Part II

Deepening uncertainties surrounding the challenges of energy transition: a widening gap between the ideal and the reality

7. Various pathways for decarbonising the road transport sector in the Global South

—Efforts and challenges towards BEV and biofuels deployment—

It is undeniable that the battery electric vehicle (BEV) plays a key role in decarbonising the road transport sector while delivering secondary benefits such as reducing air pollution and oil imports. Many countries and regions are enhancing their BEV production policies to strengthen their industrial competitiveness for the future. However, the decarbonisation pathways of countries and regions vary greatly depending on their individual circumstances, and the road transport sector is no exception. From this perspective, IEEJ Outlook 2025[31] compared various types of vehicles with different powertrains (internal combustion engine vehicles [ICVs], hybrid electric vehicles [HEVs], plug-in hybrid vehicles [PHEVs] and BEVs) in terms of their greenhouse gas (GHG) emissions and total cost of ownership (TCO) using life cycle assessments (LCAs) for different regions (Advanced Europe, Brazil, Association of Southeast Asian Nations [ASEAN] and India), to demonstrate that the optimal powertrain for decarbonisation varies depending on the individual circumstances of countries and regions.

IEEJ Outlook 2026 takes a more comprehensive approach to optimal decarbonisation pathways in the road transport sector by focusing on the diverse pathways taken by key Global South countries, namely Indonesia, Brazil and India. Specifically, the report uses a case study of Indonesia to analyse various social challenges hampering the spread of BEVs, including environmental burdens from the production and use of BEVs, infrastructure upgrades necessary for their wider adoption, and the impact on critical mineral supply and demand. It likewise uses case studies of Brazil and India to evaluate the secondary policy effects, potential and challenges of biofuels as a promising fuel option for decarbonisation.

7.1 Indonesia's initiatives for wider domestic production and use of BEVs

Indonesian government policies

Indonesia is the second-largest car producer in ASEAN (1.197 million in 2024) only after Thailand and has the largest unit sales of new vehicles in ASEAN (866 thousand in 2024)[32]. Indonesia also produces 51% of the global supply of nickel, a mineral essential for BEV batteries (as of 2023) and is striving to become the global hub for BEV production. In 2022, the Indonesian government withdrew its domestic low-emission vehicle production target that had been set in 2020 (BEVs, PHEVs, HEVs and FCEVs) and set a fresh, BEV-only target to produce 1 million domestically in 2035 (Table 7-1).

[31] https://eneken.ieej.or.jp/data/12092.pdf

[32] "Automobile production and sales trends in major countries and regions" by Japan External Trade Organization (2025) https://www.jetro.go.jp/ext_images/_Reports/01/6f831adb699b3451/20250016.pdf

Table 7-1 | Indonesia's domestic BEV production: actuals and targets

(1 000 units)

	2024 actual	2050 target	2030 target	2035 target
BEV production volume	42	400	600	1 000
[Reference] Previous target				
Total domestic production volume	1 197	2 000	3 000	4 000
Of which: LCEVs only	112	400	750	1 200

Note: LCEV stands for low carbon emission vehicle (BEV, PHEV, HEV and FCEV).
Source: The target for BEVs is based on Indonesia's Ministry of Industry Regulation of 2022 and the targets for total production volume and LCEVs are based on that for 2020; the actuals are from the Association of Indonesia Automotive Industries (GAIKINDO).

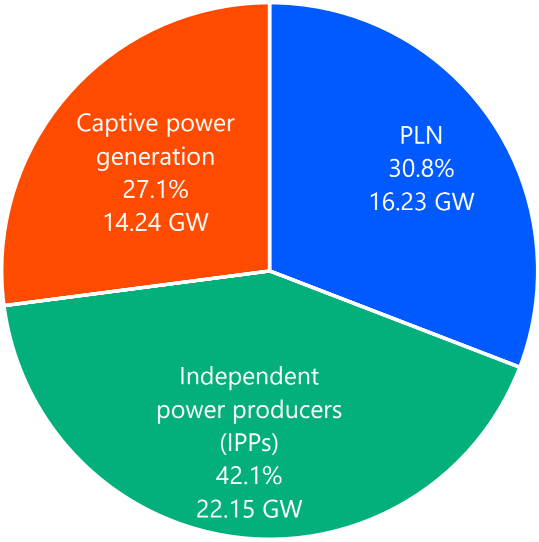
The targets for domestic BEV ownership are 2 million four-wheel vehicles in 2030 (passenger and commercial vehicles, at around 76 thousand as of the end of 2024) and 13 thousand for motorcycles. This can be seen as an ambitious industrial policy that leverages critical mineral reserves as well as the existing domestic industrial infrastructure.

Evaluation of environmental aspects

As described above, Indonesia is working on expanding the domestic production and use of BEVs by leveraging its abundant nickel resources. Meanwhile, the energy used in the nickel refining process comes mostly from coal (as a heat source) and coal-fired captive power generation, which is said to be increasing carbon dioxide (CO_2) emissions. In 2021, the Indonesian government declared that it would halt new coal-fired power plant construction from 2023, but with exceptions that include allowing new coal-fired captive power plant construction for nickel refiners and industrial complexes. Coal-fired captive power generation is also exempt from the early retirement support project for coal-fired power plants led by the Just Energy Transition Partnership (JETP), of which Japan is a member. In fact, coal-fired captive power plants account for 30% of Indonesia's coal-fired power plant capacity in operation but two-thirds of the coal-fired power capacity in the construction and planning stages (Figure 7-1 and Table 7-2).

Furthermore, in Indonesia's nickel refining sector, alongside deforestation associated with mining and ongoing impacts on marine ecosystems, there is a risk of local air pollution unless appropriate emission regulations are introduced to control the sulphur dioxide (SO_2) emissions from processing nickel sulphide ores into nickel sulphate.

Figure 7-1 | Composition of Indonesia's operating coal-fired power plants by supplier [July 2025]



Note: The figures for PLN include power plants wholly owned by PLN as subsidiaries.
Source: Created based on the Global Coal Plant Tracker and the RUPTL electricity supply business plan (2025–2034).

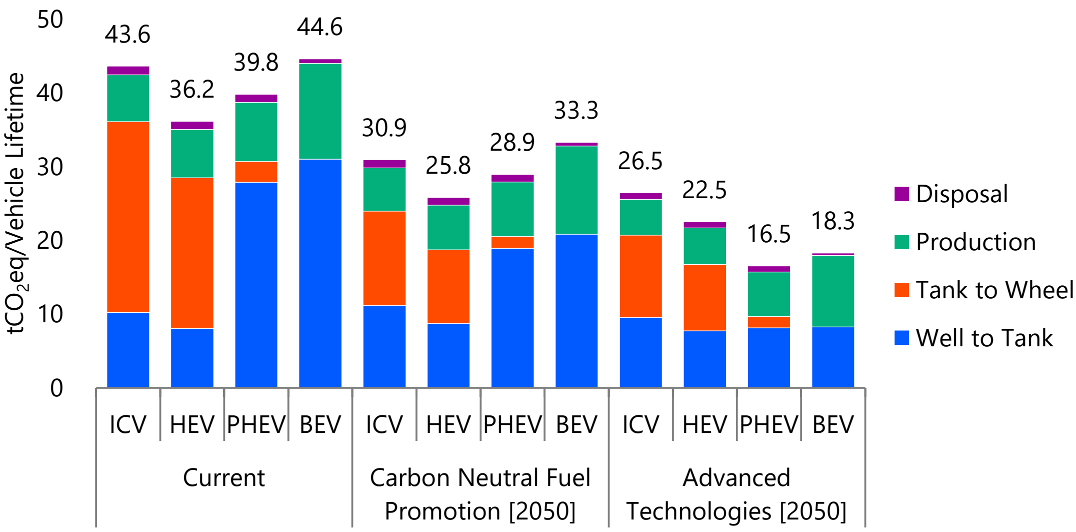
Table 7-2 | Characteristics of Indonesia's coal-fired power plants by suppliers

	PLN	Independent power producers (IPPs)	Captive power generation
In operation (GW)	16.2	22.1	14.2
In construction/ planning (GW)	1.7	4.2	11.7
Suspended (since 2021 or later) (GW)	7.0	12.0	4.1
Purpose	Supply to consumers	Sell to PLN	Power supply for the industry
Ownership/ management	State-owned	Domestic companies,	Local smelters, Chinese companies, etc.
Applicability of policy/ regulation	Early retirement and freeze on new builds by JETP apply	Early retirement and freeze on new builds by JETP apply	JETP does not apply

The current situation is thought to be due mostly to the influence of Chinese companies. The Indonesian government has been driving a policy to limit nickel ore exports and promote refining in the country. As a result, Chinese and other companies have begun planning and operating numerous refineries domestically, and approximately three-fourths of Indonesia's nickel refining capacity is said to belong to Chinese companies. These refineries are built on remote islands in conjunction with small, low-efficiency coal-fired power plants. The Chinese government announced that it would end support for new coal-fired power plant construction outside China in 2021, but this does not apply to captive power plants of industrial complexes related to the Belt and Road Initiative. BEVs, by nature, are a countermeasure against climate change and air pollution, but there will be little point if CO_2 emissions from producing BEVs increase and generate other environmental burdens, particularly for the benefit of Chinese companies. The environmental burden should be considered on a comprehensive basis that includes entire supply chains.

Are BEVs' GHG emissions smaller than the emissions of other powertrains on an LCA basis in Indonesia? As of 2023, coal-fired power generation accounts for two-thirds of Indonesia's power supply, driving up the country's carbon emission factor for electricity to 829 gCO_2/kWh, 1.4 times as large as the global average of 575 gCO_2/kWh. As such, a BEV has higher emissions than an ICV on an LCA basis, and this trend will not change in the future (2050) unless electricity is decarbonised as seen in the Advanced Technologies Scenario (Figure 7-2).

Figure 7-2 | GHG emissions from vehicles in Indonesia on an LCA basis



Note: The Carbon Neutral Fuel Promotion Case is a combination of the Reference Scenario and the carbon neutral fuel ratio of the Advanced Technologies Scenario.

The former Joko Widodo administration greatly expanded the country's power generation capacity, mainly using coal-fired power generation, in its first term through a capacity expansion project called the 35-Gigawatt Power Plant Project. As electricity demand did not grow as many as expected, Indonesia's coal-fired power generation capacity is currently said to be in overcapacity[33]. Indonesia's carbon emission factor for electricity, described earlier, is an all-day average of all power sources, and CO_2 emissions could rise further if BEVs spread and drive up the operation of coal-fired power capacity currently in excess.

The impact of the increase in BEVs greatly depends on the regional power generation mix and charging behaviour (Table 7-3).

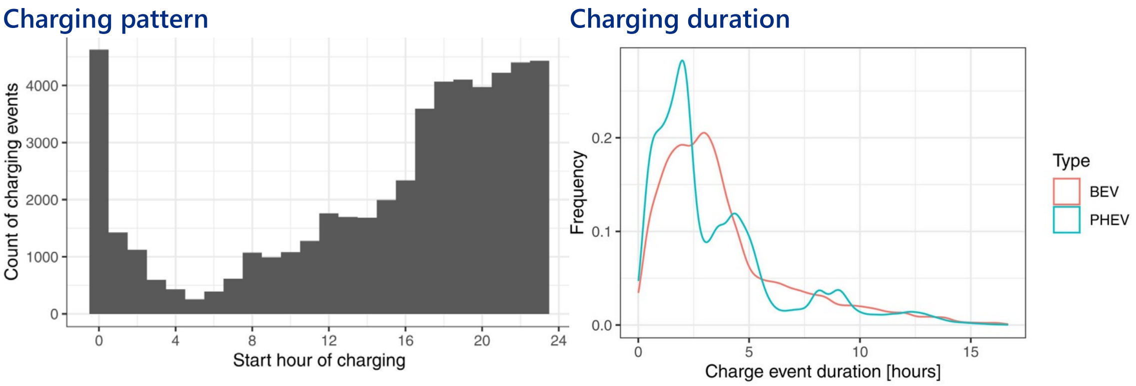
[33] https://www.transitionzero.org/insights/indonesia-net-zero-curve

Table 7-3 | BEV charging hour patterns and impact on the annual demand curve

BEV charging hour pattern	Impact (annual demand curve)	Implications on the grid and power sources
Charging at night-time after 10 p.m. is the most common	The valleys in night-time demand in winter and summer will rise	The utilisation of wind and baseload power source will improve. Additional power by thermal power generation will be needed during shortages
Charging soars from around 5 p.m. when people come home	Summer and winter evening peaks will rise further	Grid burden will increase as excess thermal power plants go into operation
Daytime charging	Day-time demand will rise from spring through autumn	Beneficial for absorbing solar photovoltaics

For example, in Norway, where BEVs are the most widespread in the world, electricity demand did increase due to BEVs, but this has led to effective use of baseload power sources, as more than 90% of Norway's power generation mix consists of hydro. Meanwhile, in California, the United States, where BEVs are spreading rapidly, charging mostly starts around 5 p.m., when people come home, usually takes two to three hours and thus tends to overlap with the evening peak demand hours (Figure 7-3). The state's solar photovoltaic-dependent power generation mix carries a risk of increased CO_2 emissions due to BEVs because while solar photovoltaics often produce excess electricity in the daytime, additional demand arising during night-time is supplied using thermal power generation.

