expanded adoption of highly efficient technologies, primary energy consumption intensity per GDP will improve at an annual rate of 2.8% until 2030 in Advanced Economies and at 3.2% in Emerging and Developing Economies (Table 1). In both Advanced Economies and Emerging and Developing Economies, the pace of improvement in intensity is fastest between 2030 and 2040, at 3.0% and 3.8%, respectively, followed by 2.6% and 3.3% between 2040 and 2050, respectively. In terms of energy intensity, Advanced Economies will see a 54% reduction in 2050 compared to 2022, while Emerging and Developing Economies will see a 63% reduction (Figure 3). Looking at the global picture, the improvement rate is expected to be 2.5% between 2022 and 2030, falling short of the 4% target even in the Advanced Technologies Scenario, which assumes maximum introduction of efficient technologies.

Table 1 | Primary energy consumption intensity per GDP and improvement rate

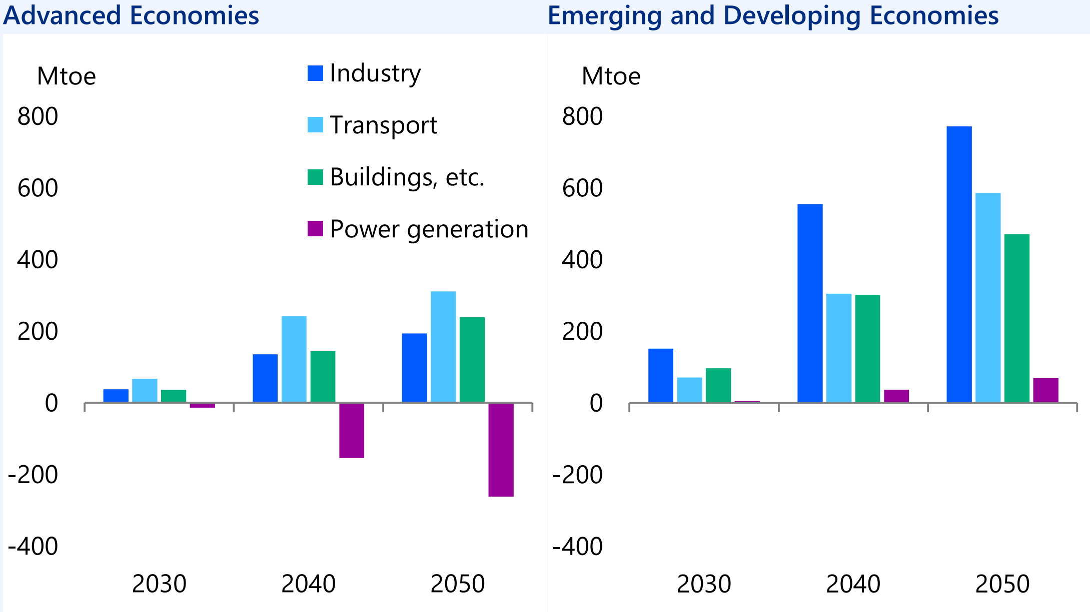
		Reference						Advanced Technologies					
	2022	2030	2040	2050	2022/ 2030	2030/ 2050	2022/ 2050	2030	2040	2050	2022/ 2030	2030/ 2050	2022/ 2050
Advanced Economies	96	79	64	53	-2.4%	-2.0%	-2.1%	77	57	45	-2.8%	-2.6%	-2.7%
Emerging and Developing Economies	255	205	153	117	-2.7%	-2.8%	-2.7%	197	133	95	-3.2%	-3.6%	-3.5%

Figure 3 | Primary energy consumption intensity per GDP



When the difference between the Reference Scenario and the Advanced Technologies Scenario is defined by energy savings, the scale of the energy conservation amount differs by sector and time axis in Advanced Economies and Emerging and Developing Economies, as shown in Figure 4. In Advanced Economies, BEVs for passenger vehicles will be more widely used after 2035, when they are estimated to offer cost advantages over internal combustion engine vehicles, contributing to energy conservation in the transport sector. In contrast, in Advanced Economies, the energy input for power generation will be higher in the Advanced Technologies Scenario than in the Reference Scenario due to a demand-side shift from fossil fuels to electricity. In Emerging and Developing Economies, the industry sector will see significant progress in energy conservation due to China's transition to a service industry and the higher efficiency of newly installed facilities. Energy conservation in the transport sector in Emerging and Developing Economies will progress after 2040, with electrification lagging 5 to 10 years behind Advanced Economies.

Figure 4 | Energy conservation by sector



Note: Regarding the difference between the Reference Scenario and the Advanced Technologies Scenario, positive values represent energy conservation and negative values represent energy increases.

As the results of the Advanced Technologies Scenario show, it will be difficult to achieve a 4% annual improvement rate in energy intensity from now to 2030, the early stage of the projection period, without 'discontinuous' actions in technology introduction and operational improvements. Accelerating energy efficiency improvements requires consideration of various factors related to equipment use and technology adoption. Specifically, these include the timing of cost reductions in high-efficiency technologies, electrification in the demand sector. Specifically, these include the speed and scale of progress of various factors, such as the timing of cost reductions in high-efficiency technologies, electrification in the demand sector and expanded introduction of renewable energy[4] in the power generation sector, and the service-oriented industrial structure of developing countries that will be the driving force of the future global economy. However, the key factor that determines the pace of energy efficiency improvement is that replacing equipment and technologies progresses continuously and takes time.

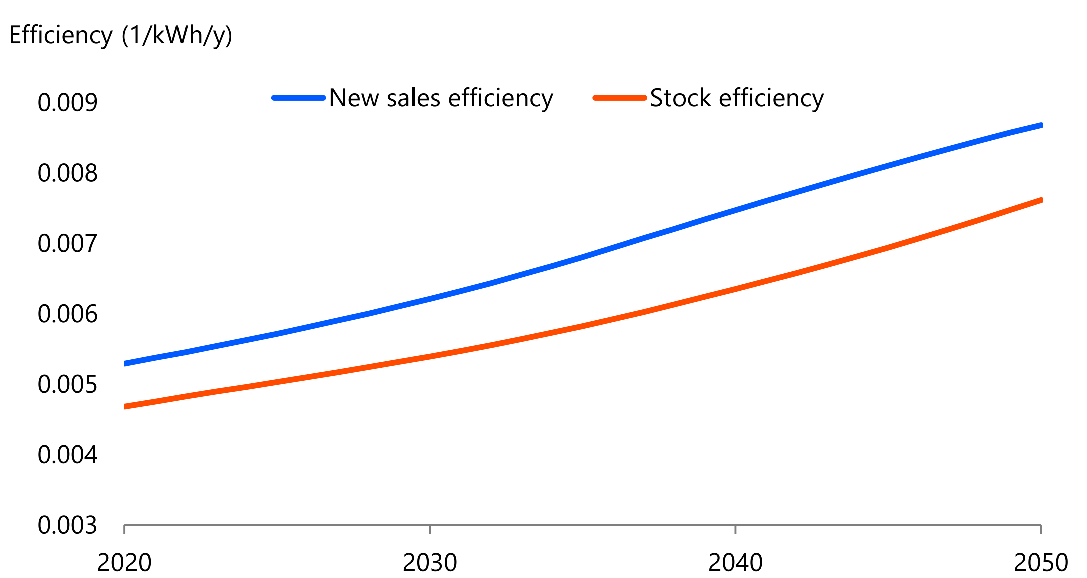
As Figure 4 shows, in terms of quantity, the difference in energy conservation between the scenarios up to 2030 is relatively small, but the gap in energy conservation between the scenarios widens after the 2040s. In terms of pace, energy efficiency improvements will accelerate in both Advanced Economies and Emerging and Developing Economies between 2030 and 2040, followed by a slight deceleration thereafter (Table 1).

This means that equipment and technology replacement inherently requires time. Household appliances and passenger cars typically take 10 to 20 years to replace, while large buildings and industrial equipment require 30 to 50 years or more, with periodic

[4] The conversion factor to primary energy per kWh for solar photovoltaics and wind is 3.6 MJ, while that for thermal power generation is around 8 MJ to 9 MJ, reflecting different efficiency levels by countries. In improving primary energy intensity, increasing the share of renewable energy in the power generation mix works advantageously.

maintenance extending their lifespans. Taking air conditioners as an example, with an average service life of 15 years, even if efficiency standards for new units are raised to optimal levels, it will take approximately 10 years for these improvements to be reflected in a country's average stock efficiency (Figure 5). In other words, policies such as strengthening standards implemented today will only yield significant results about 10 years from now, highlighting the urgency of implementing measures to accelerate the adoption of highly efficient technologies immediately.

Figure 5 | Comparison of new sales efficiency and stock efficiency (example of air conditioners)



Notes: The efficiency here indicates the inverse of the power consumption during space cooling by the air conditioner, and the higher the value, the higher the efficiency. New sales efficiency is the efficiency at the time of sale, while stock efficiency represents the efficiency of the entire air conditioner stock in a country, taking into account a 15-year service life.

Implication

Based on the long service life of equipment and technology, it is essential to accelerate measures and policies to promote the introduction of high-efficiency technology so that its energy-saving effects will bear fruit in the future. Also taking into consideration the 'lock-in effect', which means that once equipment or technology is selected, it continues to be used for 10 years or more, the improvement of efficiency should be prioritised within the energy conservation system, as well as the establishment of standards.

The amount of energy conservation from improved efficiency of equipment and technology is an accumulation of small effects. On the other hand, to achieve 'discontinuous' energy conservation effects that are not simply an extension of past efforts, packaged technologies and the approach as a system are required. For example, it is necessary to provide incentives as well as regulatory approaches to promote the introduction of Net Zero Energy Buildings (ZEB), which are an aggregation of highly efficient technologies.

Emerging and Developing Economies have significant potential for energy conservation. Furthermore, compared to Advanced Economies, they still have access to relatively inexpensive energy conservation options. However, this potential often remains unrealised due to the lack of standards, systems, incentives and information provision, as well as the high initial costs involved in introducing high-efficiency technologies. The formation of effective standards requires the thorough implementation of lighting and building standards, air conditioning regulations, automobile fuel efficiency regulations, motor standards and regulations related to energy management. However, many of these standards may not be in place in Emerging and Developing Economies due to insufficient human resources and technical know-how.

To address these issues, it is essential that developed countries provide support for the formulation of systems, transfer of know-how and implementation of energy conservation projects. Energy conservation projects may not be preferentially selected by investors in terms of profitability, given their smaller project size compared to other carbon-neutral projects, such as renewables. Taking these circumstances into account, it is also necessary to package multiple energy conservation projects.

Potential of Solar Energy Systems Considering Local Regulations and Roof Shapes

Obane Hideaki* · Sasakawa Akiko** · Morimoto Soichi* · Shibata Yoshiro* · Otsuki Takashi***,*

Some of solar energy systems in Japan had a negative effect on the local environment and wildlife such as forest. Municipalities have recently regulated the installation of solar energy systems in these areas. If more solar energy systems are to be deployed in the future, it will be necessary to install them in areas with few or no competing uses or rooftops. However, the consideration of recent local regulations or characteristics of rooftops has been insufficient in previous studies assessing suitable areas for solar energy systems. Here, we show that the suitable area for solar energy systems is significantly reduced by considering these factors, in comparison with previous studies. We found that suitable areas for ground-mounted solar energy systems are significantly limited by composing a geoinformation database including regulation areas based on policy review for 263 municipalities. Furthermore, we found that available areas for rooftop solar energy systems are mainly in small buildings, where further cost reduction of solar energy systems is required. Our results demonstrate the importance of shifting ground-mounted solar energy systems to rooftop solar energy systems, and that the Japanese government should set appropriate targets or policies for the installation of rooftop solar energy systems.

Key words: Renewable energy, Solar energy, Energy policy, Spatial analysis, Photovoltaics

1. Introduction

Solar energy is being positioned as a major energy source for achieving carbon neutrality, and there are high expectations for its large-scale adoption. However, if solar energy systems were introduced on a large scale in the future, the issue of facing constraints on installation locations is predicted to become increasingly apparent.

By the end of March 2024, 57.9 GW of solar energy of 10 kW or more has been deployed[1] through feed-in tariffs (FIT), while many solar energy systems have been installed in forests and other locations where there are concerns about the natural environment. The area for forest development that has been granted forest land development permits in connection with the installation of solar energy systems reached 171 km^2 by 2023,[2] which is equivalent to approximately 11 GW when converted to solar energy generation capacity based on installation density,[3] assuming power generation efficiency at the level when FIT was first introduced. This estimate suggests that at least one-sixth of the solar energy systems installed to date have been located in forests. In light of this situation, there has been a growing movement[4] to regulate the installation of solar energy systems in specific locations in accordance with local regulations. In order to introduce solar energy on a large scale in the future, there is a need to identify the locations suitable for installing solar energy systems and clarify the feasibility of introducing solar energy systems toward achieving carbon neutrality.

To date, many studies and surveys have been conducted on the feasibility of introducing solar energy systems in Japan. For example, research on ground-mounted solar energy systems includes a study by Shimazaki[5] and Ito et al. [6] that focused on abandoned farmland, as well as surveys conducted by the Ministry of the Environment.[7] There is also a study by Obane et al.[8] that includes weedy land in addition to abandoned farmland as potential installation locations. However, previous studies have not fully considered the impact of regulatory ordinances, which have been expanding in recent years.

Research on rooftop solar energy systems includes that by Sugihara et al.[10] and Wakeyama et al.,[11] as well as surveys conducted by the Ministry of the Environment[7], the New Energy and Industrial Technology Development Organization (NEDO),[12] and the Japan Photovoltaic Energy Association (JPEA).[13] In addition to these, there is also a study by Hirose et al.[14] that organized the ideas in various literary references and visualized the differences in thinking and approach. For building roofs, unlike weedy land, it is necessary to take into account spaces that are unsuitable for installing solar energy systems due to the presence of outdoor air conditioner units and water tanks, for example. Previous studies drew up estimates based on the assumption that a certain percentage of the entire roof can be used for installing solar energy systems, such as by using the potential greening area of a model building[15] as the basis for estimates. However, this posed the need for a more detailed assessment of roof characteristics.

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Therefore, this study aims to evaluate the feasibility of introducing solar energy systems. To that end, a geographic information system (GIS) was used to evaluate the potential of deploying ground-mounted and rooftop solar energy systems, based on a review of local regulations and an analysis of a database related to the deployment of solar energy systems in buildings.

The technical potential evaluated in this study is defined, in line with the definition provided by the Ministry of the Environment,[7)] as the amount of energy available at the time of estimation, from among the energy reserves but excluding that which cannot be used due to various constraints related to energy collection and use. This study only takes into account land use and legal systems such as local regulations, while social constraints such as economic efficiency, grid constraints, and coordination with local communities were not considered. Furthermore, to align this study with the definition by the Ministry of the Environment, changes over time, such as a decrease in housing stocks, changes in land use, and improvements in power generation efficiency, were not taken into consideration.

2. Evaluation method

In this study, we constructed a GIS database that combined two types of data: land use data with an approximate 100 m mesh (3 seconds latitude by 4.5 seconds longitude) covering all of Japan except the Northern Territories. Based on this database, we then evaluated potential locations for installing solar energy systems. Fig. 1 provides an overview of the evaluation method.

Following the concepts presented by Obane et al., we classified Japan's land into 20 categories for ground-mounted solar energy systems, based on GIS data such as the National Land Numerical Information's "Land Use Subdivision Mesh Version 2.6, FY2016," "Forest Areas," "Agricultural Areas," and the Ministry of the Environment's "National Survey on the Natural Environment." These sections were then classified into four categories: weedy land, bare land, shrubby land, and degraded farmland that is difficult to rehabilitate. Furthermore, these land classifications exclude areas that are regulated under local regulations from the potential installation locations. Moreover, from among the potential installation locations for ground-mounted solar energy systems, land use competition is likely to arise with onshore wind energy systems in areas with good wind conditions. Therefore, locations with an annual average wind speed of 5.0 m/s or more at a height of 80 m above ground level were considered as areas of potential competition between ground-mounted solar energy systems and onshore wind energy systems.

For rooftop solar energy systems, evaluation was conducted based on FY2023 data from NTT InfraNet's GEOSPACE platform, which records the type and building area of each building. Detached houses are included in the building attribute "standard building" on GEOSPACE. However, since detached houses are not distinguished by a unique attribute, when estimating the roof area of detached houses, we used the "2018 Housing and Land Survey" published by the Ministry of Internal Affairs and Communications, which records the roof area of detached houses by prefecture.

Buildings other than detached houses were classified as public facilities or non-public facilities, and evaluated based on the roof area of the entire building as provided in the GIS data. However, the roof area provided in the GIS data includes spaces that are not suitable for installing solar energy systems, for example, due to the presence of water tanks. Therefore, by using a database of buildings that actually have solar energy systems installed, we estimated an installation coefficient for each building type, defined as the ratio of roof area to actual solar installation area. The area of potential locations for the installation of solar energy systems was then estimated based on this.