Figure 7-3 | California, the United States: charging pattern and duration



Source: Alan J., Jake H., (2022) Distribution grid impacts of electric vehicles: A California case study, iScience 25 1-16.

Solar photovoltaics may become a key power source in Indonesia in the future as well, if the decarbonisation of electricity is pursued. However, even if the all-day average carbon emission factor for all power sources decreases, cheap coal-fired power plants may continue to operate as a marginal power source, limiting the emissions reduction effect. As a result, the BEV's well-to-tank emissions shown in Figure 7-2 may increase by 1.3 times currently and by 1.8 to 3.6 times by 2050. As such, it is essential to urgently decarbonise coal-fired power generation and introduce renewable energy. Moreover, considering the characteristics of renewables and consistency with

BEV charging times, BEV owners should be encouraged to charge their cars during the daytime when electricity generated by solar photovoltaics is available, or during off-peak hours. Specifically, appropriate policy design—such as shifting charging hours through time-based tariffs and promoting smart charging technologies, is essential. If this is achieved, BEVs may become flexible grid-balancing resources rather than a source of increased CO_2 emissions.

Estimation of infrastructure costs

To put more BEVs on the road, it is essential to meet the resulting increase in electricity demand by securing power sources and reinforcing transmission networks. In particular, the spread of rapid chargers, while improving user convenience, is expected to raise peak demand and increase transmission network loads in cities where demand is concentrated. If BEVs increase to meet the Indonesian government's 2030 BEV target (2 million four-wheel vehicles) and adoption accelerates thereafter to reach 10 million in 2040, and half of these BEVs are charged between 4 p.m. and 10 p.m., this can generate at least 15 GW of additional electricity demand. The Indonesian government is planning to increase installed power generation capacity from 106 GW in 2025 to around 242 GW in 2040; however, an additional demand of 15 GW is by no means negligible. Furthermore, reinforcement of battery storage, power generation facilities and transmission infrastructure will likely be necessary to address regions and seasons with tight electricity supply. Unless smart charging is widely adopted, substantial additional infrastructure investment will be required.

Development of charger infrastructure calls for national budget allocation. Indonesia plans to install one charger for every 15 BEVs by 2030 and sets a goal to boost the number of chargers from the current 3 202 medium-speed chargers to 62 918 chargers by 2030 (30 796 medium-speed, 19 538 high-speed and 12 584 ultra-high-speed). This is estimated to cost 23 trillion rupiah (approx. 200 billion yen) in total over the next six years, which, at a 50% government subsidy rate, would equal 0.05% of Indonesia's national budget. Japan has a similar plan to install 300 000 chargers by 2030, which is estimated to cost 0.03% of the national budget under comparable assumptions, and given that the cost of BEV chargers is broadly similar worldwide, the costs represent a relatively larger burden for developing economies.

Needless to say, introducing BEVs requires certain policy costs alongside infrastructure costs. These policy costs include:

1. Incentives for BEV buyers (in Indonesia, value-added tax reduction (from 11% to 1%, applicable to models with a domestic production rate of 40% or higher), exemption from luxury goods sales tax (around 15%)),
2. Reduction of running costs for BEV owners (in Indonesia, 30% discount on electricity tariffs for BEV owners from 10 p.m. to 5 a.m.), and
3. Incentives for BEV producers (in Indonesia, corporate tax reduction for BEV, BEV battery and motor producers, etc.).

While it is difficult to accurately estimate total fiscal costs, measures 1 and 2 above are estimated to require a national budget allocation of Rp5 trillion–Rp6 trillion (¥43 billion–¥52 billion) annually.

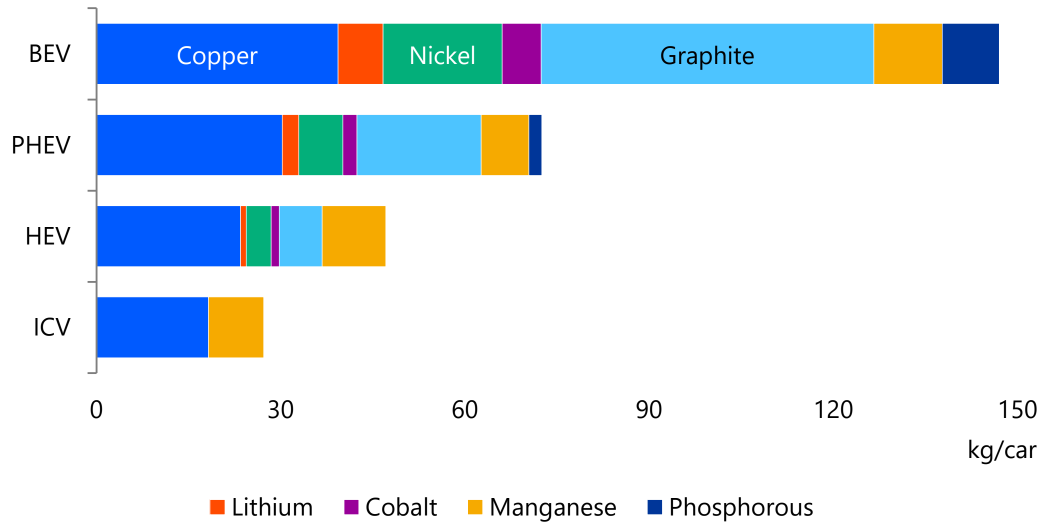
Other

It is also important to note the temperature-related deterioration of battery performance in tropical countries. A survey that collected data from 30 000 BEVs shows a 17%–18% drop in a

BEV's driving range at a temperature of 100°F (37.8°C) relative to ideal conditions[34], and a difference of 5%–6% in remaining battery capacity was observed after four-year use between moderate- and high-temperature regions[35]. Many original equipment manufacturers (OEMs) also advise users to avoid parking their BEVs at high temperatures with a full battery or charging at high or low temperatures.

Another issue for BEVs is their extensive use of critical minerals, which may affect the supply-demand balance of those minerals as BEV adoption increases, pushing up BEV prices. Also, the supply of critical mineral products depends heavily on China and is subject to the risk of supply disruptions triggered by export controls. BEVs are estimated to consume five times more critical minerals than ICVs, three times more than HEVs, and twice as much as PHEVs (Figure 7-4). Compared with the analysis in IEEJ Outlook 2024[36], the gap between BEVs and other powertrains has narrowed thanks to the wider adoption of lithium iron phosphate (LFP) batteries; nevertheless, the impact of the spread of BEVs must continue to be monitored.

Figure 7-4 | Critical mineral usage per passenger car



With the spread of BEVs, decreasing gasoline tax revenues are becoming an issue in various countries. In the United States, for example, a draft of the One Big Beautiful Bill Act (OBBBA) that passed the House of Representatives proposed imposing a surcharge of $250 per year on BEV owners. The proposal was ultimately removed from the final OBBBA, but many states do impose an annual surcharge of around $100–$200 on BEV owners. This issue is expected to be discussed in many countries, including Japan, going forward.

7.2 Use of bioethanol in Brazil

Brazil is the world leader in blending bioethanol into gasoline. The blending ratio, which had already been high at 27%, was raised to 30% in August 2025. This blending ratio in gasoline is a

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[34] Blake Hough and Liz Najman, How Hot Summer Weather Affects EV Range, Recurrent, June 2025. https://www.recurrentauto.com/research/what-a-c-does-to-your-range

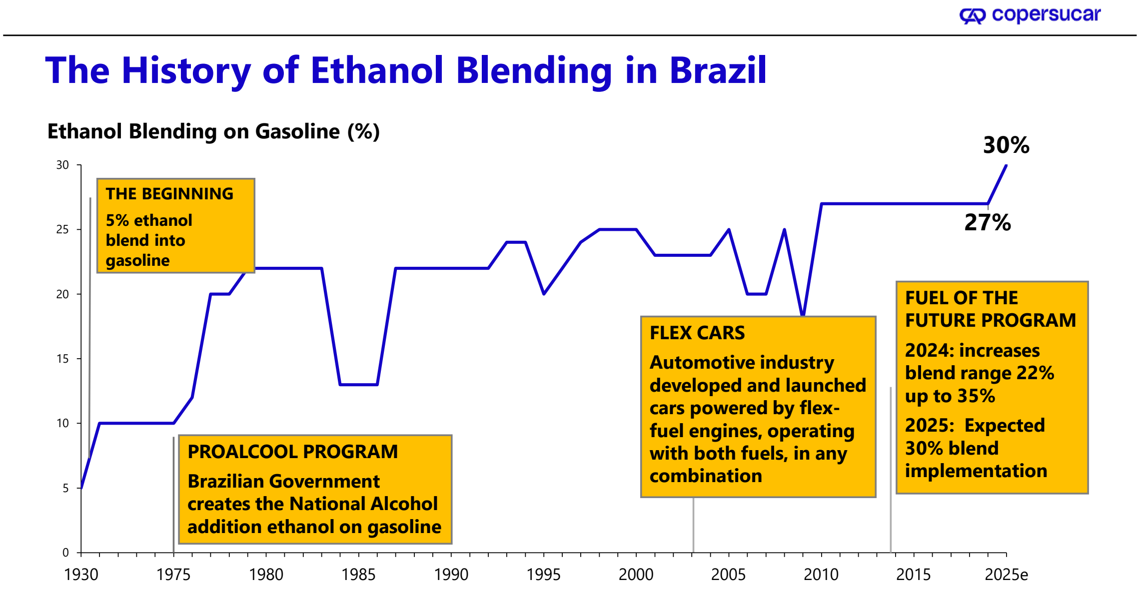
[35] Charlotte Argue, How long do electric car batteries last? What analysing 10,000 EVs tells us..., GEOTAB, July 2025. https://www.geotab.com/blog/ev-battery-health/

[36] https://eneken.ieej.or.jp/data/11380.pdf

regulatory threshold, and in fact, a ratio as high as 45% has been achieved. This has been made possible by the following historical background, in addition to the spread of flex-fuel cars, which can run on gasoline with any bioethanol blend from 0% to 100% (they accounted for 78.4% of new cars sold in Brazil in 2023) and government subsidies for bioethanol fuels.

Blending bioethanol into gasoline has a long history in Brazil and goes back about 100 years to 1931, when a 5% blend was introduced. Before climate change became a major policy issue, bioethanol was initially used in the transport sector as a means to support the sugarcane industry. Full-fledged production of bioethanol eventually began during World War II to conserve crude oil, and the blending ratio was raised to 10%. The blending ratio was raised further to 20% during the oil crises in the 1970s, and from the 2000s onwards, progress was made in the development and introduction of flex-fuel cars, leading to the present situation (Figure 7-5).

Figure 7-5 | History of bioethanol blending in Brazil

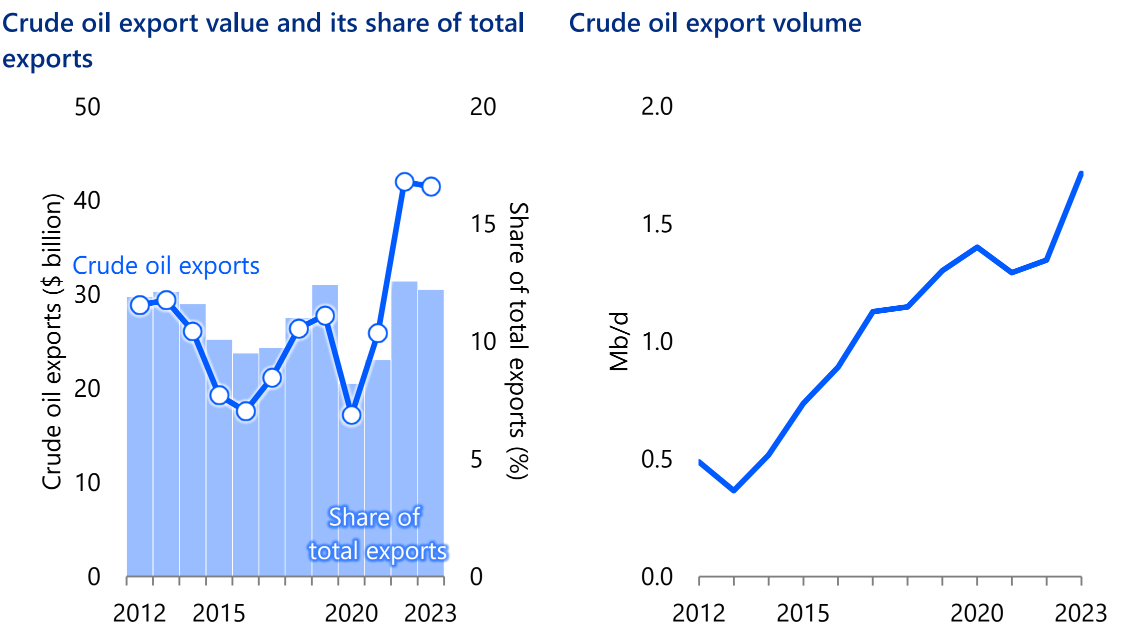


Source: Copersucar

Bioethanol production has made a major contribution to the country's energy security to date. Brazil's energy self-sufficiency rate reached 116% in 2023, and biofuels, including ethanol, account for 33% of the country's primary energy supply. Brazil is an oil producer, but it is reducing domestic gasoline consumption through bioethanol blending to help increase oil exports. Specifically, Brazil's oil exports have grown fourfold in the last 10 years and now account for 12%–13% of total exports, contributing to the country's foreign currency earnings (Figure 7-6). Domestic energy consumption grew by 470 PJ in 2023, of which crude oil accounted for 110 PJ and biofuels 320 PJ. The growth in Brazil's oil exports of 550 PJ (250 kb/d) that year would not have been possible without an increase in biofuel production.