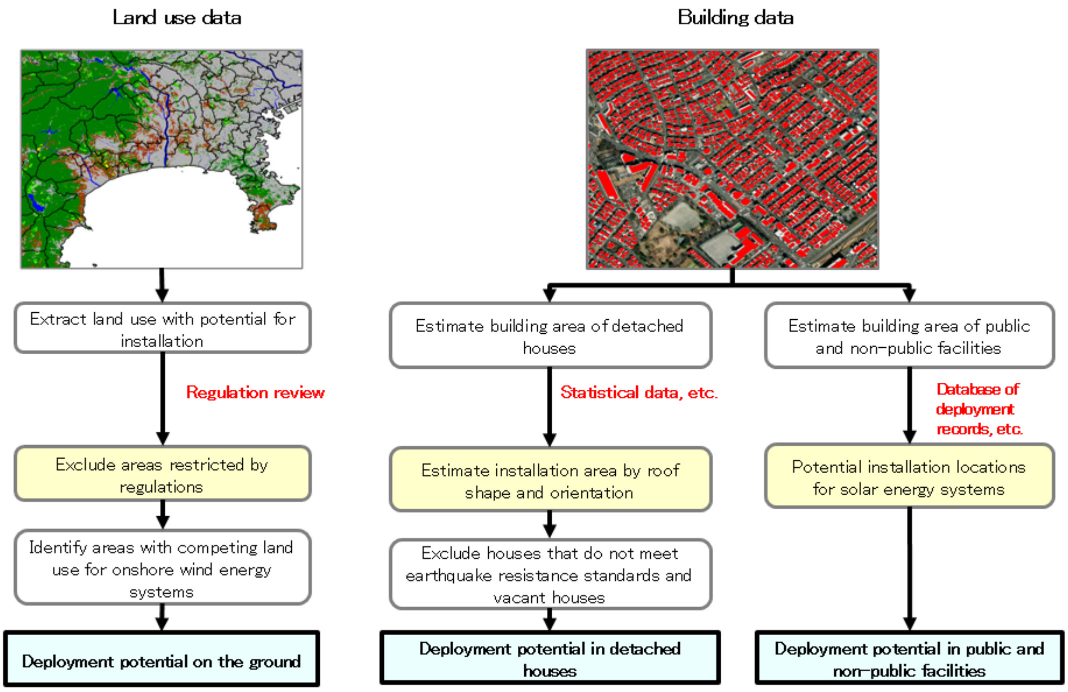


Fig. 1 Method of evaluating technical potential using a GIS database

3. Results of the evaluation of technical potential for ground-mounted solar energy systems

3.1 Area by land use

Fig. 2 shows the results of estimating area by land use based on a GIS database. According to the GIS database, the total land area of Japan, excluding the Northern Territories, is 372,835 km^2. Land use areas on which it is difficult to install ground-mounted solar energy systems, such as protected forests and farmland, make up 50% of the country's land area, while land classifications in which installation is not recommended from the perspective of environmental conservation, such as privately owned forests and national forests, account for 47% of the total. Buildings with potential for the installation of rooftop solar energy systems, which will be detailed later, comprise 2% of the total.

The total area of weedy land, bare land, shrubby land, and degraded farmland that is difficult to rehabilitate, which are areas with potential for the installation of ground-mounted solar energy systems, is estimated to be 4,887 km^2, which is equivalent to 1% of the total. However, this area does not take into account areas subject to local regulations; if such areas were considered, the number of potential locations for installing ground-mounted solar energy systems would be further reduced.

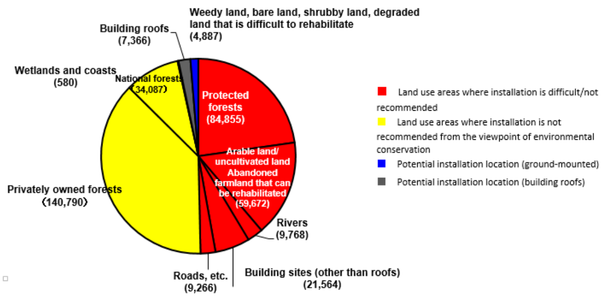


Fig. 2 Area by land use [km^2]

3.2 Results of the extraction of areas subject to local regulations

In order to consider areas subject to local regulations, we conducted a review of the regulations enacted by 263 of the 1,718 municipalities nationwide that were confirmed to have established regulations pertaining to solar energy up to March 2024, taking reference from the Research Institute for Local Government.[4] As a result, within the scope of information available on each municipality's website, 195 municipalities were found to have designated specific legal zones, and a further 12 municipalities regulate the installation of solar energy systems throughout the entire municipality. It was also confirmed that the remaining 56 municipalities have enacted regulations that only regulate aspects such as construction methods and scale of installation.

This study only covers municipalities that have clearly specified areas that specifically restrict the installation of solar energy systems, such as restricted zones, and the classifications of such areas were then extracted. The results are shown in Fig. 3, which shows the areas designated as restricted zones in order of municipalities with the highest number of designated zones. Of these, the blue bars indicate areas for which GIS data was confirmed and that were taken into account in the GIS database, while gray bars indicate areas for which GIS data could not be confirmed.

Areas subject to regulation, such as restricted zones, include areas designated for disaster prevention, areas related to the conservation of the natural environment, and areas related to landscape conservation, among others. These areas are considered to be areas where the installation of solar energy systems is not recommended, regardless of whether any regulations have been put in place. For this reason, in this study, areas extracted from all municipalities were excluded from the potential installation locations, regardless of whether the respective municipalities had actually enacted any regulations.

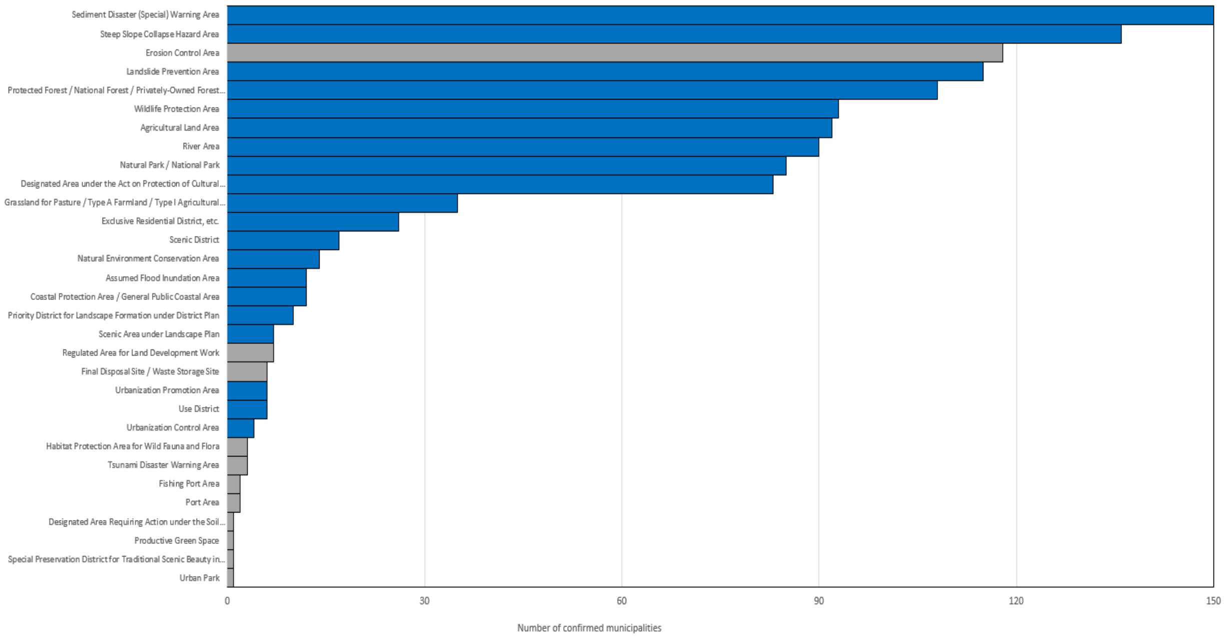


Fig. 3 Areas designated as restricted zones (in order of municipalities with the highest number of designated zones)

3.3 Area of potential installation locations, taking local regulations into account

Of the land use areas with potential for the installation of ground-mounted solar energy systems (4,887 km^2), such as weedy land, Fig. 4 shows the results that exclude areas subject to local regulations in all municipalities, in order from the municipalities with the highest number of areas.

The results show that, in the most conservative case, where all areas subject to local regulations are excluded, the area of potential installation locations was significantly reduced to 383 km^2. In this study, this is described as the "case excluding all restricted zones." In such cases, landscape planning areas contribute the most to the reduction in area. Landscape planning areas have designated restrictions on activities for the purpose of creating favorable landscapes, and it has been confirmed that at least eight municipalities have designated such areas as restricted zones by the end of FY2023. Although it is not necessarily the case that the installation of solar energy systems is prohibited in all landscape planning areas across Japan, it is difficult to quantify the installation capacity of solar energy systems that can be installed in such areas while giving consideration to specific circumstances. Therefore, a case that includes only areas designated as restricted zones by a larger number of municipalities than those designated as landscape planning areas among the potential installation locations is separately defined as the "case with partial exclusion of restricted zones." The area of the potential installation locations in such cases was estimated to be 3,250 km^2.

Fig. 5 shows the potential installation locations by municipality for each case. In (A) case with partial exclusion of restricted zones, many of the potential installation locations are concentrated in the plains of Hokkaido. However, as the whole of Hokkaido has been designated as a landscape planning area, in (B) case, excluding all restricted zones, the results show that there are potential installation locations in some municipalities in the Tohoku, Hokuriku, and Chugoku regions.

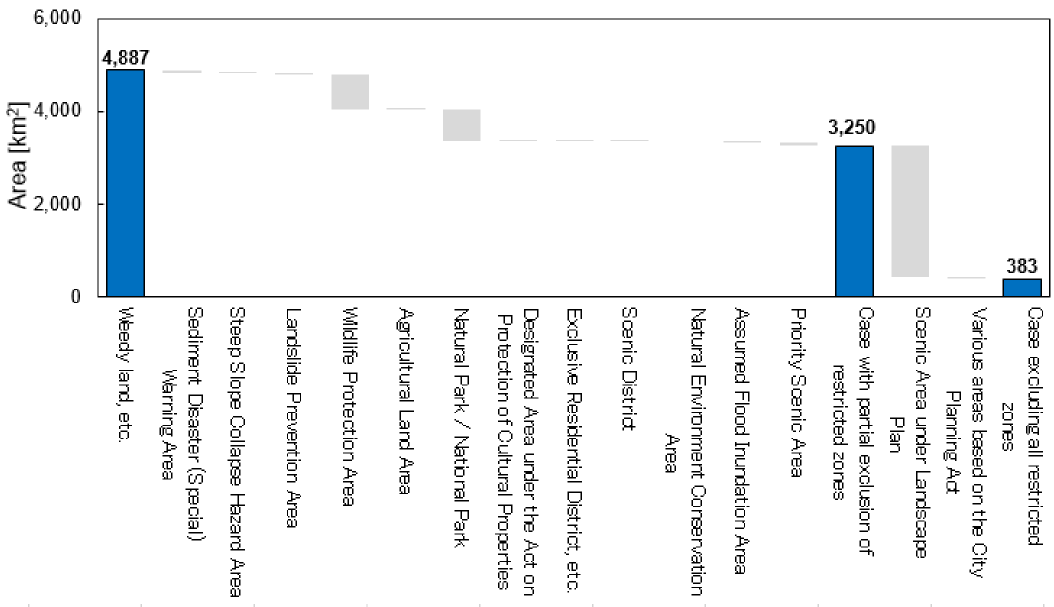
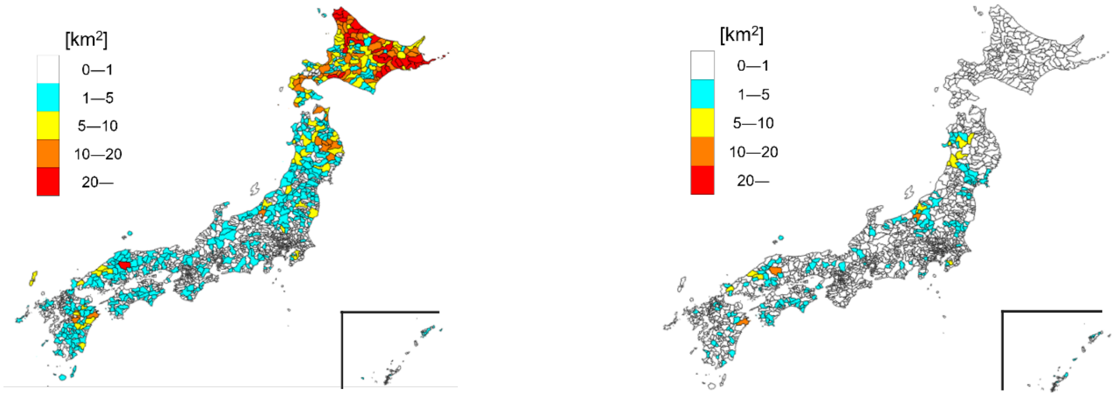


Fig. 4 Area excluding restricted zones in order of frequency [km^2]



(A) Case with partial exclusion of restricted zones (B) Case excluding all restricted zones

Fig. 5 Area of potential installation locations for ground-mounted solar energy systems by municipality [km^2]

3.4 Technical potential that takes into account competing land use with onshore wind energy systems

Of the potential installation locations for the two cases defined in the previous section, the areas of locations where land use competition occurs with onshore wind energy systems due to annual average wind speeds of 5.0 m/s or more, and of locations with wind speeds of less than 5.0 m/s, were estimated. These were then converted to technical potential based on an installation density of 0.111 GW/km^2 (ground-mounted solar energy system) and 0.010 GW/km^2 (onshore wind energy system), in line with the Ministry of the Environment.[7)]

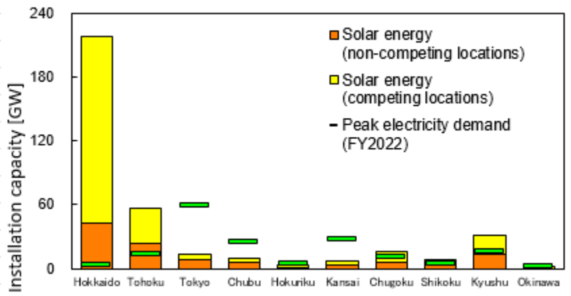
Table 1 shows the technical potential under the conditions described above, considering land use competition with onshore wind energy systems. First, if a solar energy system were to be installed in a location where there is no competition with onshore wind energy systems, the technical potential was estimated to be 20 GW (case excluding all restricted zones) and 107 GW (case with partial exclusion of restricted zones). If a solar energy system were to be installed beyond this installation capacity, it would then be necessary to take into consideration competing land use with onshore wind energy systems.

The areas that compete with onshore wind energy systems were estimated to be 2,283 km^2 and 206 km^2 in the case with partial exclusion of restricted zones and case excluding all restricted zones, respectively. Hypothetically, if solar energy systems were installed in all competing locations, the maximum installation capacity would be 253 GW and 23 GW, respectively.

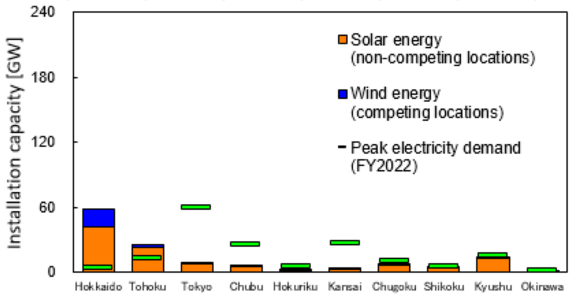
Therefore, if we were to carry out a simple comparison of the amount of power generated in order to consider the energy source suitable for the competing locations, in the competing locations in the case with partial exclusion of restricted zones, 133 TWh of power would be generated from a 253 GW-solar energy system (converted at capacity factor of 14%), while 61 TWh of power would be generated from a 23 GW-onshore wind energy system (converted at capacity factor of 30%). Hence, if we were to consider only the amount of power generated, it would be more advantageous to install solar energy systems at all competing locations. However, looking at the results of a comparison of the technical potential by the power area and peak electricity demand in FY2022 (Fig. 6), we can see that if solar energy systems were installed at all competing locations, peak electricity demand in FY2022 would be significantly exceeded in Hokkaido, Tohoku, Kyushu, and other regions. In addition to ground-mounted solar energy systems, the technical potential of rooftop solar energy systems, which will be detailed later, is also added. Therefore, if solar energy systems, which only generate electricity during the day, were deployed on a large scale beyond the peak electricity demand, there would be a need to put in place measures such as installing storage batteries and reinforcing interconnection lines. For this reason, it is necessary to determine the energy source suitable for competing locations by considering the balance of electricity supply and demand in each time period.