Brazil's bioethanol policy is also helping to make its automobile industry competitive. As mentioned earlier, around 80% of the 2.5 million new cars sold each year in Brazil are flex-fuel cars, and the share of domestically produced vehicles in total new-car sales remains at 80%–90%, suggesting that the widespread use of flex-fuel cars, which are unique to the Brazilian market, is helping to maintain this high domestic share. The share of workers on sugarcane farms in agriculture has also increased from 4% to 8% in the 2000s, indicating that bioethanol is playing a role in agricultural development and job creation in the region.

Figure 7-6 | Brazil's crude oil exports



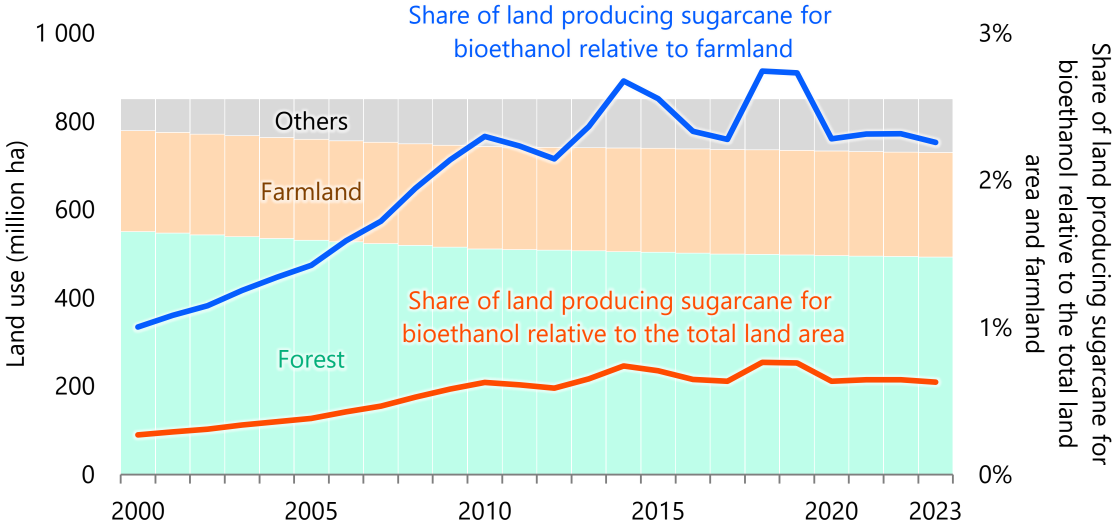
Source: Created based on data from Trendeconomy, the Organisation for Economic Co-operation and Development (OECD) and Federal Reserve Economic Data.

On the other hand, issues have been noted with utilising bioethanol, not only in Brazil, but also in any country. One of the persistent concerns about the expanded use of biofuels is land-use change, which may lead to deforestation through the expansion of arable land. However, as far as Brazil is concerned, the percentage of land producing sugarcane for bioethanol has remained stable relative to the total land area and farmland, and the impact of land-use change appears limited, at least for the time being (Figure 7-7).

Brazil's sugarcane industry is also working to reduce the carbon footprint (CFP) associated with bioethanol production. IEEJ's field study in 2024 also noted innovative efforts such as the production of biogas from bioethanol by-products for transport trucks, use as fertilisers, double-cropping sugarcane with maize, use of sugarcane residue (bagasse) for second-generation bioethanol production and power generation, and even consideration of introducing BECCS[37]. While working to expand bioethanol exports, Brazil is aware that reducing the CFP is essential for competitiveness in international markets. Brazil's challenges going forward include improving the transparency and credibility of CFP calculation and advancing related technologies.

[37] Bioenergy with carbon capture and storage. This is the capture and storage of CO_2 from biomass power generation and is one of the negative emission technologies.

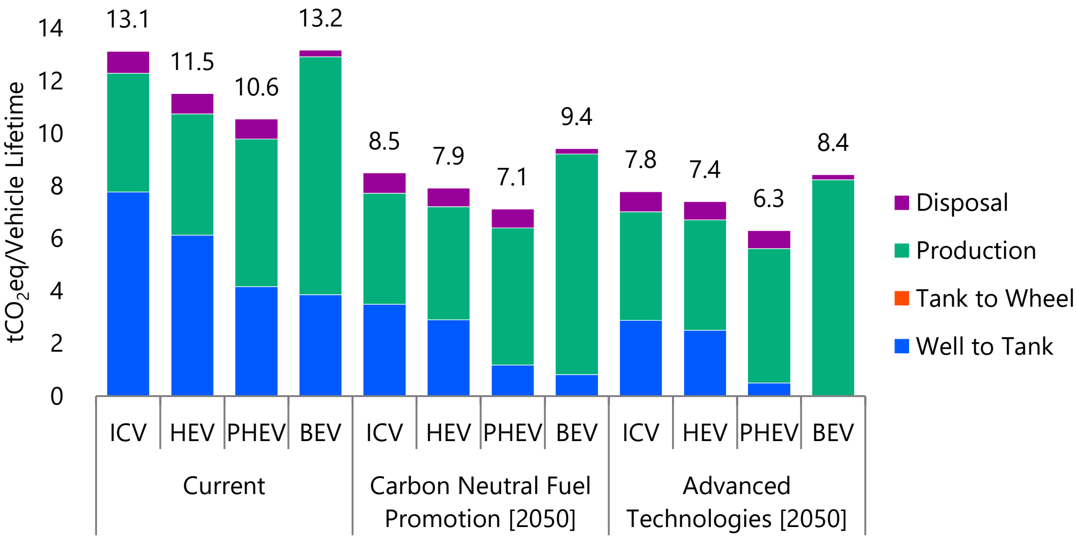
Figure 7-7 | Use of land in Brazil and share of sugarcane farmland for bioethanol



Source: Created based on the World Bank database.

An cycle assessment (LCA) of greenhouse gas (GHG) emissions in Brazil showed that compared with battery electric vehicles (BEVs), which generate high carbon dioxide (CO_2) emissions in the battery production phase, the CFP of internal combustion engine vehicles (ICVs), hybrid electric vehicles (HEVs) and plug-in hybrid vehicles (PHEVs) that run on 100% bioethanol fuel is lower than that of BEVs, and this ranking is not expected to change in the future (Figure 7-8). Brazil's carbon emission factor for electricity is extremely low at 79 gCO_2/kWh relative to the global average of 576 gCO_2/kWh, as its power generation mix consists mainly of hydro, which gives the country a significant advantage for BEVs; but even then, bioethanol was shown to be lower in carbon than BEVs on an LCA basis.

Figure 7-8 | Automobile GHG emissions on an LCA basis in Brazil



Note: The Carbon Neutral Fuel Promotion Case is a combination of the Reference Scenario and the carbon neutral fuel ratio of the Advanced Technologies Scenario.

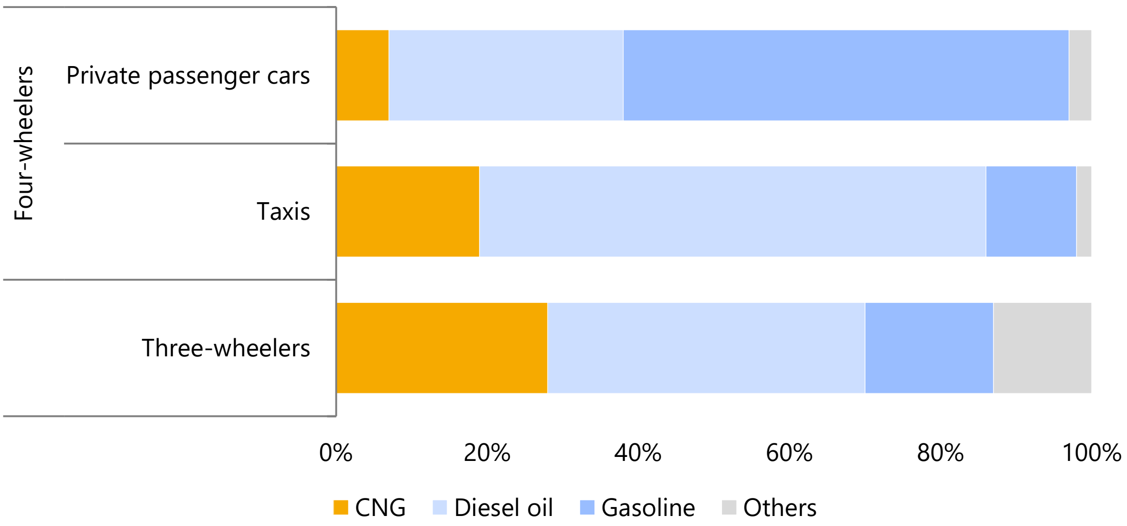
As described above, the expanded use of bioethanol in Brazil is being pursued from a wide range of perspectives including climate change, energy and economic security policies, as well as industrial policies such as automotive and agricultural policies, all while leveraging the country's abundant bioresources. Bioethanol is considered to have higher environmental performance than BEVs when combined with HEVs and PHEVs and can be seen as an excellent example of diverse decarbonisation pathways for the road transport sector.

In April 2024, the leaders of Japan and Brazil launched the Initiative for Sustainable Fuel and Mobility or ISFM, which combines sustainable fuels such as biofuels with high-performance mobility equipment such as HEVs, and in September 2025, the two countries co-hosted the first Ministerial Meeting on Sustainable Fuels in the Kansai region of Japan. There are high expectations for expanding bilateral cooperation into multilateral international cooperation.

7.3 Utilisation of biogas in India

India is also actively promoting the use of bioethanol, raising its ethanol blending ratio over the past decade from just 1.5% in 2014 to the current 20%. Meanwhile, what is even more noteworthy is that, to the extent identified in our study, it is the only country with a mandated blending ratio of biogas in compressed natural gas (CNG). In India, the use of CNG vehicles is widespread to address air pollution and because of low fuel costs, and CNG vehicles have an extremely high share of 28%, 19% and 7%, respectively, for three-wheelers, taxis and private passenger cars, respectively (Figure 7-9).

Figure 7-9 | Composition of registered vehicles in India by fuel type



Source: Created based on data from the Energy and Resource Institute (TERI).

In India, biogas policies have been reinforced to utilise abundant domestic bioresources such as agricultural residues, livestock manure and other wastes, as well as to draw on the vehicle composition described above, aiming to promote the agricultural and livestock industries, reduce liquefied natural gas (LNG) imports, save foreign currencies and contribute to a circular economy. Specifically, the Sustainable Alternative Towards Affordable Transportation (SATAT) initiative was launched in 2018, introducing voluntary biogas blending targets that would be made mandatory and gradually raised from 2025 (Table 7-4). This initiative is also part of the measures to promote agriculture.

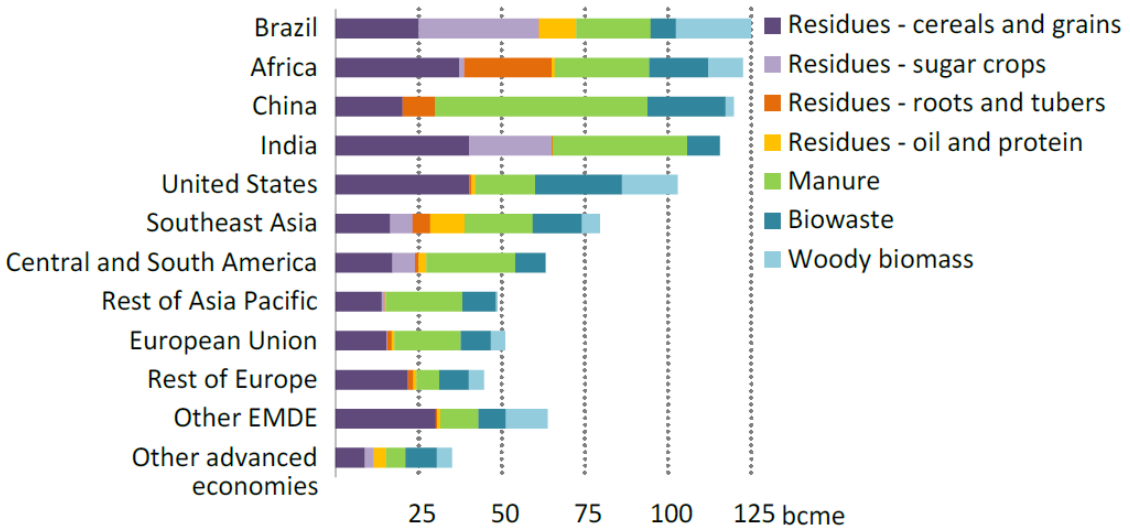
Table 7-4 | Biofuel blending ratio targets in India

	Target year	Blending ratio		Target year	Blending ratio
Bioethanol	2025	20%	Biogas	Through 2024	Not specified
				From 2025	1%
Biodiesel	2030	5%		From 2026	3%
				From 2027	4%
SAF	2028	2%		From 2028	5%

Source: Ministry of Petroleum and Natural Gas

According to the International Energy Agency (IEA), biogas production in India is built on its agricultural sector, which accounts for 18% of its gross domestic product (GDP) and 45% of employment and has a history of more than 100 years. India's biogas potential is among the world's largest, alongside Brazil and China (Figure 7-10), and its biogas policy, underpinned by this long history and abundant domestic resources, has no equivalent in any other country. It is also interesting that the title of the initiative stresses affordability as well as sustainability.

Figure 7-10 | Biogas potential of major countries and regions

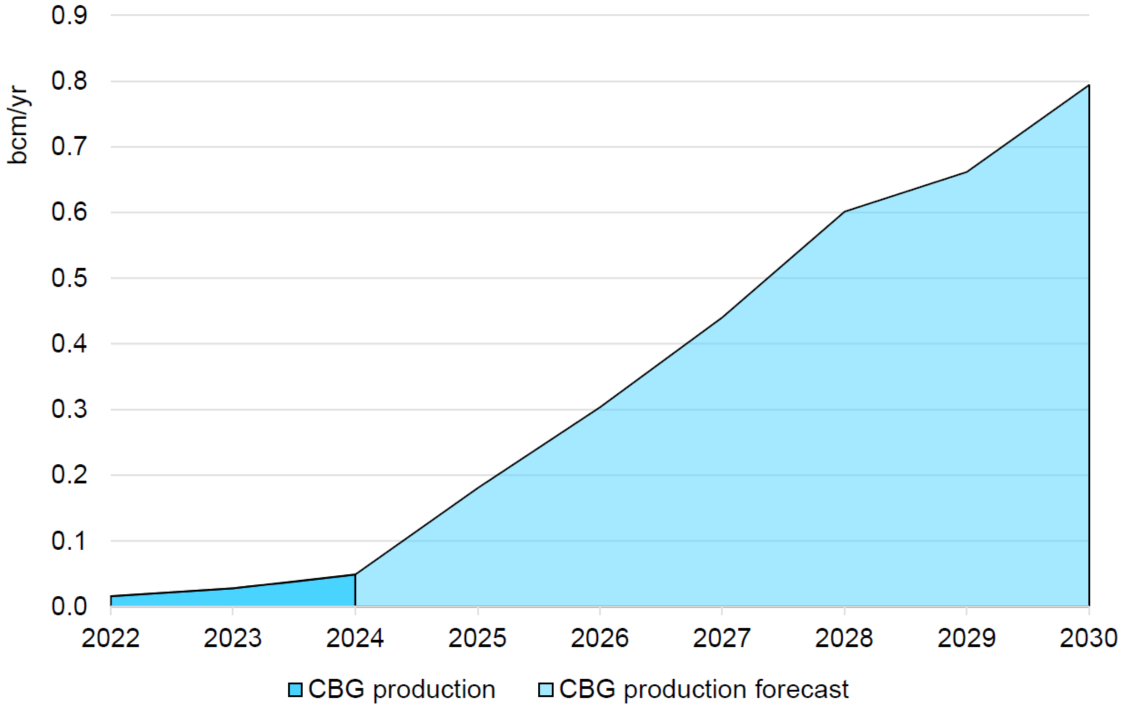


Source: IEA "Outlook for Biogas and Biomethane"

According to the IEA, India is still utilising only 5% of its vast biogas potential and a major production expansion (16 times the level by 2030) is expected (Figure 7-11).

Expanding the use of biogas in India has its challenges, as with the rollout of BEVs in Indonesia and bioethanol in Brazil. First is procuring biofeedstock, including managing seasonal fluctuations such as the concentration of agricultural residue generation immediately after harvesting, and the underdeveloped logistics infrastructure for feedstock collection in rural and other areas. Difficulty in investment decisions and financing due to non-transparent pricing and insufficient development of human resources and certification systems is also a challenge. Due partly to these challenges, according to the IEA, there are only 90 biogas production plants as of September 2024, compared with the SATAT target of 5 000 by 2024.

Figure 7-11 | Outlook for compressed biogas production volume towards 2030 in India



Source: IEA "India Gas Market Report Outlook to 2030"

As with Brazil's bioethanol, India's biogas utilisation has benefits such as reducing dependence on imported LNG and promoting agriculture, as well as contributing to carbon neutrality, and can be seen as one of the diverse decarbonisation pathways for the road transport sector that vary depending on the circumstances in each country. Suzuki Motor Corporation, a Japanese automaker, is also working with local dairy farmers to establish five biogas production plants in the state of Gujarat starting in 2025. However, we cannot say that India's biogas utilisation is supported by sufficient private-sector business incentives, unlike Indonesia's nickel refining and Brazil's bioethanol production. It is necessary to offer more carrots (support measures) alongside the stick (blending ratio regulations). While intergovernmental cooperation on climate change tends to lack variety and to focus on expanding renewable power sources and the early retirement of coal-fired power plants, going forward, it will be important to provide international assistance for more grass-rooted initiatives of this kind. With respect to Japan, utilising the bilateral Joint Crediting Mechanism (JCM) might be an option.

7.4 Conclusion

Key Global South countries such as Indonesia, Brazil and India are engaged in decarbonising the road transport sector by drawing on their regional resources and industrial strengths, from a broad perspective that transcends climate change and encompasses industrial policy and energy security. While all three countries are pursuing electrification and the broad adoption of biofuels, there are major differences in their priorities. There are a few insights we can draw from the above case analyses. First, the decarbonisation of power sources is a prerequisite for countries pursuing electrification of their road transport sector and battery electric vehicle (BEV) production. Reducing the environmental burden of production and other processes, shifting peak power demand and developing social infrastructure should follow. Biofuels provide an alternative decarbonisation pathway alongside electrification and also contribute to agricultural development. Furthermore, blending biofuels into conventional fuels may reduce the costs of developing new infrastructure. In summary, the cases of the three Global South countries clearly show that not only electrification but also diverse pathways must be examined from a comprehensive perspective when decarbonising the road transport sector.

8. Variable renewable electricity: challenges and integration costs

Decarbonisation requires adding vast amounts of non-carbon emitting power sources. In particular, solar photovoltaics (PV) and wind have been expanding significantly in recent years as their costs have come down considerably with progress in technology and economies of scale. Expectations for continued expansion of solar PV and wind remain high, and IEEJ Outlook 2026 projects that electricity generated from variable renewable energy will expand by about five times between now and 2050 in its Reference Scenario and by about seven times in its Advanced Technologies Scenario.

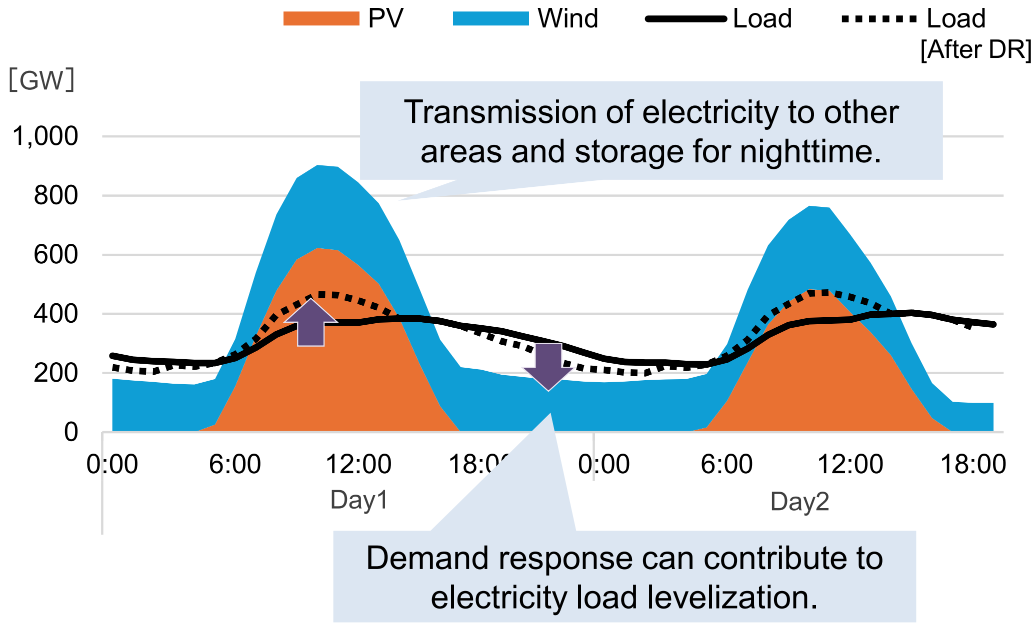
Solar PV and wind are sometimes referred to as variable renewable energy (VRE) as their power output is affected by natural conditions. As VRE deployment increases, there is a need for the electricity and energy systems to adapt to the increase in VRE. The costs necessary for this adaptation are called integration costs. This chapter describes the idea of integration costs as a challenge associated with the expansion of VRE and presents examples of analysis.

8.1 Challenges of VRE expansion

Response to output fluctuations and stable supply of electricity

As the power output from VRE fluctuates based on natural conditions, it is important to predict output and respond to changes in real time to maintain a stable supply of electricity. For example, in some countries and regions today (such as the Kyushu region of Japan), some power plants are subject to output curtailment during periods when VRE electricity supply is in surplus. Occasional electricity supply-demand tightness has also occurred when natural conditions caused VRE output to plunge and backup thermal power plants experienced unplanned shutdowns. As such, when introducing large amounts of VRE, it is essential to operate conventional power sources like thermal power generation flexibly to ensure the stable functioning of the power system. In addition, the use of technologies capable of instantly restoring the power supply-demand balance, such as power interchanges with other regions via transmission networks, demand-side load balancing (demand response) and storage batteries is being considered (Figure 8-1).

Figure 8-1 | An illustrative example of mass introduction of VRE and response by power systems



Source: IEEJ Outlook 2025

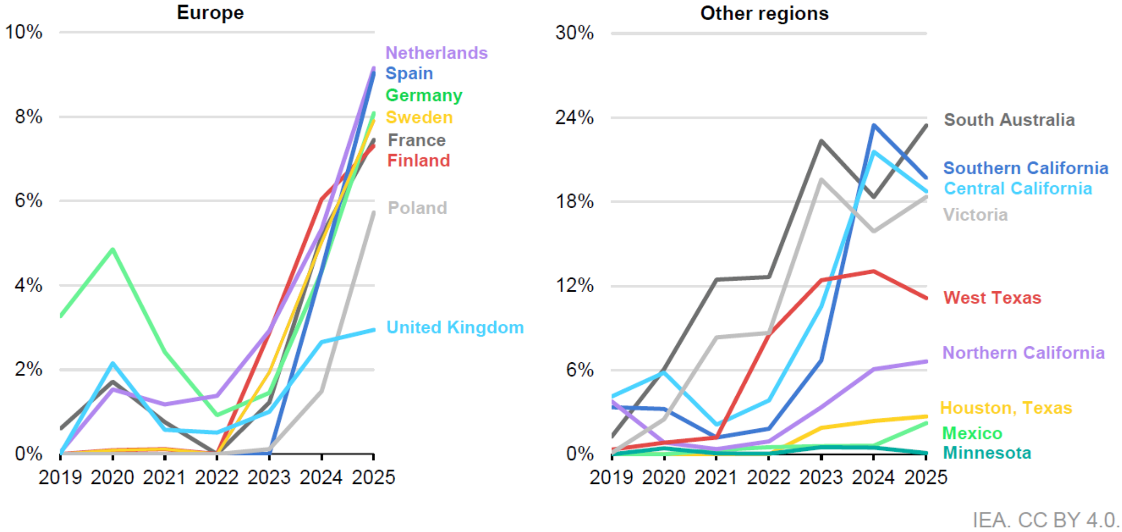
Shortage of power system flexibility and impact on the electricity market

One impact of VRE expansion is the effect on the electricity market. A notable example is negative pricing, in which wholesale electricity market prices become negative. According to the International Energy Agency (IEA) (2025), negative prices in wholesale electricity markets are still relatively rare on a global basis but have been increasing in some regions in recent years.