Table 1 Area of potential installation locations for solar energy systems and technical potential, taking into account competing land use with onshore wind energy systems

Case	Competition with onshore wind energy systems	Area [km²]	Technical potential [GW]	
Case with partial exclusion of restricted zones	Competing locations	2,283	Solar energy Onshore wind energy	0 – 253 0 – 23
	Non-competing locations	967	Solar energy	107
Case excluding all restricted zones	Competing locations	206	Solar energy Onshore wind energy	0 – 23 0 – 2
	Non-competing locations	177	Solar energy	20



(A) Case of installing solar energy systems in all competing locations



(B) Case of installing onshore wind energy systems in all competing locations

Fig. 6 Comparison of technical potential and peak electricity demand by power areas (case with partial exclusion of restricted zones) [GW]

4. Results of evaluation of technical potential for detached houses

4.1 Area that takes into account roof shapes

The building area of detached houses in the GIS database was 2,238 km². However, since this area is a projected area as viewed from above, the shapes and orientation of roofs are not taken into consideration. Therefore, the roof angle was adjusted to the angle of 5-inch roofs (26.6 degrees), which cover the largest number of houses, and the area of each type of roof was estimated for each power area based on data on the percentage of roofs by region from the Japan Housing Finance Agency[16] (Fig. 7). The results show that gable roofs composed of two roof surfaces, hipped roofs composed of four roof surfaces, and shed roofs composed of a single roof surface, make up the majority of roof types in Japan.

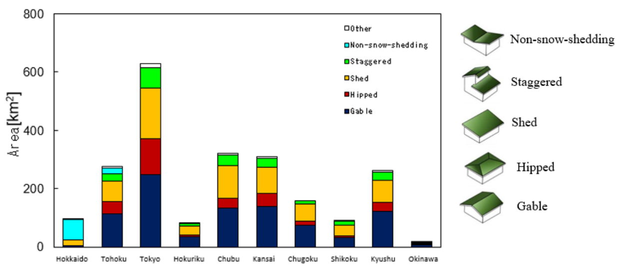


Fig. 7 Area by type of roof on detached houses[km²]
(Source for the figure: CONOIRO (Yuko Navi)[17])

4.2 Installation coefficients by type of roof

Based on the area of each type of roof, we considered the installation coefficient (the ratio of the roof area to the area available for installing solar power system) for each type of roof. Previous studies on installation coefficients have been conducted by the Japan Science and Technology Agency (JST)[18] and the Ministry of the Environment.[3] JST presented the installation coefficients for the total of all orientations for 103 flat roofs, 30 hipped roofs, and 74 gable roofs as 0.65 to 0.8, 0.65 to 0.7, and 0.7 to 0.85, respectively. The minimum installation coefficient is defined as the current standard value, while the maximum is defined as a high level based on the assumption of maximum installation in the future. On the other hand, the Ministry of the Environment has set out the installation coefficients for each orientation based on three sample roofs for a total of six roof types, and the installation coefficients for the total of all orientations are 0.34 for flat roofs, 0.68 for hip roofs, and 0.60 for gable roofs.

Comparing the installation coefficients presented by JST and the Ministry of the Environment, we can see a significant discrepancy, particularly for flat roofs; this is presumably because JST includes roofs other than those of detached houses in its sample survey. Therefore, this study takes reference from the installation coefficients by angle prepared by the Ministry of the Environment, which determined installation coefficients by roof type and orientation as shown in Table 2. Note that for staggered roofs and other types of roofs, the installation coefficients for gable roofs were applied due to the lack of available sample data.

Based on these installation coefficients, the roof areas by orientation, estimated by power area, are shown in Fig. 8. The total area occupied by the space around solar cell modules in all detached houses was estimated to be 773 km^2, and the area of the remaining installation locations, which excludes such space from the total roof area, was estimated to be 1,465 km^2.

Table 2 Installation coefficients for detached houses, by orientation

Type of roof	South	East-West	North
Gable	0.15	0.3	0.15
Hipped	0.17	0.34	0.17
Irimoya (hip-and-gable)	0.14	0.27	0.14
Flat	0.34	0	0
Shed	0.12	0.25	0.12
Staggered	0.15	0.3	0.15
Non-snow-shedding	0.215	0.435	0.215
Other	0.15	0.3	0.15

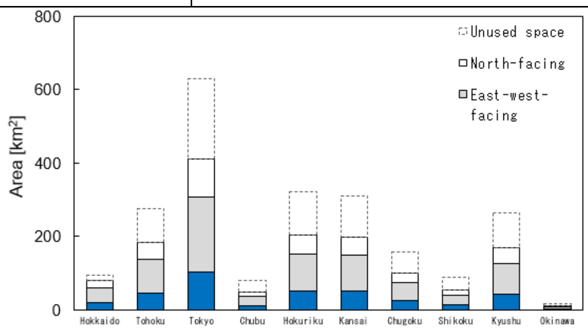


Fig. 8 Area of detached house roofs by orientation [km^2]

4.3 Technical potential that takes into account houses that do not meet earthquake resistance standards and vacant houses

The installation of solar energy systems is not recommended for detached houses that do not meet earthquake resistance standards based on the Building Standards Act revised in June 1981 (new earthquake resistance standards). Therefore, taking reference from the stance of NEDO[12)] and Table 171-1 of the "2018 Housing and Land Survey" published by the Ministry of Internal Affairs and Communications, we estimated the percentage of detached houses in each prefecture that do not meet the new earthquake resistance standards, and excluded them from the houses for which installation is feasible.

Furthermore, while it is not necessarily impossible to install solar energy systems in vacant houses, it may affect the management of solar energy systems.. However, since there is a possibility that houses built before 1980 may overlap with houses that do not meet the new earthquake resistance standards, we used Table 235-2 of the "2018 Housing and Land Survey" to estimate the percentage of vacant houses built after 1981 by building age and prefecture, and excluded these from the houses for which installation is feasible.

Following the above approach, the building area of detached houses was estimated, excluding the space around the solar cell modules described in the previous section, the area of houses that do not meet the new earthquake resistance standards, and vacant houses. The results are shown in Fig. 9. The total area of potential installation locations across all orientations was estimated to be 1,169 km^2. Based on this result, the technical potential by orientation was estimated to be 49.2 GW (south-facing), 97.1 GW (east-west-facing), and 48.0 GW (north-facing). Of these, south-facing roofs, which generate the most electricity, accounted for about one-quarter of the total technical potential (Table 3).

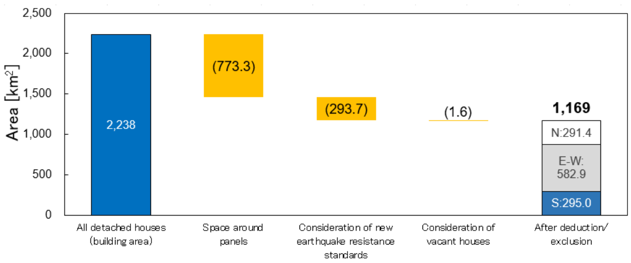


Fig. 9 Area of installation locations for detached houses, taking into account houses that do not meet the new earthquake resistance standards and vacant houses [km^2]

Table 3 Area of installation locations by orientation, and technical potential

Orientation	Area [km^2]	Technical potential [GW]
South	291.4	49.2
East-West	582.9	97.1
North	295.0	48.0
Total	1,169	194.4

5. Results of evaluation of technical potential in public and non-public facilities

5.1 Installation coefficient

The building areas of non-public and public facilities in the GIS database were 4,759 km^2 and 368 km^2, respectively. However, these areas represent the total roof areas and exclude roof spaces unsuitable for solar energy systems, such as those with water tanks and outdoor air conditioning units.

In previous studies,[3), 7), 12)] based on the concept of potential greening areas of model buildings,[15)] the percentage of the roof area excluding cooling tanks and water tanks was determined to be 86%, the remaining area excluding security spaces that must be secured was 58%, and 49.9% of all building roofs (installation coefficient 0.499) could have solar energy systems installed. However, in light of the increasing number of solar energy system installations in recent years, this study estimated the installation coefficient based on the estimated the installation coefficient using actual deployment data by building type, based on the JABMEE ZEB database containing information on buildings with solar energy systems installed, as well as data from the Ministry of the Environment,[19)] which conducted a sampling survey using satellite images. (Table 4)

For standard buildings such as offices and office buildings, the installation coefficients were estimated using the JABMEE ZEB database. This database contains information such as the addresses of buildings that are classified as Zero Emission Buildings (ZEB), Nearly ZEB, and ZEB Ready, as well as the rated output of solar energy systems, roof area, and area for the installation of solar energy systems. As of October 2024, data for 43 buildings have been included, of which data was extracted from 20 buildings that fall under the categories of "offices, etc." and "other" and which have only rooftop solar energy systems installed (excluding wall-mounted systems). The installation coefficient was then estimated based on the ratio of the area where solar energy systems have been installed to the roof area. For buildings with no indication of the solar energy system installation area, the installation area was estimated using Google Maps based on the building address.

Fig. 10 shows the frequency distribution of the installation coefficients in the JABMEE ZEB database. The results show that the average value of the installation coefficients for the 20 cases was 0.263 with a maximum value of 0.59, a minimum value of 0.02, and a standard deviation of 0.18. The buildings included in the database are based on the premise of being ZEBs, and it is likely that the maximum possible roof area is being utilized. In this study, the average installation coefficient value from the same database, 0.263, was applied

For non-standard buildings, the installation coefficient (0.079 to 0.388) was calculated by the Ministry of the Environment[19)] for each type of building based on Table 5.6-4, and used as a premise for the estimation.

Table 4 Samples used as the basis for calculating installation coefficients

Building	Sample used as the basis for calculating installation coefficients
Public offices	14 samples corresponding to "prefectural/municipal offices" and "public agencies, etc."
Hospitals	25 samples corresponding to "hospitals"
Schools	176 samples corresponding to "schools"
Defense facilities	31 samples corresponding to "other public facilities"
Housing complexes	2 samples corresponding to "housing complexes"
Factories	6 samples corresponding to "leisure facilities," "sports facilities," and "other facilities"
Leisure/Commercial facilities	
Accommodation facilities	
Markets	
Warehouses	
Gas stations	
Standard buildings	20 samples corresponding to "places of business, etc." and "other" in the JABMEE database

※ Estimated for non-standard buildings based on Table 5.6-4 (Ministry of the Environment[19)])

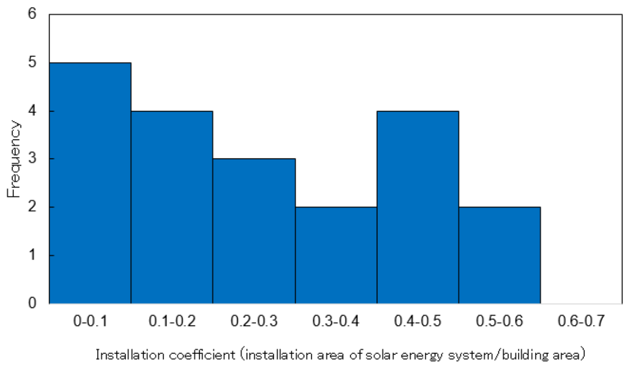


Fig. 10 Frequency of installation coefficients for buildings that correspond to "places of business, etc." and "other" in the JABMEE database

5.2 Technical potential that reflects the installation coefficients

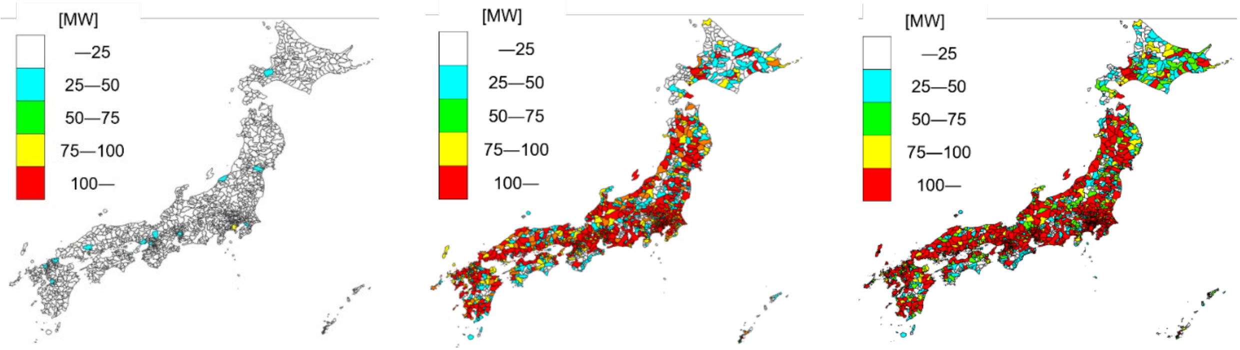
Table 5 shows the estimates for the area of potential installation locations for solar energy systems in public and non-public facilities, and their technical potential, calculated using the installation coefficients shown in the previous section. In the table, the left column shows the roof area estimated using the GIS database, and the middle column shows the results of estimations drawn up on the area of potential installation locations for solar energy systems and their technical potential, using installation coefficients based on the actual deployment of solar energy systems from the JABMEE database and other data sources. The right column shows the results of estimations drawn up for the area of potential installation locations and their installation capacity, using an installation coefficient of 0.499 based on the concept of potential greening area, as in previous research.

According to the results, of the total of 5,128 km^2 for non-public and public facilities estimated in the GIS database, the area was 1,236 km^2 when estimated based on the actual solar energy systems deployed. This was 137.2 GW when converted to technical potential. On the other hand, when estimation is carried out based on the conventional approach of potential greening area, the technical potential becomes 284.0 GW. Therefore, the technical potential estimated using the potential greening area approach is 146.8 GW larger than that based on actual solar system deployment.

Fig. 11 shows estimates for the technical potential for rooftop solar energy systems by municipality, using the installation coefficient based on the actual solar energy systems deployed. In addition to the public and non-public facilities discussed in this chapter, Fig. 11 also shows the area of potential installation locations (south and east-west installations only) in detached houses estimated in Chapter 4. First, focusing on public facilities where the mandatory installation of solar energy systems is already being considered in some areas, the installation capacity of each municipality is only a few tens of MW. This indicates that the installation capacity of solar energy systems is limited compared to non-public facilities and detached houses. On the other hand, for non-public facilities and detached houses, the results show that the installation capacity for many municipalities is more than 100 MW, suggesting that if the deployment of solar energy systems were expanded, it would be more important to introduce them in existing detached houses and non-public facilities.

Table 5 Area of potential installation locations in public and non-public facilities [km^2] and technical potential (installation capacity) [GW]

	Roof area [km^2]	Based on actual solar energy systems deployed			Based on potential greening area		
		Installation coefficient	Area of potential installation location [km^2]	Installation capacity [GW]	Installation coefficient	Area of potential installation location [km^2]	Installation capacity [GW]
Public offices	106	0.079	8.4	0.9	0.499	53	5.9
Hospitals	50	0.100	5.0	0.6		25	2.8
Schools	198	0.109	21.5	2.4		99	10.9
Defense facilities	15	0.071	1.0	0.1		7	0.8
Total for public facilities	368		36	4.0		184	20.4
Housing complexes	153	0.388	59.3	6.6	0.499	76	8.5
Factories	380	0.167	63.5	7.0		190	21.0
Warehouses	81	0.167	13.6	1.5		41	4.5
Leisure/Commercial facilities	249	0.167	41.6	4.6		124	13.8
Accommodation facilities	20	0.167	3.3	0.4		10	1.1
Markets	6	0.167	1.0	0.1		3	0.3
Gas stations	5	0.167	0.8	0.1		3	0.3
Standard buildings	3,865	0.263	1,017	112.8		1,929	214.1
Total for non-public facilities	4,759		1,200	133.2		2,375	264.0
Total	5,128		1,236	137.2		2,559	284.0



(A) Public facilities (B) Non-public facilities (C) Detached houses

Fig. 11 Technical potential for rooftop solar energy systems by municipality [MW] (estimated using installation coefficients based on actual solar energy systems deployed)

5.3 Technical potential by area of individual buildings

In order to understand the installation locations of public and non-public facilities in greater detail, the technical potential by roof area for each individual building was estimated and the results are shown in Fig. 12. In the figure, the horizontal axis shows the roof area per building obtained from the GIS database, and the vertical axis shows the estimated technical potential for each roof area range, using installation coefficients based on the actual solar energy systems deployed.

The results show the total technical potential for solar energy systems in buildings with roof areas between 0 to 99 m^2 and 100 to 199 m^2 is 60.4 GW, indicating that approximately half of the total technical potential for solar energy systems (137.2 GW) is concentrated in buildings with small roof areas. For buildings with roof areas of less than 199 m^2, even if solar energy systems were installed in ways that make the most of the building area, the installation capacity would be small, approximately 20 kW. Therefore, when encouraging the introduction of solar energy systems on the roofs of public and non-public facilities, it is important to install such systems on small-scale buildings.