For example, in South Australia, which had an annual VRE share of around 65% in 2023, prices were negative for around 25% of the annual trading time in the wholesale electricity market. Similarly, in Texas, where the annual share of VRE was around 33% in 2023, prices were negative for around 10% of the annual trading time. While negative market prices do spur electricity consumption and urge consumers to utilise load balancing in situations of excess electricity supply, they are also known to worsen market revenues and in turn negatively impact investments in power sources.

IEA (2025) noted that negative prices are a result of wider fluctuation ranges in wholesale prices caused by insufficient system flexibility. It also noted that to respond to VRE output fluctuations, it is important to ensure power system flexibility by utilising thermal power generation and demand-side load balancing.

Figure 8-2 | Cases of negative prices in the wholesale electricity markets around the world



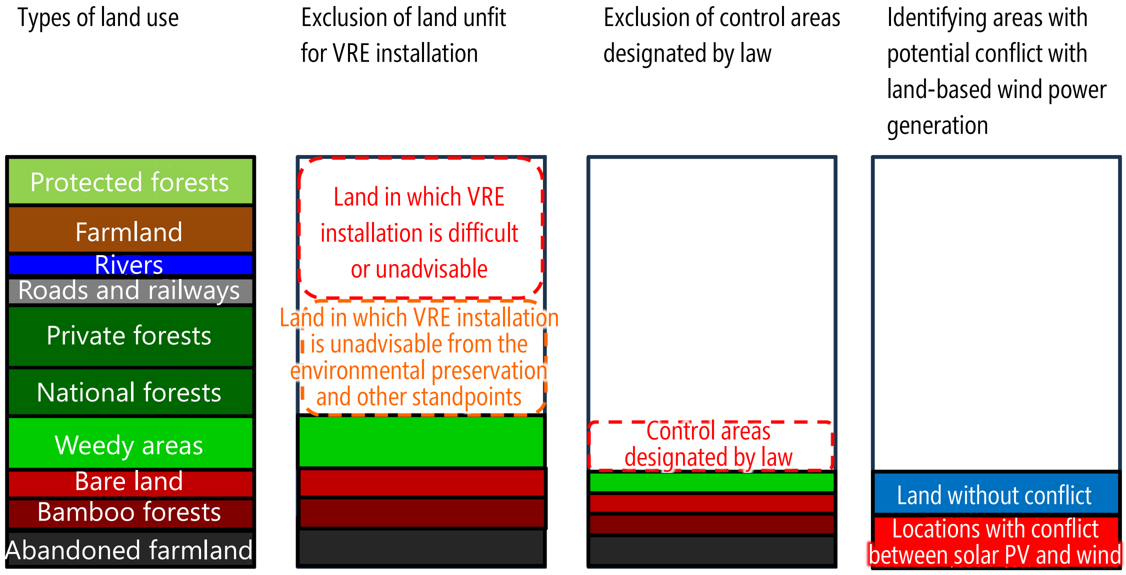
Source: IEA (2025), *Electricity Mid-Year Update 2025*, IEA, Paris https://www.iea.org/reports/electricity-mid-year-update-2025, Licence: CC BY 4.0

Constraints on resource development and land use

The availability of renewables, not limited to VRE, is affected by natural and land conditions. Regions with favourable conditions and a high energy supply potential tend to be concentrated in nature-rich areas. For instance, much of the supply potential for wind power generation is found in mountainous regions and offshore areas with favourable wind conditions that are often located far away from demand centres such as cities. This makes it necessary to build new power systems when developing these resources.

Furthermore, because developing this supply potential can disrupt harmony with the natural environment and other land uses (Figure 8-3), these factors must be considered when assessing supply potential to achieve sustainable renewable energy development. Renewable energy development usually starts in locations that are relatively easy to access from a regulatory perspective, and such sites become scarcer as projects advance. As a result, additional costs, such as those for power grid construction and environmental protection, tend to increase with time.

Figure 8-3 | Sample method for evaluating VRE plant locations



Source: 67th meeting of the Large-scale Renewable Energy Introduction and the Next-Generation Power Network, Committee on Energy Efficiency and Renewable Energy/Electricity and Gas Industry Committee, Advisory Committee for Natural Resources and Energy, Material 3; explanatory material by the IEEJ/Yokohama National University (2024)

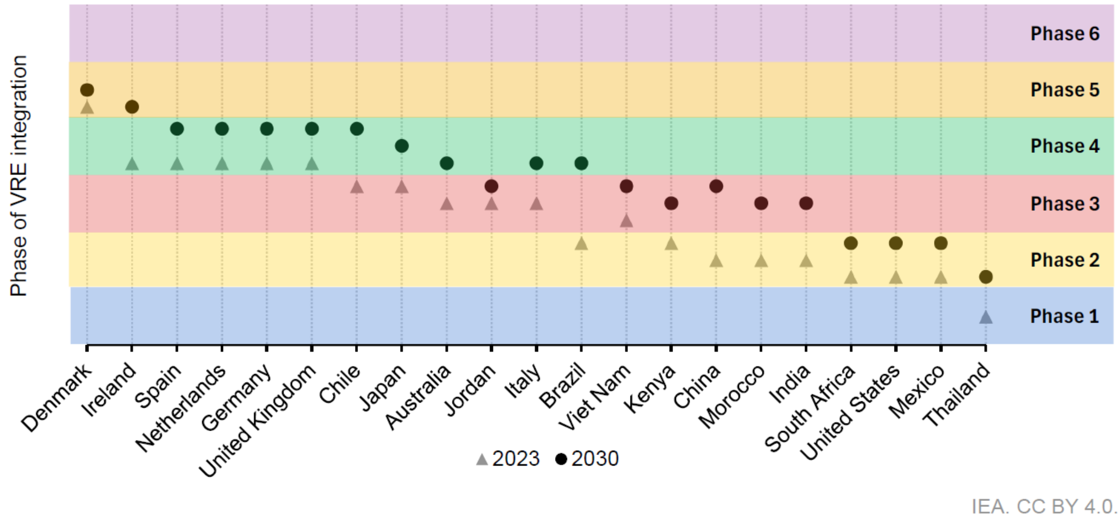
VRE grid integration challenges

IEA (2024) classifies countries by phase based on their progress in introducing VRE and other renewables, taking into account the stable supply capability of their power systems, market impact and other factors. For example, Denmark is categorised in Phase 5, an advanced phase of VRE introduction, because it can cover its electricity demand with VRE (especially wind) for almost all hours of the year. Meanwhile, Japan is lower than Denmark in Phase 3 and is expected to move up to Phase 4 in 2030 as more VRE is introduced.

The IEA expects that countries will move up in phases and notes that the measures required for their power systems will change depending on the phase.

In addition to technological and institutional measures, cost-related measures will be important going forward. The costs required for integrating a power source into the power system are essential, and these costs are referred to as integration costs. In introducing VRE, it is important to identify the integration costs as a metric that accounts for the nature of each power source, and integration costs are increasingly recognised as a challenge for the wider adoption of VRE.

Figure 8-4 | Phases of variable renewable energy introduction



Note: The phase assessments for 2030 are based, among other factors, on VRE forecasts that will be presented in the upcoming Renewables 2024 report.

Source: IEA (2024), *Integrating Solar and Wind*, IEA, Paris https://www.iea.org/reports/integrating-solar-and-wind, Licence: CC BY 4.0

8.2 Integration costs

Power system integration costs

In addition to the costs associated with power sources themselves, the Organisation for Economic Co-operation and Development (OECD)[38] notes that the following integration costs will be necessary.

- **Profile costs**: The costs for changing the operations of dispatchable power stations to address a supply-demand mismatch resulting from a deviation of power station output from the plan.
- **Balancing costs**: The costs arising from operating dispatchable power stations in grid-balancing mode to address brief output prediction errors lasting for a few seconds to a few minutes and brief output fluctuations.
- **Grid-related costs**: The costs for building core transmission networks connecting power plant locations and demand areas, and for installing power cables connecting power plants with the electric power grid.

Various approaches are being studied for analysing the power system integration costs based on these cost classifications, as shown in Table 8-1. The approaches have different focuses, such as the change in overall costs of the power system and the value of a power source in the market, thereby ensuring that integration costs are assessed from a variety of perspectives.

[38] OECD/NEA (2018) "The Full Cost of Electricity Provision"

Table 8-1 | Integration cost-related indicators and examples of analysis methods

Indicator	Description	Example of analysis
Integration cost, system cost	The cost obtained by subtracting the amount proportional to the levelised cost of electricity (LCOE) from the total cost of the power sector. There are many cases of evaluation for various regions around the world.	
System value	An indicator for evaluating the contribution of each power source to the power market. It is advocated in the IEA report “Next Generation Wind and Solar Power” (2016).	IEA
Levelised avoided cost of electricity (LACE)	An indicator proposed by the U.S. Department of Energy (DOE) and the Energy Information Administration (EIA). LACE indicates the economic advantage of a certain technology by considering the costs that would be avoided when a certain power source is introduced into the power system.	U.S. DOE/EIA, Levelized Costs of New Generation Resources in the Annual Energy Outlook (annual editions)
Enhanced levelized cost/wider system impact	This indicator expands the traditional LCOE to incorporate the marginal costs of a power source. Rather than a simple cost comparison, it enables evaluations that incorporate the impact on the power market.	Department for Business, Energy and Industrial Strategy (BEIS), Electricity Generation Costs 2020, etc.
System LCOE	This indicator is based on the marginal cost of each power source and is known to be effective for evaluating the impact of increasing new renewable capacities on the power market. By adding on the difference between marginal unit prices of each power source and demand to LCOE, the impact on the overall power system is incorporated more accurately.	Hirth et al., 2016 and others
Marginal system LCOE	This is an indicator that is based on the marginal cost of each power source and is used to compare and analyse certain power sources. It is used especially to compare two types of technologies in terms of relative economic efficiency.	Ueckerdt et al., 2013; Reichenberg et al., 2018 and others

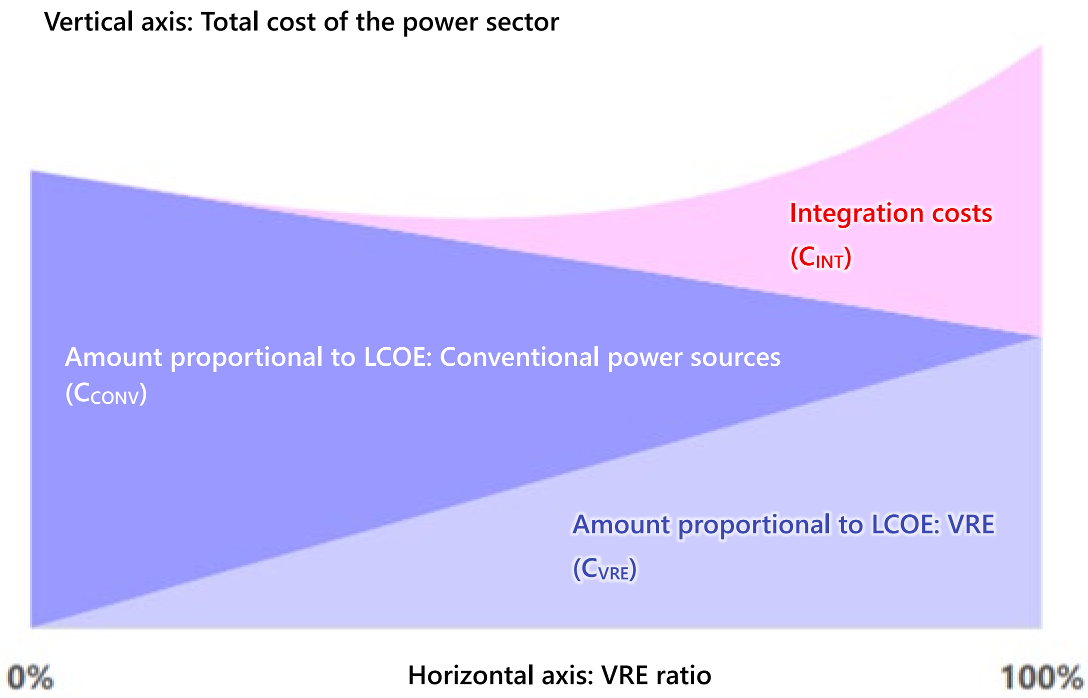
Indicator	Description	Example of analysis
Relative marginal system LCOE/ average system LCOE	This indicator evaluates the integrability of a power source and its value in the market based on its marginal cost and average cost.	Matsuo and Komiyama, 2021

Source: Created based on Matsuo (2021), Assessment of costs by power source with a focus on OECD/NEA and IEA reports

Optimal power generation mix integration costs

In considering the future power generation mix and evaluating its economic efficiency, it is important to assess total system costs including integration costs, in addition to the costs of each power source itself. Matsuo (2025) notes that when including the costs for integrating a power source into the power system (integration cost) in the evaluation, there is an optimal combination of power sources in terms of costs (Figure 8-5).