According to Japan's Procurement Price Calculation Committee,[20] the system cost for a 500 to 1,000 kW solar energy system installed in 2023 is 147,000 yen/kW, in contrast with the cost of 251,000 yen/kW for a 10 to 50 kW facility. This is a discrepancy of approximately 1.7 times due to the difference in the scale of the systems. Currently, some large-scale solar energy systems of 1,000 kW or more do not receive support in the form of subsidies, such as in cases where the supply price in Feed in Premium (FIP) bidding is 0 yen/kWh[21]. However, with local regulations limiting the locations where solar energy systems can be installed on the ground, it will be necessary to reduce the installation costs even for systems of a smaller scale in order to promote the installation of solar energy systems on building roofs.

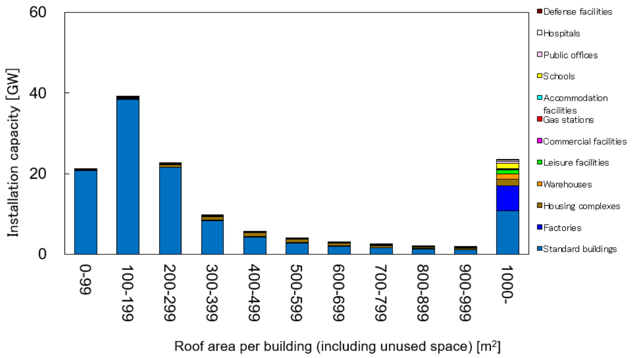


Fig. 12 Technical potential per building, by roof area [GW]

6. Conclusion

This study evaluated the technical potential of solar energy systems, taking into consideration local regulations and roof shapes. The findings and contributions of this study are summarized below.

Firstly, compared to the conventional approach to evaluating the technical potential for ground-mounted solar energy systems, this study demonstrates that the number of potential installation locations for ground-mounted solar energy systems is significantly reduced when areas that may be subject to local regulations are taken into consideration as a constraint. Until now, solar energy systems have been installed in places where there are concerns about disasters or the impact on the natural environment, such as forests and steep slopes. However, if the aim is to expand the introduction of solar energy in the future, it would be desirable to prioritize its installation on buildings. Furthermore, each restricted zone identified in this study is considered unsuitable for installing solar energy systems, regardless of whether local regulations are in place, regardless of whether regulations have actually been enacted. Therefore, this is expected to serve as basic information for the establishment of regulations by municipalities that do not currently have such regulations in place.

Secondly, with regard to detached houses, which are considered as one of the potential targets for the future expansion of solar energy system deployment, the technical potential for all orientations based on installation capacity is generally consistent with the evaluation results obtained in previous studies (167 to 201 GW).[7), 13)] However, when the orientation of the roof is taken into consideration, it was shown that the technical potential for south-facing roofs, which generate the most electricity, is only about one-quarter of the total, while the remaining half is for east-west-facing roofs. Therefore, when establishing national targets for the introduction of solar energy systems, it is necessary to account for the differences in power generation across orientations. Moreover, since the peak power generation differs depending on the orientation, the technical potential by orientation can also be used as basic information when conducting quantitative analysis using energy system models, etc.

Thirdly, by employing a method of estimating the feasible area for installing solar energy systems based on the actual solar energy systems deployed for both public and non-public facilities, this study showed that south-facing roofs, which generate the most electricity, account for only about one-quarter of the total technical potential, while approximately half is from east-west-facing roofs. When referring to the technical potential in establishing solar energy system installation targets, it is important to compare estimates based on different approaches. In addition, as approximately half of these potential installation locations are small-scale buildings, it is important to reduce installation costs for solar energy systems on buildings with small roofs.

In further refining the evaluation of technical potential for solar energy systems, one of the challenges is refining the installation coefficient. Current issues include the limited number of samples used to estimate the installation coefficient, the fact that buildings such as rooftop heliports without solar energy systems are not included in the sample, and the fact that it is based only on the actual deployment results of silicon-based solar energy systems that are in practical use. In order to evaluate the technical potential with greater precision in the future, it will be necessary to collect more current installation coefficients related to the calculation of the installation coefficient, as well as more examples of roofs.

While there are challenges in further refining the technical potential, it is expected that the risk of overestimating the technical potential of solar energy systems will be reduced by considering local regulations and roof shapes. Therefore, the approach to evaluating the technical potential presented in this study is expected to contribute to the establishment of solar energy promotion policies and deployment targets.

Acknowledgements

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Motivation Matters: How Diverse Reasons Enhance Household Energy Savings
– A Statistical Analysis Using Propensity Score Matching on Household CO_2 Microdata –

Junko Ogawa*・Yuko Hoshino**・Mika Goto ***

Abstract

This study examines the impact of energy-saving awareness on household energy consumption in Japan, using pooled data from the Ministry of the Environment's Household CO_2 Statistics (2020–2022). With Japan's "Green Growth Strategy" emphasizing the need for public awareness and engagement to achieve carbon neutrality, this research employed both multiple regression analysis and Propensity Score Matching (PSM) to estimate the energy-saving effects of various awareness motivations. First, distinct motivations, such as cost-saving, climate change, and peer influence, were analyzed individually, revealing limited energy-saving effects when these motivations exist alone. Second, combinations of these motivations showed significantly amplified impacts on energy savings, especially when cost-saving was combined with other motivations. Third, this outcome aligned with Self-Determination Theory (SDT), which posits that combining intrinsic (e.g., climate-related) and extrinsic (e.g., economic) motivations fosters stronger, more lasting behavior changes. The findings suggested that awareness-building strategies combining intrinsic and extrinsic motivations were likely more effective for encouraging sustained energy-saving behavior than approaches that rely solely on economic incentives. Furthermore, promoting diverse motivations could enhance household energy-saving behavior, providing valuable insights for energy policy design. This study also identified the potential applicability of PSM as a policy evaluation method for measuring the impact of energy policies.

Key words: Propensity Score Matching, Self-Determination Theory, Energy Conservation, Motivation, Behavior, Awareness

1. Introduction

The importance of public awareness with regard to decarbonization and energy conservation has frequently been emphasized in relation to achieving carbon neutrality goals. For example, the "Green Growth Strategy" (2021)[1] published by the government of Japan notes that it is essential for each citizen to understand the importance of carbon neutrality and take autonomous action to achieve it. In addition, the White Paper on Land, Infrastructure, Transport and Tourism in Japan, 2021 (2021) [2] states that awareness of long-term sustainable decarbonization on the part of society as a whole, while taking the diverse awareness of people into account, is important for efforts toward decarbonization. Furthermore, the 6th Strategic Energy Plan (2021) [3] also states that in order to achieve the 2050 carbon neutrality goals, it is necessary for not only companies and energy providers, but also each individual citizen to be aware of taking ownership of the decarbonized society and acting proactively. Accordingly, the importance of cultivating an awareness of decarbonization and energy-savings in the household sector is being increasingly recognized for the transformation of society toward carbon neutrality.

With regard to Japan's carbon neutrality targets, the Plan for Global Warming Countermeasures (2021) [4] sets forth the 2030 energy-derived CO_2 emissions targets for each sector, but as of FY2022, the achievement rate for the household sector is the farthest behind compared to other sectors, [5] and immediate action is required. In light of this situation, it is increasingly important to understand the state of energy-saving awareness, the drive behind purchases of energy-saving equipment and daily energy-saving behavior, and the impact it has on energy consumption.

On the other hand, much of policy and research on energy-saving to date has focused on hardware factors, such as highly energy-efficient equipment, and policy and research on so-called soft factors, such as energy-saving awareness, has been limited. Reasons for this include the belief that the energy-saving effect of the so-called soft factors is smaller than that of technological factors, and the fact that it is difficult to quantify human awareness, such as energy-saving awareness, meaning that data gathering primarily depends on questionnaires and interviews.

To address these issues, the Ministry of the Environment launched the Statistical Survey on CO_2 Emissions in the Household Sector (Household CO_2 Statistics) [6] in 2017 to identify opportunities for reduction in the housing sector and identify appropriate measures to do so. Under the Household CO_2 Statistics, a major questionnaire is issued to approximately 13,000 households throughout Japan each year. Because the use of the microdata for research purposes is allowed, it has broadened the scope of analysis that is possible. With the addition of questions regarding energy-saving awareness from FY2020 in particular, a platform for analyzing the relationship between energy-saving awareness and energy consumption in detail is becoming available.

In light of these developments, this research pooled the microdata from the Household CO_2 Statistics for the three-year period of 2020 through 2022 and examined the energy-saving effect of energy-saving awareness by employing both multiple

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regression analysis and Propensity Score Matching (PSM). PSM is a method that produces results similar to randomized experiments by performing pseudo-randomization on the observed data. The aim of this study is to examine the impact of energy-saving awareness on reducing energy consumption in the housing sector, and we use PSM in addition to multiple regression analysis to ensure the robustness of the analysis.

The results of this study confirmed that when there is a single motivation for energy-saving awareness, there are cases when there is an energy-saving effect and when there is not. However, when motivations are combined with others, even motivations for which an effect was not found in isolation, a significant energy-saving effect emerges. This result can be explained by the Self-Determination Theory (SDT) by Deci & Ryan (1985).[7] According to the SDT, people's behavior is stronger and more lasting when they have both intrinsic (e.g., to protect the environment) and extrinsic (e.g., to reduce utility costs) motivations. This study offers a new approach to conventional analysis of energy demand in that it examines the effects of the ambiguous concept of energy-saving awareness using large-scale data and new analytical methods. Furthermore, the new finding of this study, which quantitatively verifies that multiple energy-saving awareness motivations increase energy-saving effectiveness, is that it suggests a need to encourage diverse motivations rather than a single motivation in policies that promote energy-saving behavior in the household sector.

Chapter 2 of this paper examines the existing domestic and international literature that uses the Household CO_2 Statistics for the analysis of the energy-saving effect itself, and of the energy-saving effect of energy-saving awareness. We found that the primary research theme for analysis of the energy-saving effect using the Household CO_2 Statistics to date has been the technological aspects of energy-saving. Furthermore, while we found multiple studies that treated energy-saving awareness as one variable in the energy supply-demand model, research that analyzed energy-saving awareness in depth was limited. In Chapter 3, we organize the combination patterns regarding the motives for energy-saving awareness based on the Household CO_2 Statistics questions, and in Chapter 4, we analyze the verification of energy conservation effects for each motive pattern of energy-saving awareness using multiple regression and propensity score matching (PSM). Chapter 5 offers a summary and the conclusions of this study.

2. Previous Studies

2.1 Analysis of the Energy-Saving Effect Using the Household CO_2 Statistics

Research on energy demand analysis using the Household CO_2 Statistics has been carried out from diverse perspectives since it began in 2017. For example, Ishikawa et al. (2018, [8] 2024 [9]) examined factors behind CO_2 emissions nationwide and by region using multiple regression analysis to estimate the CO_2 emissions per household by municipality, while Iwafune et al. (2020) [10] estimated the potential for converting to electric household equipment and private cars and the associated CO_2 reduction effect, again using multiple regression analysis, suggesting that the adoption of energy-saving equipment may contribute to the reduction of household CO_2. Meanwhile, Shimomura et al. (2019-), [11] Mori et al. (2022), [12] and Ueno et al. (2022) [13] have each developed simulation models capable of detailed analysis of energy consumption and CO_2 emissions in the housing and transportation sectors by region, respectively. Nishio (2021) [14] analyzed the actual utility costs according to the period when houses were constructed using gradient boosting decision trees and SHAP values, and in a subsequent study in 2024, [15] examined the electricity consumption reduction effect for households that adopted HEMS using multiple regression analysis as well as propensity score doubly robust estimation. Hoshino et al. (2021) [16] organized the ratio of energy expenditure to household income and the energy burden rate by income group, broken down by region, and used multiple regression analysis to compare price elasticity by detailed region and household income in order to make policy recommendations based on those results.

Meanwhile, there also exist studies that have used the Household CO_2 Statistics to analyze energy-saving awareness. Washizu et al. (2020) [17] used multiple regression analysis to examine the number of household members, the age of the head of the household, and the rate of energy-saving behavior as factors influencing the energy consumption rate, confirming that energy-saving behavior significantly contributes to a reduction in energy consumption. Hoshino (2022) [18] also pointed out that one of the factors affecting the adoption of electric vehicles in households is the presence or lack of energy-saving awareness. Iwafune et al. (2021) [19] analyzed the changes in energy consumption over time according to life stage, noting that energy-saving awareness has an effect on CO_2 emissions reductions at each life stage. Accordingly, it is clear that energy-saving awareness has been subject to analysis as one element in analyzing energy demand.

2.2 Domestic Analysis of Energy-Saving Awareness

The following studies have been carried out to analyze energy-saving awareness in Japan. Kumeimura et al. (2024) [20]

conducted an online questionnaire targeting 1,500 residents of Tokyo, Kanagawa, Chiba, and Saitama prefectures to track changes in energy-saving awareness and behavior from September 2012 to August 2022 during the period following the Great East Japan Earthquake. While energy-saving awareness showed a declining trend from 2012 through 2016, it recovered to 2012 levels by 2022. Factors suggested for this change, a change that influenced energy-saving awareness, included rising utility costs, the situation in Ukraine, and pressure on the electricity and gas supply, in addition to the experience of the Great East Japan Earthquake itself. Incidentally, that study also included questions on the questionnaire regarding reasons for not saving electricity. The top responses from the 2022 survey were "physical discomfort" at 42.4% and "inconvenience in daily life" at 39.9%, with "physical discomfort" a common answer among the elderly and "inconvenience in daily life" common among younger segments. Hotta et al. (2023) [21] surveyed 19 households that were using an energy usage visualization system over an extended period, regarding their energy usage and user evaluation of the system, to ascertain changes in energy consumption and user awareness before and after adopting the system. The study showed that users found that the ability to regularly review feedback reports on home energy usage over fixed periods of time, along with comparative data, made the information more accessible. The study suggested that the ability to compare home energy usage to other homes or to past usage in the same home may lead to an awareness of energy-saving behavior. Hirayama et al. (2021) [22] conducted a randomized controlled trial (RCT) of 450,000 households in different regions and climates and examined the CO_2 saving effect of sending home energy reports (HER) using difference in differences (DID) analysis. The results showed an energy-saving effect in all regions for almost all months starting from the month when the HERs started to be sent. Furthermore, they examined the sustainability of the intervention effect in a follow-up study by comparing 80,000 households to which HERs were sent in the treatment group with a control group of 100,000 households determined through RCT. While the treatment group showed a slight elevation over the control group in terms of daily energy-saving awareness and intent after the reports were ceased, the difference was not statistically significant. Sasa (2018) [23] conducted a questionnaire on the implementation and continuation of energy-saving behavior among 134 female university students, while simultaneously measuring ambient temperature around the body, daily behavior, air conditioning usage, and self-reporting for 12 test subjects, to examine the effect on awareness and behavior from the receipt of energy-saving messages via social media. The results showed that energy-saving awareness was raised through receipt of the messages, confirming the effect of promoting energy-saving behavior. Takada et al. (2017) [24] combined a questionnaire with a survey of actual energy usage to analyze the relationship between parent and child energy-saving awareness and behavior and energy consumption in the home. Specifically, a questionnaire and survey on actual energy usage were conducted for 11 monitor households, and an intervention strategy was adopted for the surveyed households, including the presentation of energy-saving targets and reflection on daily life. While the presentation of targets did have some effect on increasing energy-saving awareness and behavior, it did not have an effect on actual consumption. The results suggested that reflecting on daily life led to a reduction in water consumption, but did not have a significant effect on gas and electricity consumption. Mori et al. (2016) [25] argued that it is possible to apply concepts of motivation from psychology to the cultivation of energy-saving awareness, and discussed the sustainability of energy-saving awareness by dividing motivations into extrinsic motivation, or evoking behavior through external factors such as reward and punishment, and intrinsic motivation in which behavior results from finding interest and enjoyment in the behavior itself. A field study was conducted by recruiting 69 households from the public residing in Asahikawa City to survey the effect of intrinsic motivations for energy-saving behavior on energy consumption over a one-year period. As a result of continuing the study for one year, it was found that the higher the intrinsic motivation, the lower the actual energy consumption and the higher the frequency of energy-saving behavior, according to self-reporting. The study also suggested that in order to promote sustainable energy-saving behavior, long term intervention is more effective than short-term temporary intervention. However, the study also pointed out that because there are many difficulties and limitations to maintaining constant external intervention, it was necessary for people to become able to maintain the behavior autonomously after the intervention ceases.