Figure 8-5 | Conceptual diagram of power generation costs (LCOE) and integration costs



Source: First meeting of the Power Generation Cost Verification Working Group, Material 1, Material 5 Overview of Assessment by Power Generation Cost Verification Working Group (material submitted by Committee Member Matsuo (2024)

With technological progress, the generation cost of renewables per 1 kWh of output (LCOE) is now lower than that of conventional power sources. As such, there are high expectations for replacing conventional power sources with new renewable capacities on cost-competitiveness grounds. This means that C_{CONV} will be gradually replaced by C_{VRE} as shown in Figure 8-5.

Meanwhile, additional costs for installing battery systems and reinforcing the grid will arise as VRE is introduced in large amounts. As a result, costs represented by C_{INT} in Figure 8-5 will be necessary for some power sources in addition to their development costs.

8.3 Power generation including integration costs

Assessing the power generation mix with integration costs

To analyse the integration costs with incremental amounts of variable renewable energy (VRE), we identified the power generation mix that produces the smallest energy system costs for the Association of Southeast Asian Nations (ASEAN) as a whole using a model that analyses the entire energy system.

For the analysis, the NE_ASEAN model[39], a linear planning model co-developed by the IEEJ and the Otsuki Group at Yokohama National University based on the NE_Japan model developed by the Otsuki Group, was used. The amount of VRE capacity to be introduced by 2060 and its integration costs were analysed based on the assumption that each country will reduce greenhouse gas (GHG) emissions in line with the Nationally Determined Contributions (NDCs).

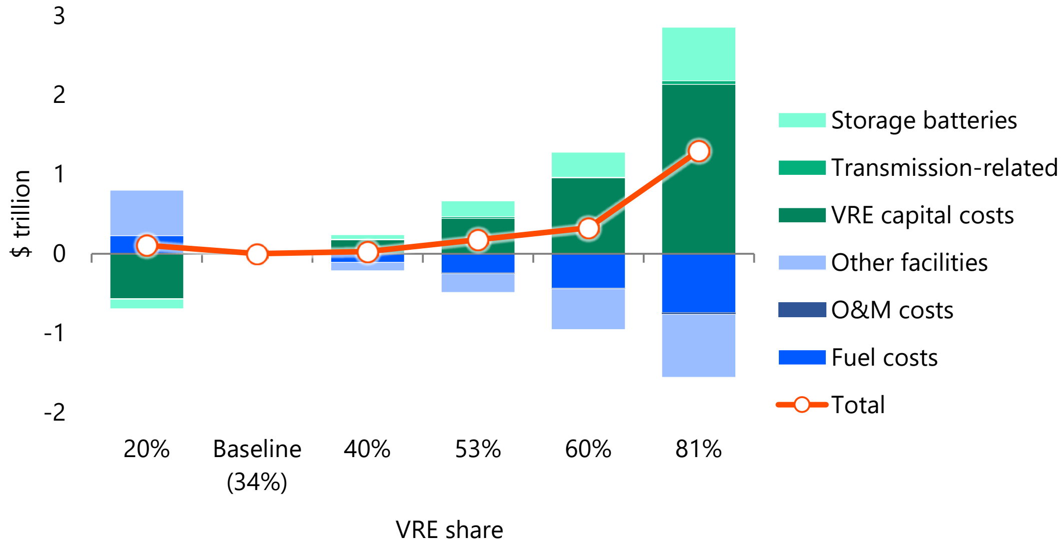
Analysis of power generation mixes including integration costs

For nations to reduce their GHG emissions in line with their NDCs, introducing decarbonised energies is essential. Based on the conditions of this estimation, ASEAN's energy system costs are estimated to be the lowest in 2060 when the VRE share is around 30%. Using this result as the baseline, we charted the system costs for higher and lower shares of VRE.

Facility and fuel costs for conventional power generation decrease as VRE increases from the baseline. On the other hand, the costs for introducing VRE itself increase, along with additional costs for integration, such as those for storage batteries (Figure 8-6). For example, when the share of VRE is raised to 60% for ASEAN as a whole, the costs would increase by 300 billion dollars between 2030 and 2060, as opposed to a much greater increase of $1.3 trillion if the share is raised to 80%.

[39] The IEEJ-NE_ASEAN model analyses the combination of energy technologies, including power generation and storage facilities, that minimises the overall cost of the energy system. See below for an overview of the model and an example analysis. IEA (2023), Decarbonisation Pathways for Southeast Asia, IEA, Paris https://www.iea.org/reports/decarbonisation-pathways-for-southeast-asia, Licence: CC BY 4.0

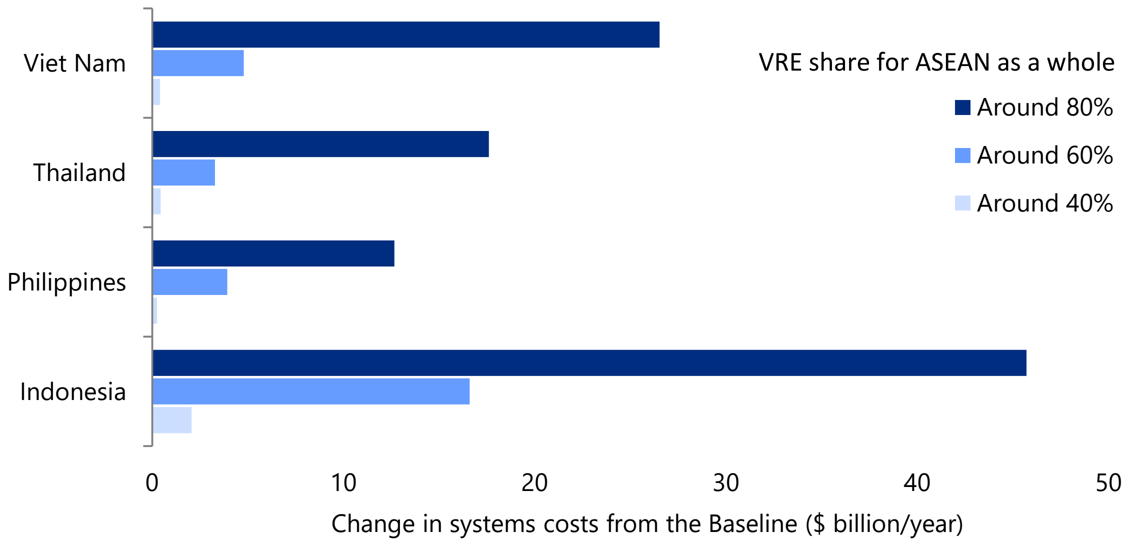
Figure 8-6 | VRE shares and system costs in ASEAN [total for 2030–2060]



Notes: The assumptions for international and other key transmission lines are based on the maximum scale of grid development being considered under the ASEAN Power Grid initiative. All numbers are in real terms; 2017 prices.

To promote the energy transition required to decarbonise the ASEAN region, ASEAN-wide collaboration and cooperation are essential, alongside strengthening efforts within each country. Meanwhile, attention must be paid to the potentially significant differences in additional costs between countries. Behind these gaps lie variations in geographical and natural conditions and the availability of infrastructure, between the ASEAN nations, resulting in major disparities in their abilities to add more VRE (Figure 8-7). The impact of the cost increase associated with adding VRE is particularly significant in Indonesia, Viet Nam and Thailand, which have large populations and economies.

Figure 8-7 | VRE shares and system costs in ASEAN [2060]



Notes: The assumptions for international and other key transmission lines are based on the maximum scale of grid development being considered under the ASEAN Power Grid initiative. All numbers are in real terms; 2017 prices.

Here we present an analysis of different shares of VRE and integration costs. Some ASEAN nations are rich in non-VRE renewables, such as hydro and geothermal resources. Meanwhile, the ability to bear additional costs associated with reaching carbon neutrality varies between nations depending on their economic circumstances and national scale. To utilise VRE and other renewable energies even further, alongside cross-border cooperation, it is essential for each country to decarbonise through a pathway that suits its individual circumstances.

9. Importance of reality-based climate targets and adaptation

—Advanced Technologies Scenario as a pathway for reaching the 2°C climate target—

The 2015 Paris Agreement sets a target to limit global warming to well below 2°C above pre-industrial levels and encourages 'efforts' to stay below 1.5°C. In other words, the target of the Paris Agreement is 2°C and 1.5°C can be seen as an additional, non-binding target. However, following the issuance of the Special Report on Global Warming of 1.5°C by the Intergovernmental Panel on Climate Change (IPCC) (2018) and the declaration of net-zero emissions targets by a number of key nations around 2020, the 26th session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP26) held in 2021 passed a 'resolution' that contains special language highlighting the significance of efforts to stay below 1.5°C on its own, rather than in tandem with the 2°C target. At present, the Group of Seven (G7) countries including Japan are explicitly committed to the 1.5°C target (except the US Trump administration). In July 2025, the International Court of Justice issued an advisory opinion stating that the Nationally Determined Contributions (NDCs) of the parties to the Paris Agreement must be aligned with the 1.5°C temperature target of the Agreement.

However, in reality, the world's greenhouse gas emissions continue to rise, and the prospects for achieving the 1.5°C target are becoming increasingly challenging. This chapter analyses the current status of major nations and others regarding the 1.5°C target, and it demonstrates that the 1.5°C target is no longer achievable based on the remaining carbon budget and that the Advanced Technologies Scenario of the IEEJ Outlook 2026 provides a pathway for reaching the alternative 2°C target. The increasing significance of adaptation in efforts to achieve the 2°C target is also discussed.

9.1 Recent developments regarding the 1.5°C target

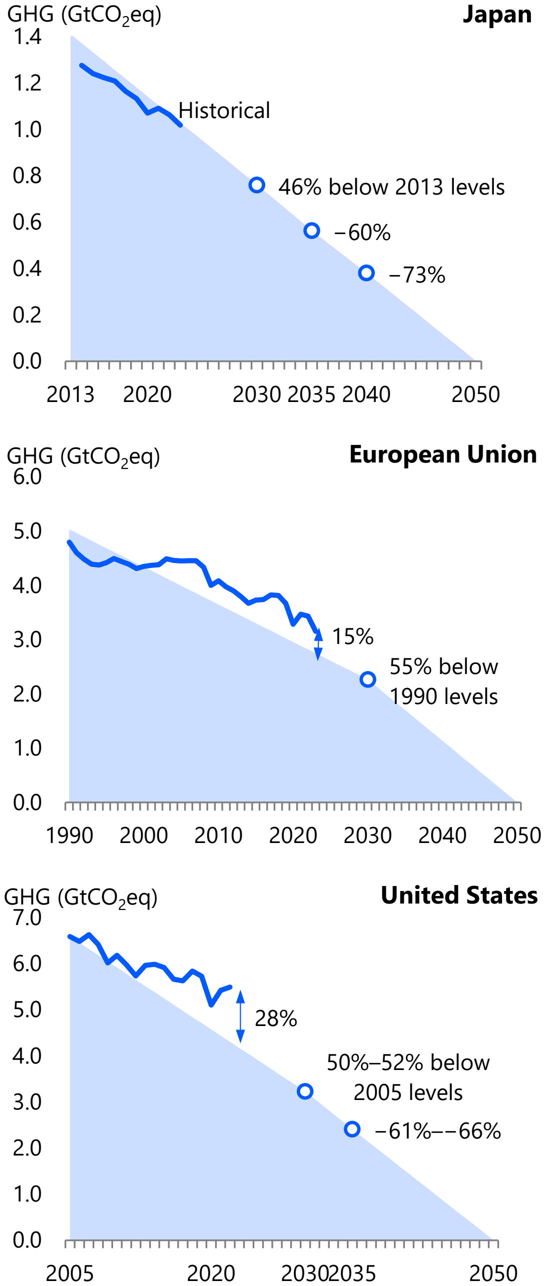
Moves in advanced economies

As mentioned earlier, advanced economies, particularly the G7 countries (excluding the United States; see Section 5.1 for the situation in the United States) are committed to the 1.5°C target. However, the GHG emissions of no country other than Japan are on track to meet the 2030 targets, and emissions remain above the required levels (Figure 9-1)[40].

While all countries need to reinforce their emissions reduction measures to reach net-zero in 2050, unlike around 2020, when climate action was a top policy priority, energy security and the need to ensure affordable energy supply have gained much greater weight in recent years. As a result, the G7 countries have faced considerably more difficulty in managing their policies.

[40] As Italy has not set its own reduction targets, a strict comparison is not possible; however, when compared to the European Union-wide targets, it is still not on track.

Figure 9-1 | Emission reduction pathways of G7 nations and their progress



	Latest GHG emissions ($MtCO_2$)	Deviation from the 2030 target pathway ($MtCO_2$, %)
Japan	1 017	−9.3 (−0.9%)
European Union	3 152	406 (14.8%)
United States	5 489	1 186 (27.6%)
Germany	741	143 (24.0%)
France	339	40 (14%)
United Kingdom	389	30 (8%)
Canada	670	143 (27%)

The Parties to the Paris Agreement were required to submit their 2035 NDCs by February 2025. However, only 52 countries, including nine advanced economies, have done so as of the end of September 2025. To meet the 1.5°C target, countries were encouraged to set a reduction target of 60% from 2019 levels for their 2035 NDCs based on the global stocktake at COP28 (2023). However, the only advanced economy governments that have met this target are a small number of non-EU European countries such as the United Kingdom, as well as Australia (Table 9-1). Most advanced economies remain committed to the 1.5°C target but are assumed to be taking more realistic actions regarding the 2035 target.