2.3 International Analysis of Energy-Saving Awareness

Similar studies on energy-saving awareness have been conducted outside Japan as well. Some of the leading studies thereof are discussed here. Pekez et al. (2024) [26] conducted workshops on energy efficiency and climate change at elementary schools in Serbia to increase environmental knowledge and track changes in environmental awareness across generations. As a result of the workshops on children's attitudes towards energy efficiency and climate change, and a survey conducted to measure the transfer of the knowledge gained from the children to their parental guardians to evaluate their changes in awareness before and after the workshop, the study suggested that raising awareness through knowledge may have a significant effect on the attitudes not only of the students, but their parents as well. Baidoo et al. (2024) [27] conducted a survey of 396 households from nine communities in the Cape Coast metropolitan region of Ghana, selected through random sampling, to analyze the relationship between household energy-saving practices and the level of energy-saving awareness education. The study showed that the principal factors influencing the selection of home appliances with high energy efficiency were the academic background, income level, expenditure, age of the head of the household, and the number of power outages experienced per day. The study offered an overall assessment that the level of energy-saving awareness in the household was low in Ghana, and suggested that this was caused not only by the inadequacy of energy-saving and conservation campaigns, but a lack of methods for communicating those to households effectively. The study recommended the implementation of energy literacy programs to raise awareness of practicing energy efficiency in the home by ensuring energy cost conservation, environmental protection, and climate change mitigation. Keller et al. (2021) [28] measured the effectiveness of a campaign using public service advertising on television and websites in Rocky Mountain City. First, they identified common hurdles to energy-saving using a focus group (40 people). They then examined changes in energy-related behavior through self-reporting by implementing a survey before and after implementing the campaign. The study used the Population Health Management (PHM) framework from health psychology for the energy-saving advertising campaign, including bringing awareness of the severity of energy waste, increasing self-efficacy (awareness that one has the ability to achieve a goal) to conserve energy, and increasing response efficacy (awareness that the presented method can help reduce risk) to conserve energy. As a result, the subjects showed a positive change towards replacing lightbulbs, and an increased motivation to lower thermostat temperatures, unplug devices, and turn off lights. The study noted that a follow-up study was required to examine the precise mechanism of the psychological processes, while pointing out, based on analysis, that both self-efficacy and response efficacy were important as elements required to transform behavior. Webb et al. (2013) [29] used the framework of Self-Determination Theory to analyze consumer motivation in energy-saving behavior in the home. An online survey was conducted for 200 consumers who were motivated by energy-saving in the home, and the relationship between the motivations and behaviors was analyzed using confirmatory factor analysis (CFA) and structural equation modeling (SEM). The study examined the effects of intrinsic and extrinsic motivations on energy-saving behavior, and the results suggested that the higher the intrinsic motivations of the consumer, the more proactive their energy-saving behavior.

2.4 Issues of Previous Studies and Positioning of this Study

In light of these previous studies, the following three points are offered regarding the issues with those studies and the positioning of the analysis in this study.

First, many of the previous studies on energy-saving awareness used specific, limited samples of several tens to several hundreds of subjects. This is likely because the standard approach has been to construct data through questionnaires and interview questions, because energy-saving awareness is a variable that cannot be quantified, but if those questionnaires and interviews are implemented on a national level, it would require an unreasonable amount of time and cost. With regard to this issue, it is believed that in Japan, the Household CO_2 Statistics survey conducted by the Ministry of the Environment, which covers a massive nationwide sample exceeding 10,000 subjects each year, may compensate for this deficiency to some degree.

Second, we found that the main research theme of previous studies that analyzed the energy-saving effect using the Household CO_2 Statistics tended to be the technological aspects of energy-saving. While we found multiple studies that treated energy-saving awareness as one variable in the energy supply-demand model, research that analyzes energy-saving effects in depth was limited.

Third, while the range of analytical methods available is expanding because analysis using large scale microdata sets has been made possible by the Household CO_2 Statistics, and some studies have attempted demand analysis using new approaches based on machine learning, to date, the trend has continued to be analysis primarily based on multiple regression analysis for both measuring the energy-saving effect and energy demand analysis.

In light of these three issues, this study pooled the data from the Household CO_2 Statistics for the three-year period starting in 2020, when the questions on energy-saving awareness were added, until the latest year to measure the energy-saving effect of energy-saving awareness using a microdata set of roughly 30,000 subjects. Specifically, we examined the effect of energy-saving awareness patterns with a variety of motivations on energy consumption using multiple regression analysis, while adopting propensity score matching (PSM) as a new analytical method. PSM is a method that is considered to be superior at eliminating confounding bias, able to produce results similar to randomized controlled trials by using quasi-randomization with observational data. The use of PSM in addition to the standard multiple regression analysis ensures the robustness of the measurements of the energy-saving effect on fluctuating energy-saving awareness.

3. The Household CO_2 Statistics

3.1 Overview of the Household CO_2 Statistics

The Survey on the Actual Conditions of Carbon Dioxide Emissions from Residential Sector (Household CO_2 Statistics) is a general statistical survey carried out by the government of Japan, launched by the Ministry of the Environment in 2017 to track the state of energy consumption and CO_2 emissions in the household sector. The survey covers roughly 13,000 households each year, including an investigator survey based on random sampling from the Basic Resident Registry, and an online monitor survey selected from survey monitors registered with private companies. The survey gathers a wide variety of data on household demographics, home characteristics, and energy consumption.

One of the characteristics of the Household CO_2 Statistics is the ability to handle detailed energy consumption data based on the factors and energy usage background that differ from household to household. For example, in addition to physical characteristics such as family composition, annual household income, and age of the home, the survey also began including questions on the presence or lack of energy-saving awareness from the 2020 survey.

3.2 Motivational Patterns for Energy-Saving Awareness

As noted in section 3.1, a question on energy-saving awareness was added to the Household CO_2 Statistics from the 2020 survey. The specific question that was added is, "Does the following description apply to anyone in your family (including you)? *Reply "Yes" if there is even one person to whom the description applies." There are five answer choices for this question.

1. *Anyone who is mindful of energy-saving to save on utility costs.*
2. *Anyone who is mindful of energy-saving for global warming.*
3. *Anyone who is mindful of energy-saving because other households are doing so.*
4. *Anyone who is mindful of energy-saving for a reason other than the above.*
5. *Anyone who is mindful of energy-saving without a clear reason.*

Note that being "mindful of" energy-saving for a variety of reasons means always keeping it in mind or being aware of or cautious of it, and this study has abbreviated the term as "energy-saving awareness" for the sake of simplicity.

Also, because multiple answers are allowed for choices 1 through 5, many combinations of those choices are conceivable, such as households that select both "to save on utility costs" and "for global warming," or households that select only "because other households are doing so." Due to the structure of this question, households can be categorized into multiple patterns based on the energy-saving awareness of each (Table 1), and there are households that practice energy-saving for multiple reasons, households that practice energy-saving for one reason, and even households without energy-saving awareness. Therefore, this study will analyze the energy-saving effects for each combination of energy-saving awareness reasons. Note that for choice 4, "a reason other than the above," and choice 5, "without a clear reason," the motivations are unclear and difficult to interpret. Households that include those reasons are very likely to include a wide range of reasons depending on values and situation, which tends to obscure the results of the analysis. Accordingly, this study will focus on analyzing the effects of the three motivations, which are clearer, including "to save on utility costs," "for global warming," and "because other households are doing so." Note that for this study, the treatment group, consisting of households with energy-saving awareness with any of the above three reasons, is called "households with energy-saving awareness," while the control group of households without any of the above three reasons is called "households without energy-saving awareness." This is because even if a given household is carrying out energy-saving behaviors, a clear energy-saving awareness cannot be confirmed if they do not fall under one of the above three reasons. In summary, categories B1 through B7 on the table represent the treatment group, while category B8 represents the control group.

Table 1: Energy-saving awareness motivations Combination Patterns

Group No.	Description	Utility costs	Global warming	Other households	Combination Pattern	Observations
B1	Mindful of energy-saving to save on utility costs	1	0	0	100	6,755
B2	Mindful of energy-saving for global warming	0	1	0	010	275
B3	Mindful of energy-saving because other households are doing so	0	0	1	001	42
B4	All three reasons are present (utility costs, global warming, other households)	1	1	1	111	9,472
B5	Two reasons (utility costs, global warming)	1	1	0	110	7,732
B6	Two reasons (utility costs, other households)	1	0	1	101	628
B7	Two reasons (global warming, other households)	0	1	1	011	73
B8	None of the three reasons (utility costs, global warming, other households)	0	0	0	000	3,985

Source: Created from the Ministry of the Environment's Household CO_2 Statistics [6]

4. Methods for Analyzing the Measurement of the Energy-Saving Effect

4.1 Overview of the Analysis

This chapter will quantitatively analyze the effect on energy consumption in the household sector of each combination of energy-saving awareness motivations, as shown in Table 1. The data used in the analysis is microdata pooled from the Household CO_2 Statistics for the years 2020 through 2022, during which the question on energy-saving awareness was included, including a total of 28,962 samples of the 29,298 responses after subtracting the 336 samples for which the answers were unclear. Furthermore, samples were excluded from analysis when there were missing values in explanatory variables, resulting in a total of 23,722 samples that were actually used.

Previous studies on energy demand analysis widely use multiple regression analysis, so this study first implements multiple regression analysis using the energy consumption per household as the explained variable. The advantages of using multiple regression analysis are that trends can be understood for the data overall by using all samples, and the ability to measure the effects of individual explanatory variables on the explained variables when multiple explanatory variables are used. On the other hand, there are cases in which the effects of confounding factors cannot be adequately controlled. Therefore, after using multiple regression analysis, we used propensity score matching (PSM), which is superior at controlling the effects of confounding factors, to estimate the amount of energy-saving effect of energy-saving awareness to ensure the robustness of the analysis.

4.2 Multiple Regression Analysis

For the analysis, we use a standard multiple regression model shown in (1).

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n + \epsilon \quad \ldots(1)$$

Here, Y is the energy consumption per household, while X_1 through X_n are dummy variables representing energy-saving awareness and the household attributes (floor area, household income, family composition, etc.). β_0 is the intercept, β_1 through β_n are the regression coefficients for each explanatory variable, and ϵ is the error term. We selected the explanatory variables to use by referring to structural energy consumption analysis for the household sector in previous studies [15][17] while considering such factors as statistical significance, the sign, and the avoidance of multicollinearity. Note that since energy demand is determined through the complex interaction of numerous elements, this model includes variables thought to be important from the standpoint of understanding the household energy demand structure, while considering the overall fit with the model, rather than only considering the statistical significance of each variable in isolation. Energy consumption per household was used as the explained variable, while dummy variables for each energy-saving awareness pattern for the "without energy-saving awareness" group used as the control group, were used as explanatory variables. Factors were included that are thought to have an effect on energy consumption, such as household income, family composition, and housing type, as shown in Table 2.

4.3 Propensity Score Matching Analysis

Propensity score matching (PSM) was proposed by Rubin and Rosenbaum in 1983 as a method to estimate causal effects by adjusting covariates in observational studies where random assignment is difficult and confounding is likely to occur [30]. PSM estimates the probability, or propensity score, that each subject has of receiving a treatment, and then matches the individuals in the treatment and control groups with similar propensity scores, thereby mimicking the conditions of a random controlled trial. We believe that this approach reduces confounding bias and allows for estimation of the effect of energy conservation awareness itself more precisely.

The procedure of analysis is as follows. First, the propensity score is calculated using the logit model in formula (2) and using each of the seven groups in Table 1 with energy-saving awareness (the treatment group) as the explained variables.

$$\mathrm{P(T = 1 \mid X)} = \frac{\mathrm{e}^{(\beta_0+\beta_1X_1+\beta_2X_2+\cdots+\beta_nX_n)}}{1+\mathrm{e}^{(\beta_0+\beta_1X_1+\beta_2X_2+\cdots+\beta_nX_n)}} \quad \ldots(2)$$

P(T=1 | X) in the above equation denotes the probability that the sample belongs to the treatment group (T=1), X'β is the linear combination of the covariate X and the corresponding regression coefficient vector β, and e is the Napier number. In this study, a variety of energy-saving awareness patterns were set as the treatment groups, and with reference to the method used by Nishio (2024) [15], the variables used for the multiple regression analysis in 4.2 were used as covariates with the exception of household energy consumption, which is used as the explained variable for propensity score matching.

Then, each treatment group sample was matched with the control group sample with the closest propensity score. This study used the nearest neighbor matching method to match the closest samples in the treatment and control groups. The advantage of using this method is that it limits the complexity of the calculations and enables comparison of samples with similar characteristics in the treatment and control groups, making the results easier to interpret. Furthermore, the following two processes were performed to increase the robustness of the analysis. First, a caliper was set as an upper limit (the maximum allowed distance between the propensity scores of samples to be matched), and matching was not performed when the given distance exceeded the caliper. The caliper distance was set at 0.25 times the standard deviation used by Rosenbaum & Rubin (1985) [31]. Second, we established a common support range using the conditions shown in formula (3) below and excluded samples outside the range.

$$\min(\mathrm{P(T = 1 \mid X)}) < \mathrm{P(T = 0 \mid X)} < \max(\mathrm{P(T = 1 \mid X)}) \ldots(3)$$

Here, P(T=1|X) and P(T=0|X) are the propensity scores for the treatment and control groups, and the common support range is defined as the overlap between the two ranges. Furthermore, this study evaluated the balance of each covariate based on the standardized mean difference (SMD), shown in formula (4), in order to confirm whether the covariates were appropriately balanced between the treatment and control groups.

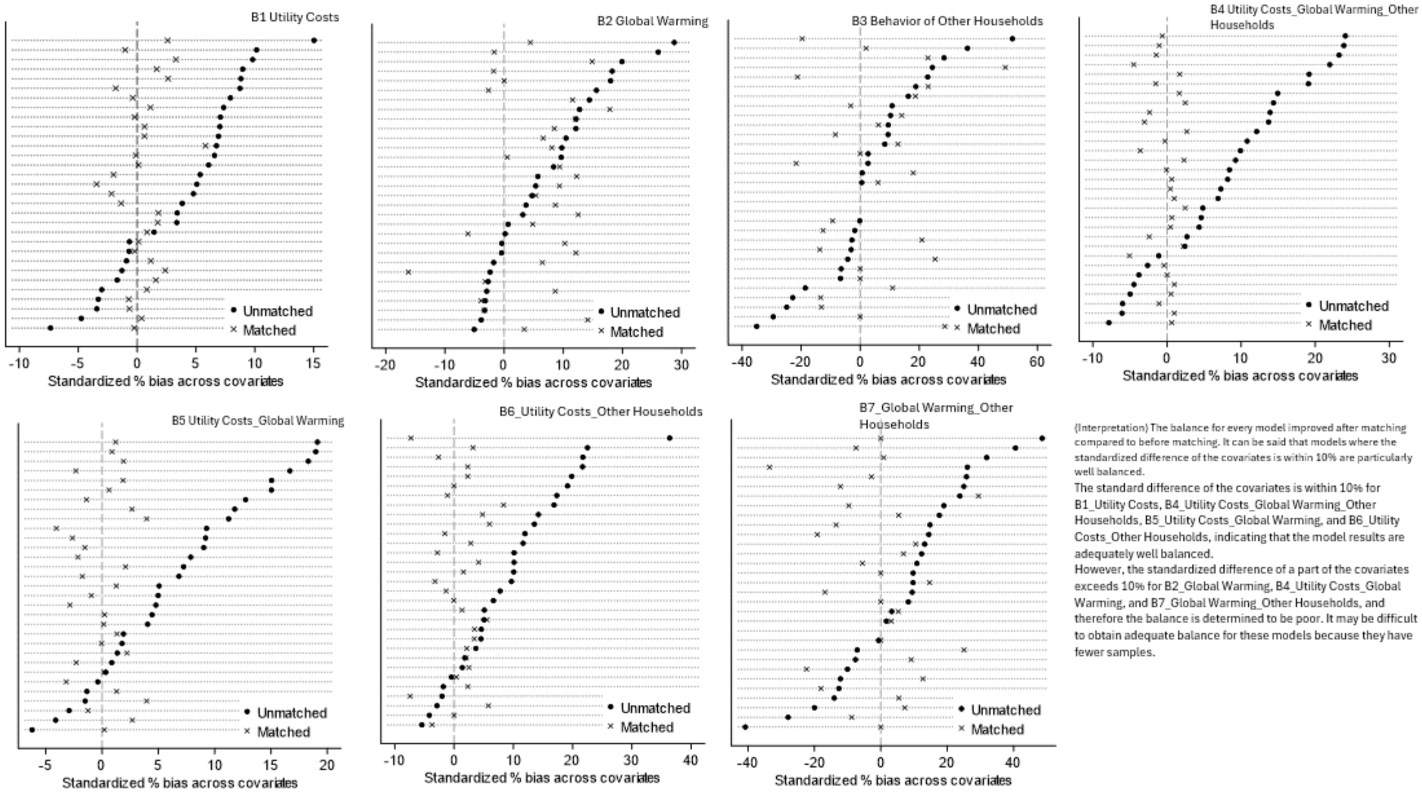

Figure 1: Standardized differences in covariates per model (unadjusted, adjusted)

$$SMD = \frac{\bar{X}_T-\bar{X}_C}{\sqrt{\frac{\sigma_T^2+\sigma_C^2}{2}}} \quad \ldots(4)$$

Here, $\bar{X}_T$ and $\bar{X}_C$ are the average values for the treatment and control groups, while σ_T^2 and σ_C^2 are the standard deviations for the treatment and control groups. In accordance with Rosenbaum & Rubin (1985), [31] we determined each covariate to be balanced when the SMD was 0.1 or smaller, and to evaluate the overall model, we evaluated whether the covariates of the treatment and control groups were evenly distributed using a standard where the mean difference in propensity score for the

compared to households without energy-saving awareness.

First, an effect of -2.92 GJ/household (an 8.4% energy savings over the average annual household energy consumption of 34.9GJ,

Table 2: Estimation Results of Multiple Regression Analysis

Variable	Unit	Description	Regression coefficient	Standard Error (SE)
Constant term		Regression constant	178.9***	17.58
Household income	1K yen	Annual household income	0.005***	0.000
Residents	People	No. household members	6.121***	0.152
Weekdays present at home	Hours	Days/weeks present at home on weekdays	0.293***	0.053
Year built	Years	Year house built	-0.089***	0.009
Floor area	m²	Residential floor area	0.036***	0.004
No. TVs	Units	No. TVs	1.061***	0.128
No. refrigerators	Units	No. refrigerators	3.826***	0.259
No. AC	Units	No. AC	1.469***	0.101
[Energy-saving awareness dummy] Standard: B8_Without energy-saving awareness				
B1_Utility costs	1=applicable 0=not applicable	For utility costs	-2.923***	0.351
B2_Global warming		For global warming	-1.859	1.219
B3_Other households		Other households	1.789	2.405
B4_Utility costs_Global warming_Other households		Utility costs, global warming, other households	-4.378***	0.344
B5_Utility costs_Global warming		Utility costs, global warming	-3.393***	0.349
B6_Utility costs_Other households		Utility costs, other households	-3.721***	0.794
B7_Global warming_Other households		Global warming, other households	1.269	3.243
[Household attribute dummy]				
Member under 19	1=applicable 0=not applicable	Are there any members under the age of 19?	-1.888***	0.364
Member over 65		Are there any members over the age of 65?	0.750**	0.253
Detached home		Detached home?	4.094***	0.297
Form of ownership		Type of home ownership (1=owner-occupied, 0=rental)	1.070***	0.299

Variable	Unit	Description	Regression coefficient	Standard Error (SE)
[Energy-saving equipment dummy]				
W/wo double sash	1=applicable 0=not applicable	Is there double sash?	0.292	0.222
W/wo HEMS		Is HEMS installed?	-0.483	0.686
W/wo storage batteries		Is there a storage battery?	1.622**	0.798
W/wo residential fuel cell		Is there a residential fuel cell?	17.15***	1.427
W/wo solar power generation system		Is there a solar power system?	-6.441***	0.488
W/wo solar heating system		Is there a solar heating system?	-2.495**	1.188
W/wo heat pump water heater		Is there a heat pump water heater?	-6.095***	0.336
W/wo central heating		Is there central heating?	12.45***	0.858
All-electric		Is the home all-electric?	-6.260***	0.307
[Region dummy] Standard: Kanto Koshin				
Hokkaido	1=applicable 0=not applicable	Do they live in Hokkaido?	23.38***	0.618
Tohoku		Do they live in the Tohoku region?	11.31***	0.448
Hokuriku		Do they live in the Hokuriku region?	6.445***	0.444
Tokai		Do they live in the Tokai region?	-2.906***	0.343
Kinki		Do they live in the Kinki region?	-0.781**	0.323
Chugoku		Do they live in the Chugoku region?	-2.361**	0.338
Shikoku		Do you they in the Shikoku region?	-3.504***	0.357
Kyushu		Do you they in the Kyushu region?	-4.651***	0.324
Okinawa		Do you they in Okinawa?	-7.618***	0.357
[Year dummy] Standard: 2020				
2021 dummy	1=applicable 0=not applicable	Dummy variable for 2021	-1.680***	0.255
2022 dummy		Dummy variable for 2022	-2.280***	0.236

Multiple regression model statistics F= 411.33, R^2= 0.5235, RMSE= 14.906, number of observations= 23,722, VIF= 1.56

***p<0.01: Significance level 1%, **p<0.05: Significance level 5%, *p<0.1: Significance level 10%.

treatment and control groups (value B) was 25% or less, and the variance ratio of the propensity scores for the treatment and control groups was within the range of 0.5 to 2 (value R). Figure 1 shows the change in bias before and after matching for the standardized mean differences for each model. The balance has been improved after adjustment for all models after the matching adjustment, compared to before matching.

After the preparations above, the average treatment effect on the treated (ATT) was obtained using formula (5).

$$ATT = \frac{1}{N_T} \quad \sum_{i \in T}\left(Y_i^T - Y_i^C\right) \quad \ldots(5)$$

Here, i ∈ T denotes that i is a sample belonging to the treatment group (T), N_T is the number of samples in the treatment group, Y_i^T is the energy expenditure of sample i in the treatment group, and Y_i^C is the energy expenditure of the matched control group sample i. The ATT represents the mean difference in energy expenditure between the matched treatment and control groups. In other words, it indicates the amount of energy-saving promoted by energy-saving awareness.

4.4 Estimation Results

Table 2 shows the multiple regression analysis for each energy-saving awareness combination, while Table 3 shows the results of the propensity score matching (PSM). As shown in formula (5), the ATT (average treatment effect on the treated) used here is an indicator of the extent to which energy-saving awareness contributes to a reduction in energy consumption on the part of households with energy-saving awareness, in the treatment group,

the same applies below) was confirmed via multiple regression analysis, and an effect of -3.28 GJ/household (9.4%) was confirmed via PSM, for group B1 with the single motivation of “to save on utility costs,” demonstrating that economic motivations are a factor in promoting energy-saving behavior. However, no effect of statistical significance was found via both multiple regression analysis and PSM for group B2, with the single motivation of “for global warming,” and for group B3 with the single motivation of “because other households are doing so.”

The cases of particular interest are those that combine multiple energy-saving awareness motivations. For example, no energy-saving effect was found for the single motivation groups B2 (global warming alone) and B3 (other households alone), but the energy-saving effect was confirmed to have been amplified when combined with B1 (utility costs alone). Specifically, the energy-saving effects confirmed for group B4 (the case combining utility costs, global warming, and other households) were -04.38 GJ/household (12.5%) via multiple regression analysis and -5.01 GJ/household (14.3%) via PSM, demonstrating a significant rise in the energy-saving effect even when compared to the only single motivation group, B1 (utility costs alone), that showed a statistically significant effect. Similarly, the other combined energy-saving awareness patterns tend to produce an energy-saving effect when multiple motivations are combined. For example, the effects were -3.39 GJ/household (9.7%) via multiple regression analysis and -2.89 GJU/household (8.3%) via PSM for group B5 (combining utility costs and global warming), and -3.72 GJ/household (10.6%) via multiple regression analysis and -4.58 GJ/household (13.1) via PSM for group B6 (combining utility costs and other households), confirming an expansion of the effects.

Accordingly, these results confirmed the energy-saving effect of energy-saving awareness via both multiple regression analysis and PSM, and we learned that the effect on reducing energy consumption tended to increase, particularly when multiple motivations are combined.

and the ability to understand the effects of individual explanatory variables on the explained variables when multiple explanatory variables are used at the same time. However, because it is necessary to assume the correct relationship between the outcome (explained variable) and the covariates (explanatory variables), it may not be possible to accurately control for confounding factors in the presence of nonlinear relationships or interactions between covariates. In comparison, PSM focuses on treatment assignment rather than outcome modeling, making it a method that mitigates the influence of confounding factors by making the distribution of covariates similar in the treatment and control groups. Accordingly, PSM is well suited for measuring the effects of specific policy, and the use thereof in the analysis of the effects of future energy policy can be expected to increase.

Table 3: Estimation Results of Propensity Score Matching

Items	B1 Utility costs	B2 Global warming	B3 Other households	B4 Utility costs Global warming Other	B5 Utility costs Global warming	B6 Utility costs Other households	B7 Global warming Other households
After matching							
Treatment group mean	35.60	36.95	44.08	35.41	35.41	37.56	41.96
Control group mean	38.88	44.24	34.64	40.41	38.75	42.14	41.88
Average treatment effect (ATT)	-3.275***	-7.296**	9.442*	-5.012***	-2.893***	-4.581**	0.079
Standard Error (SE)	0.683	3.414	4.818	0.6801	0.6877	1.723	5.052
PsR2	0.002	0.035	0.358	0.002	0.003	0.014	0.197
Mean Bias	1.5	6.1	15.5	1.6	1.8	3.1	10.9
B value	10.2	44.8	134.4	11.2	12.5	28.2	112.2
R Value	1.07	1.16	1.44	1.06	1.07	1.15	1.16
Balance test	Good	Bad	Bad	Good	Good	Somewhat good	Bad
(Reference) Before matching							
Treatment group mean	35.74	37.06	44.08	35.41	35.43	37.50	41.96
Control group mean	38.88	36.74	36.6	36.74	36.74	36.74	36.67
Average treatment effect (ATT)	-1.124**	0.322	7.483*	-1.326***	-1.31**	0.7601	5.287
Standard Error (SE)	0.492	1.587	4.087	0.46	0.481	1.095	3.023
PsR2	0.023	0.042	0.098	0.033	0.025	0.037	0.115
Mean Bias	5.6	8.4	14.2	9.9	7.5	10.5	17.1
B value	36.2	55.3	111.9	44.6	38.4	50.4	114.3
R Value	0.97	1.51	0.66	0.99	1.19	1.11	0.78
Balance test	Bad	Bad	Bad	Bad	Bad	Bad	Bad

***p<0.01: Significance level 1%, **p<0.05: Significance level 5%, *p<0.1: Significance level 10%, achieving statistical significance.

Note: While value B in the results for group B6 slightly exceed the standard, the overall matching quality was categorized as "somewhat good" because all other values were good.

5. Conclusions

5.1 Analysis Results of This Study and Discussion Thereof

The following is a summary and discussion of the results obtained in this study.

First, the results suggest the potential of utilizing propensity score matching (PSM) in the analysis of energy demand. Similar analytical methods tried to date include inverse probability weighting using propensity scoring by Hirayama et al (2021) [32] for measuring the effects of adopting HEMS, and a double robust (DR) method using propensity scoring by Nishio et al (2024) [15], but the examples of applying PSM to the analysis of energy demand have been extremely limited. One reason for this may be the difficulty of collecting detailed data on energy demand. However, this study was able to apply PSM analysis because the use of an adequately large amount of microdata for research purposes was made possible thanks to the Study Group on Utilizing the Statistical Survey on CO_2 Emissions in the Household Sector of the Japan Society of Energy and Resources. The advantages of using multiple regression analysis are that trends can be understood for the data overall by using all samples,

Second, from the standpoint of the energy-saving effect of energy-saving awareness, the use of the two different analytical methods of multiple regression analysis and propensity score matching (PSM) demonstrated that an energy-saving effect from energy-saving awareness was verified from both methods.

Third, it was confirmed that the energy-saving effect was greater when multiple motivations for energy-saving awareness overlapped compared to when there was a single motivation. The results of this study confirmed that while individual motivations, such as "for global warming" or "because other households are doing so," did not show a statistically significant effect, combination with other motivations such as "to save on utility costs" produced a statistically significant energy-saving effect, and furthermore, that effect tended to exceed the effects of single motivations.

Fourth, we believe that the effects produced by the overlapping energy-saving awareness motivations observed in this study can be explained by Self-Determination Theory (SDT). [7] SDT is a theory for understanding motivations for human behavior proposed by psychologists Edward L. Deci and Richard M. Ryan in 1985. This theory explains why people engage in certain behaviors and how these behaviors are sustained, and focuses on two types of motivations: intrinsic motivation and extrinsic motivation. Dividing energy-saving awareness into its extrinsic and intrinsic motivations in accordance with SDT reveals the differences in the impact each has on energy-saving behavior. While extrinsic motivators, such as reward and punishment, bring about short-term behavioral transformation in consumers, that behavioral transformation typically only occurs in the form of backlashes or temporary compliance, and when economic incentives decline, behavior tends to revert to its former state (Kaiser et al, 2020). [33] For example, the energy-saving effect of increased energy costs through energy taxes in the household sector, where price elasticity is low, is not only limited (Hoshino et al, 2021) [16], but is also unlikely to lead to sustained energy-saving awareness (Mastria et al, 2023). [34] In comparison, intrinsic motivations are highly likely to trigger sustained behavioral transformations over the long term. Since intrinsic motivations are rooted in contributing to environmental protection and a sense of ethical responsibility, and behavior is sustained through fulfillment of the sense of autonomy and competence, an increase in intrinsic motivations evokes autonomous behavior without dependence on external pressure, so even when external economic incentives are removed, energy-saving behavior is more likely to be maintained (Silvi et al, 2021). [35] This suggests that, accordingly, it is difficult to sustain behavioral transformation purely through reward and punishment based extrinsic motivations, such as economic measures, in energy-saving policy.

As described above, it is likely that the potential for promoting effective and sustained energy-saving behavior can be increased by balancing extrinsic and intrinsic motivations in accordance with SDT (Duong et al, 2023). [36] A multifaceted approach from the standpoint of multiple motivations, including extrinsic and intrinsic motivations, is suggested by the results of this and previous studies, particularly regarding measures to cultivate an energy-saving awareness as the drive behind the adoption of energy-saving technology and energy-saving behavior, and measures to sustain that awareness.

5.2 Directions for Future Research

This study primarily analyzed the effects of the types and combinations of energy-saving awareness motivations on the reduction of energy consumption. The results suggested that, in addition to superficial aspects, such as the reasons and motivations behind energy-saving awareness, an awareness of the type of psychology that gives rise to that awareness is also an important clue in considering measures to cultivate sustainable energy-saving awareness among people. Particularly, it is likely that using self-determination theory (SDT) to categorize energy-saving motivations would be useful. On the other hand, there is a gradation between extrinsic and intrinsic motivations, and there are cases when it is difficult to divide them into clear categories. For example, a particularly large energy-saving effect was obtained through PSM analysis when combining “other households” with “to save on utility costs,” and it is possible that this can be categorized as both intrinsic and extrinsic motivation. It is possible that the social approval acquired through the “desire to fit in,” as an extrinsic motivation, combined with the sense of competence from believing that “if other households can do it, so can I” as an intrinsic motivation, brought about the motivation to tackle the challenge of saving energy. One issue for the future is a more in-depth analysis of energy-saving awareness that includes such diverse motivations.

Accordingly, for future research, an analysis of the specific behavioral transformations brought about by a wide variety of energy-saving awareness motivations is called for. For example, by clarifying how specific energy-saving awareness patterns influence such specific behaviors as practicing electricity conservation in the home, the purchase of high energy-efficiency equipment, or promoting the use of renewable energy, it will be possible to propose more specific and effective measures. Conducting factorial analysis of which energy-saving awareness motivation promotes behavioral transformation the most in particular, could serve as a reference for planning measures to evoke energy-saving behavior effectively. Furthermore, a deeper exploration of the relation of socioeconomic factors such as family composition, household income, region of residence, and educational level as factors behind energy-saving awareness would enable planning approaches geared toward specific regions and household characteristics.

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Voluntary Carbon Credit Trends (October-December 2024) Initiatives to Improve Credit Quality

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1. Introduction

AlliedOffsets, which provides carbon market data for the voluntary carbon market, concluded in their report that "2024 was a year of focus on quality.[1]" For example, the Integrity Council for the Voluntary Carbon Market (ICVCM), an organization that sets and evaluates quality standards for voluntary carbon credits, announced the first carbon credit methodologies that meet the Core Carbon Principles (CCPs) on June 6, 2024.[2]

Trends to ensure credit quality were also observable in the fourth quarter of 2024, as shown by the following events: 1. The Verified Carbon Standard (VCS) updated the methodology for requantification, 2. International exchange regulators issued guidelines for the quality of credits, and 3. An interim report on transition credits for aiming at the early phase-out of coal-fired power plants was published. These trends are crucial for ensuring the high integrity and reliability of credits, which will lead to new demand.

2. Verra released the VCS methodology change and requantification procedure[3]

On October 16, 2024, Verra announced a Verified Carbon Standard (VCS) methodology update and permission for the requantification procedure.[4] Verra is a carbon credit registry that manages the VCS, which is the biggest standard in the carbon market and is based on market share. Verra is also responsible for reviewing and verifying projects developed and implemented by project developers under the VCS framework.

This update allows for the requantification of previously issued Verified Carbon Units (VCU) in accordance with the latest methodology. It also permits the retroactive application of updated methodologies to carbon reduction and removal figures that were originally calculated using previous methodologies during prior verification periods. Upon Verra's approval of the requantification process, VCU holders will have the option to reconcile the number of credits previously issued with the quantity recalculated under the revised methodology.