Table 9-1 | 2035 targets in the new NDCs of advanced economies

	2030	2035
Japan	46% reduction from 2013 levels	60% reduction from 2013 levels (54% reduction from 2019 levels)
European Union	55% reduction from 1990 levels	66.25%–72.5% reduction from 1990 levels*1 (54%–62% reduction from 2019 levels)
United Kingdom	68% reduction from 1998 levels	81% reduction from 1990 levels (66% reduction from 2019 levels)
Switzerland	50% reduction from 1990 levels	65% reduction from 1990 levels (60% reduction from 2019 levels)
United States (under the Biden administration)	50%–52% reduction from 2005 levels	61%–66% reduction from 2005 levels (55%–61% reduction from 2019 levels)
Canada	40%–45% reduction from 2005 levels	45%–50% reduction from 2005 levels (44%–49% reduction from 2019 levels)
New Zealand	50% reduction from 2005 levels	51%–55% reduction from 2005 levels (50%–54% reduction from 2019 levels)
Norway	55% reduction from 1990 levels	70%–75% reduction from 1990 levels (70%–75% reduction from 2019 levels)
Australia	43% reduction from 2005 levels	62%–70% reduction from 2005 levels (53%–63% reduction from 2019 levels)
Iceland	41% reduction from 2005 levels	50%–55% reduction from 2005 levels (48%–53% reduction from 2019 levels)
Russia	30% reduction from 1990 levels	33%–35% reduction from 1990 levels (39%–44% reduction from 2019 levels)

*1: The next NDC is yet to be released as the IEEJ Outlook 2026 is being written. The information is based on the State of Intent released on 18 September 2025.

Under such circumstances, the leader of the UK Conservative Party, Kemi Badenoch, made a noteworthy comment in March 2025 that 'Net zero by 2050 is impossible. I don't say that with pleasure. I want a better future, a better environment for our children. But we have to get real'. The Tories were the ruling party when the United Kingdom hosted COP26. It was the current leader of that same party who stated that net zero is impossible, not for the world, but for the United Kingdom.

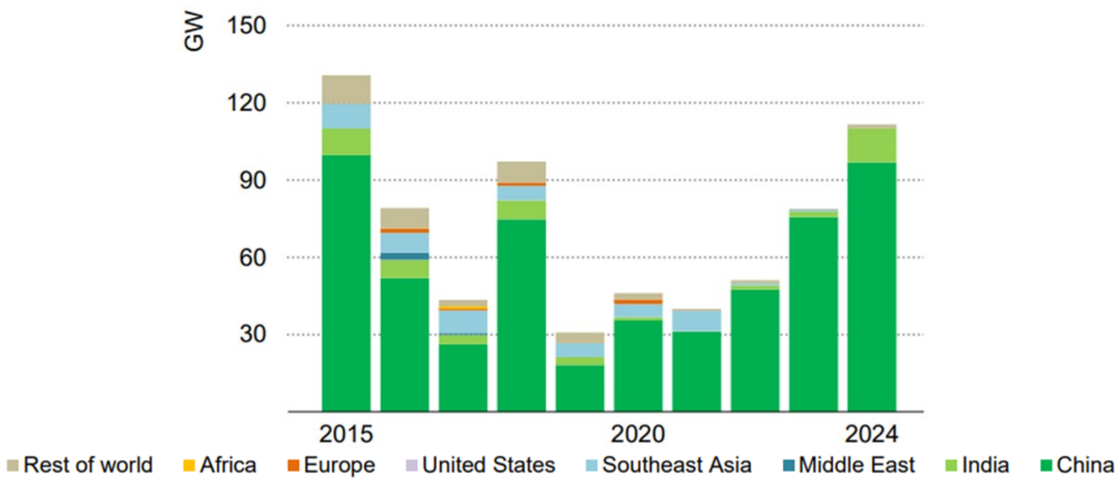
There are moves to revise the 1.5°C target in the private sector as well. The Net-Zero Banking Alliance (NZBA) was launched at COP26 to align the GHG emissions financed by financial institutions with the 1.5°C target. However, with the withdrawal of six key US banks at the end of 2024, and subsequent withdrawals by Japanese banks, the NZBA revised its policy in April 2025 to also recognise the 2°C target.

Moves in emerging economies

One of the reasons for the continued increase in the world's energy-related carbon dioxide (CO2) emissions is the ongoing growth in coal consumption in China and India. As of 2024, China and India account for 56% and 15%, respectively, of global coal consumption, ranking as the world's first and second largest consumers.

According to the International Energy Agency (IEA), in China, final investment decisions (FIDs) for building 100 GW of coal-fired power plants were made in 2024 alone (Figure 9-2). FIDs for new coal-fired power plants in China decreased to about 30 GW in 2019 but subsequently increased, reaching 100 GW in 2024, the highest level in the last decade.

Figure 9-2 | Final investment decisions for new coal-fired power plants



Source: IEA "World Energy Investment 2025"

It goes without saying that existing coal-fired power plants are being retired as new ones are built. However, only 4.7 GW/year of plant capacity has been scrapped in the last five years, resulting in a significant net increase in coal-fired power generation capacity in China. The installed capacity of renewables has also grown significantly, with 341 GW of solar photovoltaic power generation capacity and 80 GW of wind power generation capacity newly constructed in 2024. However, based on the capacity factor of these renewable power sources in China, the output from new coal-fired capacity would match that of new solar photovoltaic and wind capacity even if the capacity factor of the coal capacities is around 50%. Therefore, building 100 GW of new coal-fired power plants per year would have an immeasurable impact on China's CO_2 emissions.

At the Climate Summit held on the margins of the United Nations General Assembly in New York on 24 September 2025, Chinese leader Xi Jinping announced China's next NDC to 'reduce GHG emissions by 7% to 10% from peak levels by 2035'. European think-tanks estimate that China is actually capable of reducing its CO_2 emissions by at least 30% from 2023 levels by 2035 and staying on track to meet the 1.5°C target, and the view that China's next NDC is insufficient is becoming increasingly widespread.

According to the IEA, in India, FIDs for building 15 GW of coal-fired power plants were made in 2024, again the largest in the last decade. The world's largest coal company, Coal India Limited, which supplies three-fourths of India's coal demand, announced in June 2025 that it would reopen 32 of its defunct coal mines and develop five new ones, citing the inability of renewables to meet the growing demand. The share of coal-fired power generation, which is currently over 70% of the total electricity generated, will still be 50% in 2031–2032, according to the Indian government, indicating that coal will remain in use in the future.

9.2 Comparison of the Advanced Technologies Scenario and the 2°C target

The viability of the climate target was quantitatively evaluated based on the carbon budget[41]. As mentioned in previous IEEJ Outlook[42], the remaining carbon budget needed to keep the increase in global temperature below 1.5°C with a 50% probability is quickly decreasing from the level reported at the time of the Sixth Assessment Report (AR6) Synthesis Report (SYR) of the Intergovernmental Panel on Climate Change (IPCC) due to annual emissions. Specifically, IPCC AR6 SYR estimated the remaining carbon budget to be 500 $GtCO_2$ from 2020 onwards. However, the latest estimate from the Indicators of Global Climate Change (IGCC)[43] (IGCC 2024)[44] shows a significant decline to 130 $GtCO_2$ from 2025 onwards. This value is barely four years' worth of emissions at current levels, and, based on a simple calculation using a linear decrease in emissions, the world will need to go net-zero in 2032 (Figure 9-3). According to the IGCC 2024, the difference from the level of 500 $GtCO_2$ as of IPCC AR6 SYR consists of a decrease of 200 $GtCO_2$ due to emissions in 2020–2024, a decrease of a little over 100 $GtCO_2$ due to an upward revision of warming associated with a reduction of cooling aerosols, and a decline of about 40 $GtCO_2$ due to the rise in estimated warming based on the high temperatures observed in recent years. Given this estimated value, the 1.5°C target is already effectively unattainable. Therefore, the realistic option would be to pursue 2°C as the target aligned with the Paris Agreement. This is not necessarily a step back, but rather represents a return to the original target of the Paris Agreement.

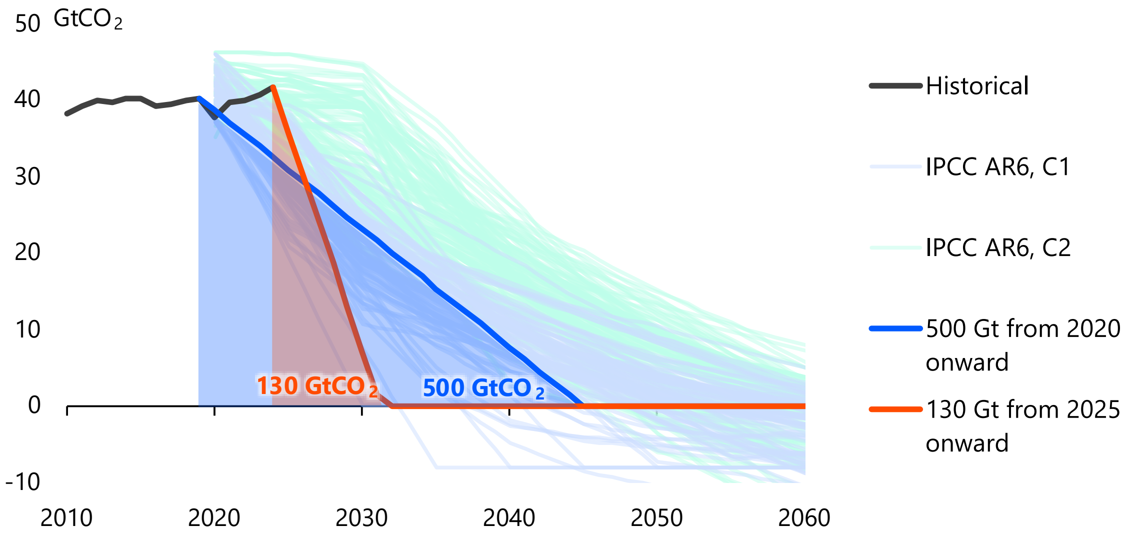
[41] The carbon budget is the maximum value of cumulative net CO_2 emissions artificially achieved to keep temperature rise below a certain threshold with a given probability. The residual carbon budget is the amount remaining after subtracting the quantity already emitted in the past.

[42] IEEJ Outlook 2024 and IEEJ Outlook 2025

[43] IGCC is an international research project that publishes the residual carbon budget annually. A similar initiative is the Global Carbon Budget (GCB).

[44] Forster et al., "Indicators of Global Climate Change 2024: annual update of key indicators of the state of the climate system and human influence", ESSD, 17, 2641–2680, 2025. https://essd.copernicus.org/articles/17/2641/2025/

Figure 9-3 | Carbon dioxide emission pathway consistent with the 1.5°C target



Notes: 'Historical' was obtained from Global Carbon Budget 2024[45]. 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'[46].

We used the carbon budget concept again to see whether the carbon dioxide (CO_2) emission pathway of the Advanced Technologies Scenario of the IEEJ Outlook 2026 is consistent with the 2°C target. To do so, it is necessary to extend the energy-related CO_2[47] emission pathway of the Advanced Technologies Scenario, which ends in 2050, into a pathway that continues until anthropogenic CO_2 emissions, including non-energy-related emissions, reach net-zero. For this purpose, we roughly estimated energy-related CO_2 emissions for 2051 onwards, assuming that the pace of reduction in 2050 (−0.61 $GtCO_2$/year) will continue thereafter. We assumed that emissions would be flat after reaching net-zero. Next, we set the amounts of non-energy-related CO_2 emissions (land-use change, cement process, cement absorption, flaring, etc.) by referring to the Illustrative Mitigation Pathways (IMPs) in the IPCC AR6 Working Group 3 (WG3) report. Among the IMPs with various mitigation levels, for non-energy-related CO_2 emissions, we referred to the Moderate Action (ModAct) aligned with the climate policies based on the Nationally Determined Contributions (NDCs) submitted in 2020, to adopt a slightly conservative assumption. Lastly, non-energy-related CO_2 emissions and energy-related CO_2 emissions were aggregated to obtain an estimated CO_2 pathway.

The estimated CO_2 pathway reaches net-zero in 2073, as shown in Figure 9-4. As the IPCC AR6 WG3 report assumes that the 2°C CO_2 emission pathway reaches net-zero around 2070–2080 (with a 67% probability)[48], the estimated pathway appears broadly consistent with the 2°C target.