The methodology update was driven by regulatory developments, environmental considerations, and improvements in quantification techniques. This announcement enables the application of the updated methodology to VCUs issued under earlier standards. Doing so aligns project outcomes with current monitoring and verification practices, ensuring more accurate reporting of carbon reductions and removals. It is important to note that the application of these updates is optional and not required for all project proponents.

The requantification procedure is a significant advancement, as it enhances the transparency, reliability, and

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1 AlliedOffsets. (2024). "VCM 2024 Review: Emerging Trends for 2025."

2 We also published a report on this topic: Kojima, Mai, Soichi Morimoto, and Keita Katayama. (2025). "Voluntary Carbon Credit Trends (April-June 2024): New Guiding Principles for Carbon Credit Market." *IEEJ Energy Journal* 20 (1): 12-14.

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4 VERRA. (2024, October 16). *Verra Releases Methodology Change and Requantification Procedure*. https://verra.org/verra-releases-methodology-change-and-requantification-procedure/.

accuracy of carbon credit valuations. This change has been introduced for the following three reasons:[5]

- As mentioned above, the latest methodology is applied to the previously verified carbon reductions/removals.
- A project proponent must apply this change when they wish to apply the Integrity Council for Voluntary Carbon Markets (ICVCM) Core Carbon Principles (CCP) labels to previously issued VCUs.
- Projects with mixed carbon reductions and removals can be updated to the latest methodology so that carbon reductions and removals can be calculated separately.

The procedures for applying this change are as follows:エラー! ブックマークが定義されていません。

i Notices from project proponents to Verra; the project proponents will notify Verra of their intention to make a requantification approval request by email

ii Notices from Verra to VCUs owner; Verra will display the requantification form, project details, and vintage information on the Verra website, and Verra notices to the owners who have valid VCUs.

iii Preparation for requantification; the project must conform with all the requirements of the new methodology and meet all applicability conditions when applying the new methodology. Based on the selected methodology, project proponents will re-evaluate baseline scenarios and validity (integrity, additionally, permanence, etc.), and requantify the amount of carbon reductions and removals. After the re-verification, the valid projects will be requantified and a report of the results will be issued.

iv Evaluation by the validation/verification bodies (VVB[6]); VVB will evaluate the report issued at the former step.

v Evaluation by Verra; Verra will evaluate the report and the results of the evaluation by VVB.

vi Adjustment of the number of VCUs; if procedures are confirmed, Verra notifies the project proponents and VCUs holders, whose VCUs will be adjusted to the number of VCUs issued. (If VCUs holders hope to implement the CCP label, they must apply ICVCM.)

Even though the Verified Carbon Units (VCUs) have been validated in accordance with methodologies used in previous versions, these VCUs remain valid. Furthermore, VCU holders retain the right to reject the results of requantification, which may alter the number of credits held. Requantification results are valid for five years. However, VCUs that have already been retired are not subject to this process.

The author contemplates that these changes will enhance the credibility of the VCS and contribute to an increase in credit prices. As reported in the press,[7] the credibility of nature-based voluntary carbon credits has been questioned for several years, leading to a reduction in the issuance volume and a decline in credit prices. In this context, Verra's announcement of ICVCM's consistency with CCPs, as described in the article,[8] should lead to an

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[5] VERRA. (2024). "VCS Methodology Change and Requantification Procedure." https://verra.org/wp-content/uploads/2024/10/VCS-Methodology-Change-and-Requantification-Procedure-v4.0-1.pdf.

[6] VVB refers to a third-party validation and verification body accredited by Verra. VERRA. (n.d.). *VALIDATION and VERIFICATION*. https://verra.org/validation-verification/. Retrieved May 17, 2025.

[7] S&P Global. (2024, January 6). *Commodities 2024: Price slump in 2023 clouds outlook for voluntary carbon market*. https://www.spglobal.com/commodity-insights/en/news-research/latest-news/energy-transition/010524-price-slump-in-2023-clouds-outlook-for-voluntary-carbon-market.

[8] VERRA. (2024, October 30). *ICAO Approves Verra's VCS Program for CORSIA Eligibility*. https://verra.org/icao-approves-verras-vcs-program-for-corsia-eligibility/.

improvement in the credibility of the VCS. On the other hand, the first period (2024-2026) of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), which is a framework for carbon offsetting and reduction for international aviation, has also approved Verra's VCS for the first period (2024-2026), which will further support the credibility and market position of the standard.

3. Guidance for trading carbon credits[9]

In general, traders want to avoid the risk of funding carbon credits that will not reduce emissions. In response to such concerns about the quality of credits, the International Organization of Securities Commissions (IOSCO) published a report on the VCM. Moreover, the Commodity Futures Trading Commission (CFTC), the US commodity futures regulator, released final guidance on voluntary carbon credits around the same time.

The IOSCO is the international body that brings together the world's securities regulators and is recognized as the global standard setter for financial markets regulation.[10] They released the final report on the Voluntary Carbon Market on November 14, 2024.[11] They already published a report on protecting investors and developing a fair, efficient, and transparent market last year.[12] This new report proposes 21 Good Practices for voluntary markets. The Good Practices relate to the following: I. regulatory frameworks, II. primary market issuance, III. secondary market trading, and IV. use and disclosure of use of carbon credits

Table: IOSCO's Good Practices

I. Regulatory Frameworks
Good Practice 1 – Regulatory treatment ➢ Consider ways to provide clarity regarding the legal and regulatory treatment of carbon credits. Good Practice 2 – Regulatory approach and scope ➢ Consider ways to apply appropriate and effective regulation, supervision, and oversight to VCMs, covering, among other things, the issuance, trading, and retirement of carbon credits. Good Practice 3 – Domestic and international consistency and cooperation ➢ Consider seeking both domestic and international consistency. Good Practice 4 – Participants' skill and competence ➢ Consider promoting the need for financial and investment firms and senior management to have adequate skills and competence.
II. Primary Market Issuance
Good Practice 5 – Standardization ➢ Consider standardizing a taxonomy of carbon credit attributes, strengthening verification methodologies, and streamlining verification processes. Good Practice 6 – Transparency ➢ Consider appropriate ways to promote transparency around the creation of carbon credits. Good Practice 7 – Disclosure ➢ Consider appropriate requirements to promote complete, accurate, and understandable disclosure of information related to the primary issuance of carbon credits, as well as the transparent disclosure of

[9] This part is mainly written by Kojima.
[10] International Organization of Securities Commissions. (n.d.) "About IOSCO." Retrieved May 17, 2025.
[11] The Board of the International Organization of Securities Commissions. (2024). "Voluntary Carbon Markets: Final Report." https://www.iosco.org/library/pubdocs/pdf/IOSCOPD774.pdf.
[12] The Board of the International Organization of Securities Commissions. (2023). "Compliance Carbon Markets: Final Report." https://www.iosco.org/library/pubdocs/pdf/IOSCOPD740.pdf.

any associated risks.
Good Practice 8 – Soundness and accuracy of registries ➢ Consider appropriate requirements around registries, as custodians of carbon credits, to ensure they are accurate, complete, and current in order to serve as reliable sources of information regarding the attributes, issuance, ownership, transfer, and retirement and/or cancellation of carbon credits.
Good Practice 9 – Due diligence ➢ Consider appropriate requirements to ensure that carbon crediting programs adequately perform know-your-customer (KYC) and due diligence procedures to prevent the use of carbon credits for money laundering.
III. Secondary Market Trading
Good Practice 10 – Access to VCMs ➢ Consider requirements or policies to foster open and fair access to secondary market trading on VCMs for interested market participants.
Good Practice 11 – Integrity of trading ➢ Consider requirements to ensure that VCM participants observe high standards of integrity and fair dealing with respect to business activities relating to carbon credits.
Good Practice 12 – Public reports ➢ Consider requiring trading venues and registries to make public reports that disclose, on an equal basis to all market participants, relevant data regarding trading, including pre- and post-trade price transparency, trading volume, bid-ask spreads, and deliveries of carbon credits.
Good Practice 13 – Pre- and post-trade disclosure ➢ Consider requiring an entity operating a VCM derivatives exchange or an intermediary, to provide pre- and post-trade disclosures in a form and manner that is the same.
Good Practice 14 – Derivatives standards ➢ Consider ways to ensure that contract specifications for carbon credit derivatives include sufficient details on the standards by which the underlying credits were certified, the applicable delivery requirements, and procedures for market participants.
Good Practice 15 – Governance framework ➢ Consider requiring VCM participants to have a comprehensive governance framework with clear lines of responsibility and accountability for the functions and activities they are conducting.
Good Practice 16 – Risk management ➢ Consider requiring carbon credit intermediaries, marketplaces, and exchanges to have effective enterprise risk management frameworks in place to address any potential operational or technological risks associated with the trading of or provision of services relating to carbon credits.
Good Practice 17 – Conflicts of interest rules ➢ Consider whether laws and applicable rules within their remit and jurisdiction appropriately address conflicts of interest raised by the issuance, verification, certification, transfer, and retirement of carbon credits.
Good Practice 18 – Enforcement actions ➢ Consider bringing enforcement actions if there are fraudulent or abusive practices in VCMs, such as false or misleading statements regarding the attributes of carbon credits.
Good Practice 19 – Market surveillance and monitoring of trading ➢ Consider appropriate ways to conduct market surveillance and trade monitoring to identify fraud, manipulation, price distortion, and/or other market disruptions.
Good Practice 20 – Trading venue resources ➢ Consider ensuring that trading venues maintain adequate resources to detect and investigate fraudulent or manipulative practices, including, where appropriate, personnel to perform the functions of a Chief Compliance Officer and Chief Regulatory Officer.
IV. Use, Disclosure of Use and Retirement of Carbon Credits
Good Practice 21 – Disclosure of Carbon Credits Use

- Consider encouraging or requiring disclosures regarding an entity's use of carbon credits to achieve any net GHG emission targets.

The IOSCO identifies several key vulnerabilities in this report, such as the quality of carbon credits and availability of information, lack of transparency, conflicts of interest across the value chain, and the lack of standardization. With regard to carbon credit quality in particular, the report shows that multiple stakeholders are concerned at the project level regarding environmental integrity. There has been growing attention on credit quality not only for rating agencies but also for credit buyers. Credit quality standards are expected to be discussed more in the future.

In the United States, the CFTC published the final guidance on the listing of voluntary carbon credit (VCC) derivative contracts.[13] This guidance aims at promoting transparency and liquidity, and the scaling of high-integrity voluntary carbon markets. The CFTC stipulates that designated contract markets (DCMs)[14] should meet the following three conditions relevant to the listing for trading of voluntary carbon credit derivative contracts:

A. A DCM shall only list derivative contracts that are not readily susceptible to manipulation

To make VCC derivatives contracts less susceptible to manipulation, guidance is needed on quality standards (transparency, additionality, permanence and accounting for the risk of reversal, and robust quantification), delivery procedures (governance, tracking, and no double-counting), and inspection provisions (third-party validation and verification).

B. A DCM shall monitor a derivative contract's terms and conditions as they relate to the underlying commodity market

A DCM is responsible for monitoring the integrity of VCC derivative contracts, which must comply with the latest certification standards. Through such monitoring mechanisms, it is possible to detect and prevent price manipulation or distortion.

C. A DCM must satisfy the product submission requirements

A DCM needs to submit certain information regarding VCC derivative contracts, including the terms and conditions of those contracts, to the CFTC.

This guidance does not impose new regulations but rather clarifies the CFTC's expectations on how DCMs should supervise VCC contracts. However, then-Chairman Rostin Behnam announced his resignation after the inauguration of the Trump administration.[15] Some reports indicate that this guidance may be reviewed or even revoked if the CFTC approves final guidance.[16]

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[13] Commodity Futures Trading Commission. (2024). "Commission Guidance Regarding the Listing of Voluntary Carbon Credit Derivative Contracts." https://www.cftc.gov/sites/default/files/2024/10/2024-23105a.pdf.

[14] DCMs are CFTC-regulated exchanges and must comply with statutory "Core Principles" that are set forth in the Commodity Exchange Act (CEA) as well as applicable CFTC rules and regulations.

[15] Commodity Futures Trading Commission. (2025, January 7). *Chairman Rostin Behnam Announces Departure from CFTC.* https://www.cftc.gov/PressRoom/SpeechesTestimony/behnamstatement010725. The position of the chairman is still vacant.

[16] For example: Malyshev, Peter. (2025, January 16). CFTC Under Trump Administration Will Focus More on Existing Laws. *Bloomberg Law*. https://news.bloomberglaw.com/us-law-week/cftc-under-trump-administration-will-focus-more-on-existing-laws. Szabo, Mike. (2025, February 4). Republican senators seek to block US CFTC oversight of voluntary carbon market. *Carbon Pulse.* https://carbon-pulse.com/365031/.

4. An interim report on coal-free transition credits[17]

As coal-fired power generation produces carbon dioxide, transition credits for the early retirement of coal power stations are gaining more attention. The Transition Credits Coalition (TRACTION) was established by the Monetary Authority of Singapore (MAS) at COP28 (2023), and it recently published an interim report on transition credits.[18] The report clarifies the challenges and opportunities of transition credits from the perspectives of (a) supply, (b) risk analysis, and (c) demand.

(a) Supply: multiple transition credit methodologies have emerged globally. Existing transition credit methodologies adopt either a project-based approach (which credits emissions reductions from the early retirement of individual coal-fired power plants) or a sectoral approach (which credits emissions reductions across the power sector at the national or sub-national level). Both approaches have high integrity standards and guidelines for a just transition. The TRACTION will identify common factors that would increase integrity from different approaches and use them to expand the transition credits in the future.

(b) Risk analysis: the use of transition credits is complex and entails multiple risks. Despite the need for urgent financing, there is a frequent timing mismatch when cash flow from the sales of transition credits is only generated after the verification of emissions reductions. This mismatch is particularly significant in Asia, where coal-fired power plants are young in terms of operational life. To avoid such risks, the report proposed combining conventional financing instruments (e.g., debt and/or equity) and innovative financing instruments (e.g., carbon credits insurance and advance market commitments).

(c) Demand: high integrity and the credible use of transition credits are prioritized by all buyers. Moreover, transition credits generated from projects related to the buyer's businesses will be more appealing to voluntary buyers. Some companies acquire credits before regulations are introduced, which implies that there is great demand for high integrity credits. The TRACTION will continue to identify relevant market schemes to increase interest from potential buyers. They will also incorporate elements of high integrity and risk mitigation tools to secure demand from buyers.

The report shows a case study of ACEN Corporation (the Ayala Group), which implemented the world's first Energy Transition Mechanism (ETM). The company is involved in many renewable energy power generation projects in the Philippines. The project aims to quickly phase out a 246MW coal-fired power plant owned by South Luzon Thermal Energy Corporation (SLTEC), one of the ACEN subsidiaries.

The final report of the TRACTION will be released at COP30 in 2025. It will be necessary to monitor the progress of the actual projects. Further updates should be carefully examined.

[17] This part is mainly written by Kojima.

[18] Monetary Authority of Singapore. (2024). "Transition Credits Coalition (TRACTION): An Interim Report on the Application of Transition Credits for Accelerated Coal Retirement." https://www.mas.gov.sg/-/media/mas-media-library/development/sustainable-finance/traction---interim-report---final.pdf.

Hydrogen Value Chain Trends and Challenges

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Abstract

In Europe, since the formulation of the European Hydrogen Strategy, a number of policies and projects have been initiated to establish a multilateral hydrogen value chain. This unprecedented large-scale initiative faces many issues that we can learn from. Meanwhile, North America and China are also making great strides with increased investment in the hydrogen value chain, supported by their industrial policies. As Japan is also attempting to create a hydrogen value chain for the sake of climate action, and with the expectation of making it a future competitive industry, it is worth analyzing the experiences in these countries. Against this background, this report first outlines the hydrogen development plan in Europe. Second, it discusses the various challenges, including competition with those in North America and China. Finally, it tries to deliver implications for Japan.

Key words: Hydrogen, Value Chain, Trends, Issues, Investment

1. Background

An energy transformation (hereinafter “GX”) is taking place in the world on an unprecedented scale in the form of decarbonization. Its implementation will require substantial investment in order to convert the infrastructure. Electric power generated from renewable energies (hereinafter “renewables”) will become a major energy source, but hydrogen will complement that as an important medium that can be utilized for the storage and transport of energy.

Europe has pioneered the introduction of renewables, and it is also striving to construct a strategy to systematically promote hydrogen. However, the change in circumstances since Russia’s invasion of Ukraine in 2022 has brought about major changes to Europe’s GX efforts, and hydrogen is also being affected. In light of that, this report presents an outline of the circumstances and challenges of Europe’s hydrogen value chain construction, while also considering the challenges to constructing a hydrogen value chain in Japan, through comparisons with the situations in the US and China.

2. Hydrogen’s characteristics

2.1 Characteristics

Hydrogen, which is attracting attention amid GX, has the following characteristics:

- It can be produced from electric power generated by renewables, is a multi-vector energy source that can be converted into various fuels as well as electricity, and does not emit CO_2 when used
- It can be stored for long periods without energy loss during storage
- It serves as a medium for transporting renewables over long distances, and as an alternative to fossil fuels utilized to meet heat demand
- It is a gas at room temperature and has a low energy density by volume, but it can also be transported and utilized by converting it into a liquid or ammonia and synthetic fuels, etc.

In addition, hydrogen has multifaceted roles and dimensions, and there are competing energy technologies for each.

- Fuel for producing heat/ Fossil fuels (+CCUS), biofuels
- Transport medium for renewables/ Power lines
- Storage of renewables/ Storage batteries
- Raw material for chemical goods/ Fossil fuels (+CCUS), biofuels
- As a target for investment, PV and wind power are also competitors

2.2 Production cost

In the case of green hydrogen, the cost of the electric power used for electrolysis accounts for 70% of the cost, so the price of hydrogen is influenced by electricity prices. In addition, compared to fossil fuels, the initial investment is large and the rate of return on investment is low (12% or lower). In order to reduce the initial investment, it will be necessary to lift the operating

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rates of electrolysis equipment. Currently, because hydrogen is more expensive than fossil fuels, support in the form of environmental premiums or subsidies is needed. Going forward, the price of hydrogen can be expected to decrease as a result of larger facilities and improved efficiency, increases in the supply of renewables, increases in the quantity of hydrogen in circulation, and other developments.

3. Trends in Europe

3.1 Constructing strategies and frameworks

Japan formulated the world's first hydrogen strategy in 2017. Europe's hydrogen strategy was formulated in 2020, later than Japan's, but subsequently, Europe has begun to move rapidly and is seeking to promote hydrogen by establishing various organizational entities. Hydrogen strategies are also being constructed in respective countries, and an emphasis is being placed on developing supply, transport, and utilization technologies as components for GX.

Following the 2022 invasion of Ukraine, The EU, mainly Germany, has accelerated efforts to reduce its dependence on fossil fuels from Russia, and the EU, under the REPowerEU plan, stepped up its shift to renewables and advancement of its hydrogen strategy.

Table 1 Europe's hydrogen-related policies and organizational

Year	Policy / Organizational Entity
2018	European Hydrogen Initiative
2019	European Green Hydrogen Roadmap
2020	European Hydrogen Backbone (EHB) initiative established 2x40 GW Hydrogen Initiative EC: "European Hydrogen Strategy" Germany: "National Hydrogen Strategy" Important Project of Common European Interest (IPCEI) established
2021	Germany: H2Global established
2022	REPowerEU -Hydrogen Accelerator Clean Hydrogen Partnership established
2023	EU: Green Deal Industrial Plan, Renewable Energies Directive European Hydrogen Bank established Germany: Hydrogen strategy revised ISO/TC 197 (GHG calculation method for hydrogen) issued
2024	EU: Net-Zero Industry Act, Critical Raw Materials Act Germany: Hydrogen import strategy

However, the rapid conversion from Russian fuels led to inflation, including due to soaring energy costs, and so moves to postpone or halt projects, including wind and solar projects, are surfacing due to their profitability deteriorating in the face of the cost increases. In addition, as a result of powerful industrial policies in the US and China, competition is increasing, particularly in renewables-related industries, and competition to attract investment is also intensifying. Nevertheless, this is not to suggest Europe will withdraw from GX—in the long term, it is steadily pursuing GX and moving toward building a hydrogen value chain.

3.2 Constructing a value chain

Wind conditions in high altitude regions of Europe are good, and on the Iberian Peninsula potential renewable capacity exceeds demand. On the other hand, in countries where there is a large demand, such as Germany, there are shortfalls, and so overall, like Japan, it is necessary to import energy from outside the region. Furthermore, even within the region, heavy industries and other industries for which shifting from fossil fuels to electricity is said to be difficult are congregated in center of Europe and particularly in Southern Germany, meaning there is a large number of potential hydrogen consumers located there. It will therefore be necessary to transport hydrogen from locations in the vicinity of Europe to center of Europe, and so five hydrogen corridors are being planned. One is a plan to transport hydrogen from the African continent, a neighboring continent that also has a large potential renewable capacity, via a seabed pipeline. The Netherlands has come out with a hydrogen hub concept for importing by sea and is planning to upgrade ports and supply hydrogen to within the European continent via pipelines. In addition to this, the EU and respective European countries are undertaking diplomatic efforts to secure imports from regions with large potential renewable capacity, such as Canada, Australia, the Middle East, and Africa.

There is a large amount of heating demand in Europe, and inter-seasonal gaps in demand for natural gas for heating purposes are managed using underground storage. If hydrogen is used as an alternative, similar underground storage in the base rock layer is being planned, but this will also fulfill a role in absorbing fluctuations in renewables for which output varies (so-called variable renewable energy; hereinafter "VRE"). In 2021 there was a lengthy period during which wind conditions deteriorated, and this was covered using gas-fired power generation and other sources. Addressing VRE fluctuations is one of the roles that will become increasingly important going forward.

Where demand is concerned, the intention is to switch to hydrogen to cover demand where electrification is difficult, and the steel division is developing hydrogen reduction ironmaking technology. Regarding transportation, there are plans to install infrastructure such as hydrogen stations at 200 km intervals along the roads in the Trans-European Transport Network towards increasing the adoption of fuel cell-powered long-haul trucks.

Additionally, focused support is being provided for new, GX-related industries such as electrolysis equipment for hydrogen production, and industry-nurturing policies are being pursued for regional production, industrial transformation, and job retention.

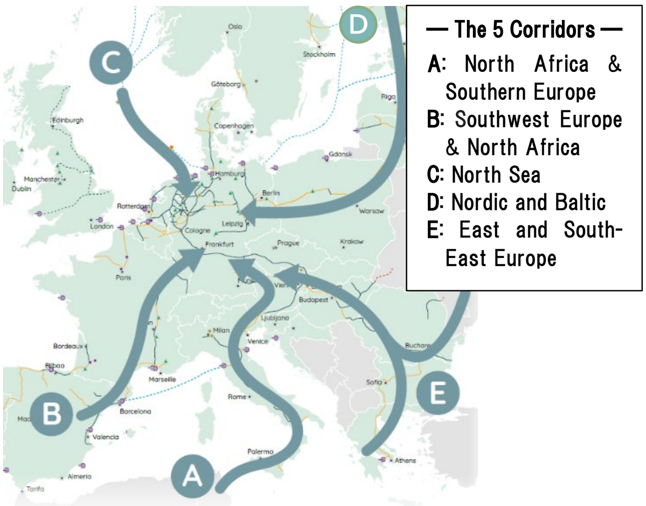

Fig. 1 Five hydrogen pipeline corridors

(Source: EHB2022, edited by the author)

3.3 Promotion policies and system construction

Support is being ramped up—in 2020, the Important Projects of Common European Interest (IPCEI) was established in order to support GX, including hydrogen, and then in 2023, the European Hydrogen Bank was set up to encourage investment in hydrogen. Additionally, systems such as the EU Emissions Trading System, carbon taxes, and the Renewable Energies Directive are having the effect of lifting the environmental value of hydrogen, and vigorous efforts are underway to construct systems and create benchmarks for that.

4. Europe's challenges

GX is a procedure for remodeling the major energy value chains that have been constructed up to now, from upstream to downstream. Because the geographical flows of energy will change, the construction will require enormous investment and a lengthy timespan. Investment from the private sector, not just governments, will be essential, and policies for attracting investment are needed.

4.1 Massive infrastructure investment needs, and rapid advances by North America and China

The hydrogen value chain will require massive infrastructure investment, from production through to transport, delivery, and use modification. According to Hydrogen Insights 2024, Europe has the largest number of announced hydrogen projects in the world, with total investment reaching 199 billion US dollars by 2030 (as of May 2024), followed by Latin America at 107 billion US dollars and North America at 96 billion US dollars. However, in the most recent six-month period (October 2023 to May 2024) Europe's investment in new projects was low, while in North America, India, China, and Latin America, the scale of investment increased.

There are fears of a slowdown in investment, including in relation

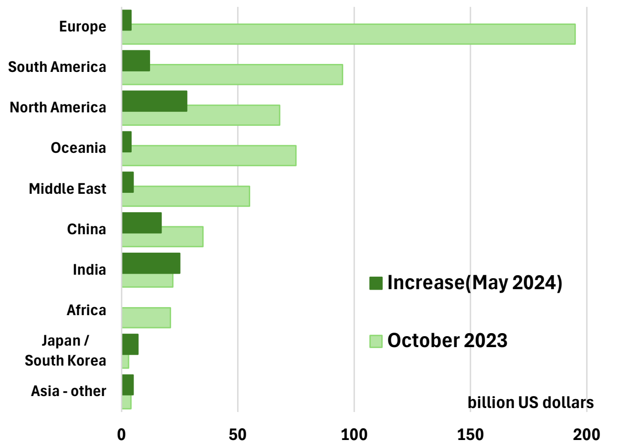

Fig. 2 Investment amount of announced hydrogen projects (from Hydrogen Insight, edited by the author)

to renewables, in Europe. One backdrop to this is competition with policies to promote GX investment in regions outside Europe. The US' incentives, such as its clear and effective Inflation Reduction Act (hereinafter "IRA"), and China's strong industrial policy, driving costs down thanks to deployment at scale, are proving effective, while Japan's contract-for-difference instruments are also effective for driving offtake.

In addition, one reason the US and China have been moving rapidly ahead with hydrogen projects is that their policy decisions are concluded domestically. In contrast to this, in Europe, it is a two-tiered process involving consensual decisions by the EU countries and each country's policies. Because value systems also differ depending on the country, promoting policies takes time.

In North America, hydrogen production projects are advancing the most, with final investment decisions having been reached on projects totaling 2.4 million t/year by 2030 (75% is low-carbon hydrogen, not green hydrogen, however). Even in China, final investment decisions total 1.4 million t/year (with green hydrogen accounting for 95%). In Europe, however, final investment decisions remain at 0.3 million t/year. In Europe, a large proportion of investment is in projects at the early phase of development (pilots), but in North America, there is a lot of investment in large-scale projects at the commercial stage, and so a large percentage of projects have reached the final investment decision.

China accounts for 66% of the world's current cumulative capacity of electrolysis equipment, at 1,150MW, followed by Europe at 14% and North America at 9%. However, because a large amount of hydrogen in North America is low-carbon hydrogen arising from fossil fuels + CCS, North America accounts for 52% of hydrogen producing capacity, followed by China at 30% and Europe at 8%. Europe has been investing in building a renewables industry, but the US' and China's industrial policies are powerful, so Europe will face fierce competition in the future also.

4.2 Profitability being undermined by inflation

GX requires substantial investment, but soaring energy prices in Europe since 2022 have eroded the private sector's capacity for investing and are also having an impact on public finances.

Rising energy costs are driving inflation, and the soaring cost of materials is undermining the profitability of projects, leading to cases in which projects are having to be deferred or halted.

4.3 Uncertainty surrounding projects

In the future, increases in scale and increases in supplies of renewable electric power are expected to bring down costs, but there are also predictions that this progress will be slow. Projects' earnings are deteriorating, and a loss of certainty around the offtake outlook is occurring. On the demand side, the uncertainty surrounding supply periods, quantities, and prices is making investment decisions difficult.

The EU Emissions Trading System, carbon taxes, and the Renewable Energies Directive can enhance the value of hydrogen, but the extent and timing are uncertain factors.

4.4 The renewables supply hurdle

Unless renewables expand, the cost of green hydrogen will not decline. However, due to the barriers created by regulations, procedures, and other factors a slowdown in the growth of renewables is also occurring. Transmission grid enhancements are not keeping pace, and in more than a few instances, renewable power generation facilities are still awaiting connection.

Given the high level of uncertainty surrounding green hydrogen supply in particular, in the US, for example, the intention is to position blue hydrogen produced from fossil fuels with carbon capture at the center of distribution for the time being, and then pursue a gradual shift to green hydrogen.

5. Considerations

I have undertaken a comparison between the circumstances in Europe, which has been engaging in building a hydrogen value chain, and other regions, and have sorted through the various challenges. Based on this, I will consider the implications for Japan, which is likewise moving to build a hydrogen value chain.

5.1 Policies that are strongly conscious of international industrial competition

Competition is intensifying as a result of **international** industrial protectionism. Under these circumstances, GX that curbs energy costs while preserving one's own country's competitiveness, will be needed. In Europe, the so-called "Draghi report" points out that Europe needs policies and investment that are strongly conscious of **international** industrial competition. With green hydrogen, for which cost reductions are not advancing, it is difficult to win demand from companies exposed to strong competition. A strategy of securing distribution with relatively low priced low-carbon hydrogen initially, and then gradually switching to green hydrogen subsequently, as the US is doing, would likely prove effective in Japan also.

5.2 Selecting means of transport based on geography

In Europe, which I have presented a general overview of, there is a large-scale demand in the central part of the continent. While I did not discuss this in detail, because the US and China are also continental countries, they are moving ahead with supply via land-based pipelines. Japan, on the other hand, is long and narrow and surrounded by sea, and because many of its industrial sites and habitable flat land are located in coastal areas, areas of large-scale demand are concentrated in coastal areas. Conceivably, much of Japan's hydrogen supply will be imported, and given also that marine transport will be Japan's core means of transporting hydrogen, it would be effective for the country to focus on building a marine transport network.

5.3 Making investments efficient

Transforming energy chains requires a massive investment. It is not as though capital is abundant, so efficient investment that has assessed effective chains is demanded. In addition, ideally, exporter countries will undertake development and export their hydrogen using their own funds. Conceivably, Japan will rely on imports to cover a greater proportion of its hydrogen needs than

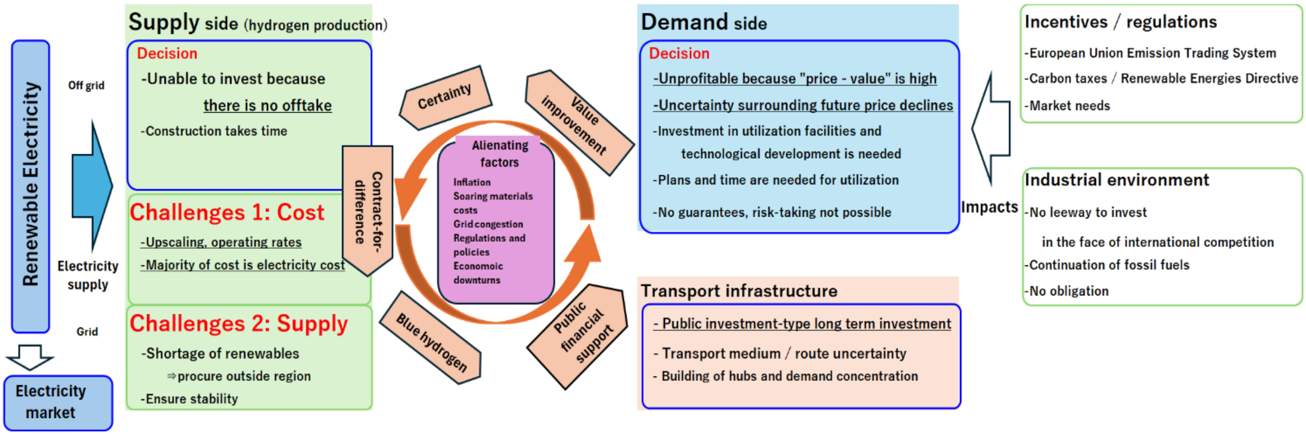

Fig. 3 Cause and effect of hydrogen market formation in GX

Europe will. Consequently, international marine distribution for hydrogen will need to be established, and it will be essential to build networks with countries that have export potential. Furthermore, because expansion in the hydrogen market can be expected to result in supply and prices stabilizing, building an international network that includes the demand side will likely prove effective also. If it is possible to strengthen ties, including mutual economic benefits, then even better.

5.4 Overcoming cause and effect in supply and demand

In the hydrogen market, because the supply side cannot invest if there is no offtake, demand creation is said to be important. From the other, demand side perspective, unless the cost of hydrogen declines, it is not possible to invest in utilization facilities. In other words, a “chicken and egg” relationship exists, and because both are in a reciprocal causative relationship making the decision to sever that is difficult. This is the largest factor contributing to hardship in hydrogen investment. In addition, there is also significant uncertainty in the long lead times that accompany facility construction. Contract-for-difference support, FIT, and other schemes are accompanied by government (ultimately citizens’) expenditure, but they are effective measures for enhancing the certainty of investment. Because the prolonging of support increases the burden, there are measures in which rapid market growth is desirable. In policies, it is undoubtedly effective not just to set goals but also to resolve risks and to have four-dimensional roadmaps that give meaning to milestones. It is important to create a virtuous cycle on both the supply and demand sides and to ensure that market formation continues without interruption.

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