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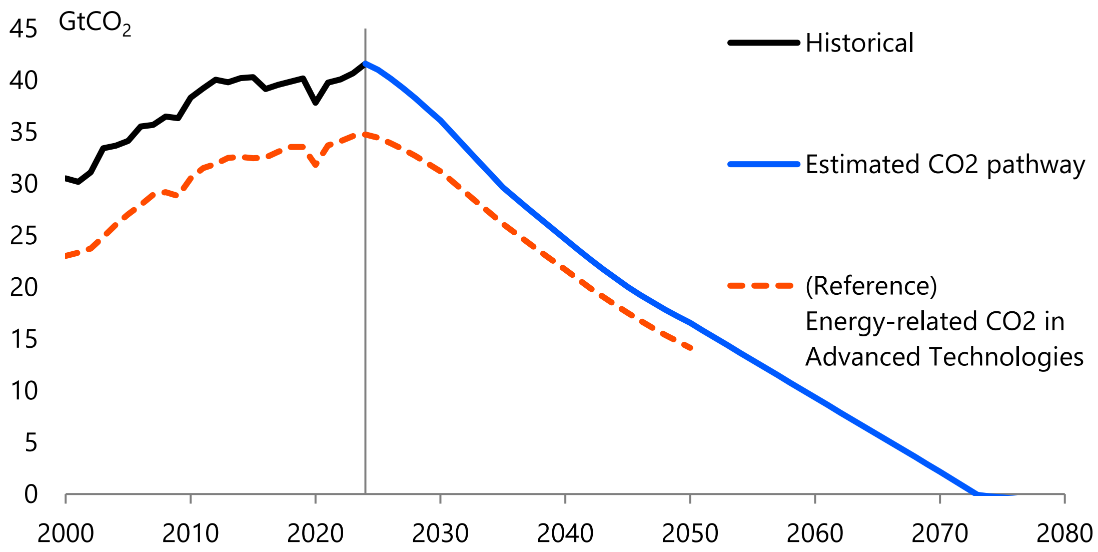
[45] Global Carbon Budget, "GCB 2024". https://globalcarbonbudget.org/gcb-2024/.
[46] Byers et al., "AR6 Scenarios Database hosted by IIASA", International Institute for Applied Systems Analysis, 2022. https://data.ene.iiasa.ac.at/ar6/#/login?redirect=%2Fworkspaces.
[47] The amount removed via Direct Air Capture and Storage (DACCS) has been taken into account.
[48] IPCC, "Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change", 2022, Figure SPM.5.
https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SummaryForPolicymakers.pdf

However, our estimate must be compared with the latest remaining carbon budget for accuracy. The total CO_2 emissions along the pathway from 2025 until net-zero is reached are 906 $GtCO_2$, which is a level capable of limiting the global temperature increase to within 2°C (50% probability) based on the latest remaining carbon budget (Table 9-2). However, total emissions slightly exceed the remaining carbon budget of IGCC 2024 for the 2°C target (67% probability).

Figure 9-4 | Estimated anthropogenic CO_2 emission pathway until reaching net-zero, created by extending the energy-related CO_2 emission pathway of the Advanced Technologies Scenario to 2050



Notes: 'Historical' was obtained from Global Carbon Budget 2024[49]. '(Reference) Advanced Technologies Scenario' is the energy-related CO_2 emission pathway of the Advanced Technologies Scenario. 'Estimated pathway' is the estimated anthropogenic CO_2 emission pathway until reaching net-zero, created by extending the energy-related CO_2 emission pathway of the Advanced Technologies Scenario to 2050.

[49] Global Carbon Budget, "GCB 2024". https://globalcarbonbudget.org/gcb-2024/.

Table 9-2 | Comparison of cumulative CO_2 emissions from the estimated pathway and the remaining carbon budget

Scenario		Cumulative CO_2 from 2025 onwards ($GtCO_2$)
Estimated pathway (cumulative total till net-zero is reached)		906
2°C (50% probability)	IPCC AR6 SYR (start year adjusted)	1 150
	GCB 2024	1 110
	IGCC 2024	1 050
2°C (67% probability)	IPCC AR6 SYR (start year adjusted)	950
	GCB 2024	Not specified
	IGCC 2024	870
2°C (50% probability)	IGCC 2024	490

Note: As the remaining carbon budget in IPCC AR6 SYR is for the period starting from 2020, the emissions for the five years from 2020 to 2024 (200 $GtCO_2$) have been removed to obtain the values in the table.

Given the uncertainty of the estimated energy-related CO_2 pathway and remaining carbon budget in this analysis, and to maximise the probability of achieving the 2°C target, it is important to continue exploring possibilities for deeper emissions reductions beyond those in the Advanced Technologies Scenario.

9.3 Adaptation

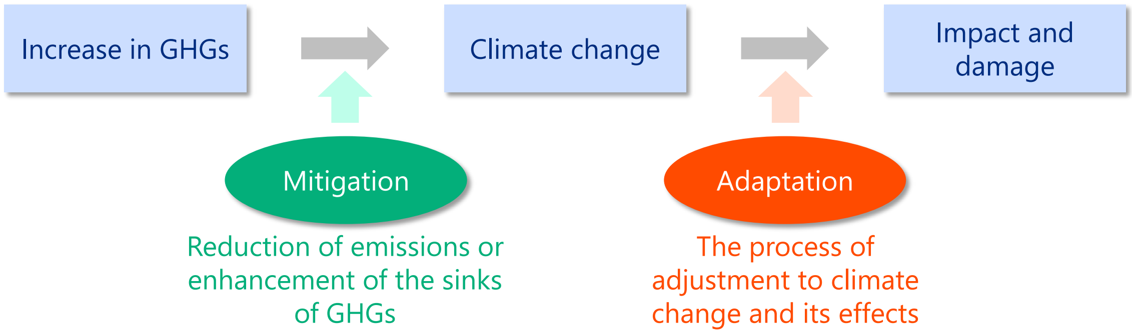
What is adaptation?

Mitigation (reduction) actions have not reached the scale or degree necessary to limit the increase in average global temperature in line with the long-term target of the Paris Agreement, and the temperatures are rapidly approaching and, in some cases, surpassing 1.5°C above pre-industrial levels. The unprecedented frequency and intensity of recent climate impacts underscore their scale and the challenge of adapting to them. Effective and appropriate adaptation actions are needed more urgently than ever.

Measures to address climate change can be divided into ‘mitigation’ and ‘adaptation’. 'Mitigation' means reducing greenhouse gases (GHGs) and expanding sinks to prevent climate change from worsening. On the other hand, ‘adaptation’ is the process of adjusting to and responding to climate change and its impacts to reduce the damage (Figure 9-5).

It is important to first alleviate the impacts of climate change through mitigation, and, where this proves insufficient, implement adaptation measures as well. With the 1.5°C target becoming effectively unachievable, adaptation will increase in importance going forward.

Figure 9-5 | What is adaptation?



How large is the adaptation finance gap?

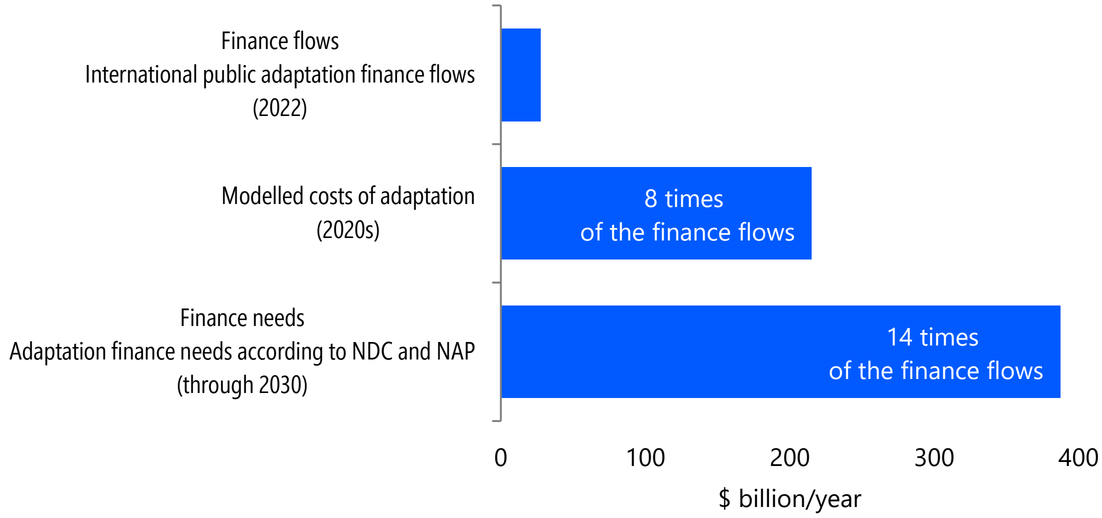
On the demand for adaptation financing, the Adaptation Gap Report 2023[50] of the United Nations Environment Programme (UNEP) describes the method for estimating adaptation financing needs and modelled adaptation costs, as well as their results. Adaptation financing needs were estimated by evaluating and analysing those presented in the National Adaptation Plans (NAPs) and the Nationally Determined Contributions (NDCs), by extrapolating the results to all countries including those that have not submitted their NAPs or NDCs. Modelled adaptation costs estimate the economic impacts of climate change and evaluate the costs required to reduce those impacts. It should be noted that the modelled costs and financing needs do not include private sector adaptation needs such as those for private infrastructure, increased air-conditioning demand and impacts on labour productivity due to rising temperatures.

UNEP's Adaptation Gap Report 2024[51] presents updated estimates. For adaptation needs, the modelled costs of adaptation amounted to 215 billion dollars per year and the financing needs to $387 billion per year, while merely $28 billion were provided to developing countries via international public adaptation finance flows in 2022 (Figure 9-6). We can see there still lies an extremely large gap if we compare the adaptation needs and the international public finance flows in 2022. There is still an extremely large gap between the adaptation needs and the international public finance flows in 2022. The finance needed for adaptation is 8 to 14 times the amount currently available. The priority is to bridge this significant gap in adaptation finance.

For adaptation finance and mitigation finance, Article 9.4 of the Paris Agreement stipulates that 'the provision of scaled-up financial resources should aim to achieve a balance between adaptation and mitigation'. This is understood to mean that the ratio of adaptation to mitigation finance should be brought to 1:1.

[50] https://www.unep.org/resources/adaptation-gap-report-2023
[51] https://www.unep.org/resources/adaptation-gap-report-2024

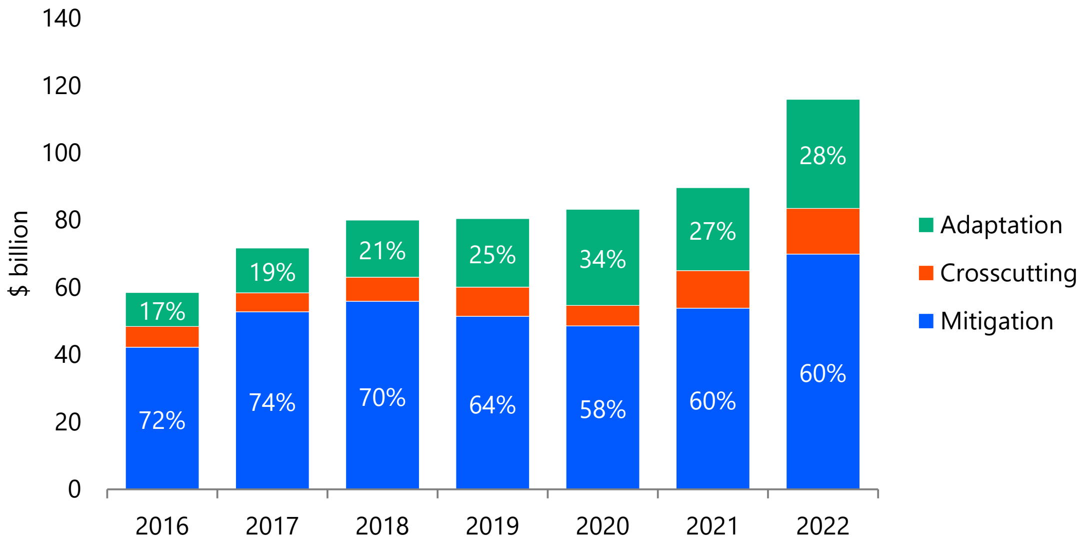
Figure 9-6 | Adaptation finance gap



Source: Created based on UNEP (2024) Adaptation Gap Report 2024.

If we compare the amounts of adaptation and mitigation finance within the climate finance provided and mobilised by advanced economies, mitigation finance accounted for 72% and 60% in 2016 and 2022, respectively (Figure 9-7). On the other hand, adaptation finance accounted for 17% and 28% in those same years, remaining far short of the amount of mitigation finance. It is necessary to take measures to ensure a balance between adaptation and mitigation finance.

Figure 9-7 | Climate finance provided and mobilised by area (including private sector finance)



Source: Created based on Organisation for Economic Co-operation and Development (OECD) (2024), Climate Finance Provided and Mobilised by Developed Countries in 2013–2022.

Various areas of adaptation

UNEP's Adaptation Gap Report gives the following as the key areas and sectors for adaptation: 'infrastructure, energy and settlement', 'water and floods', 'agriculture and fisheries', 'coastal and marine resources', 'forests and ecosystems', 'extreme weather and disaster risk' and 'human health'. These areas and sectors are described in detail in Table 9-3.

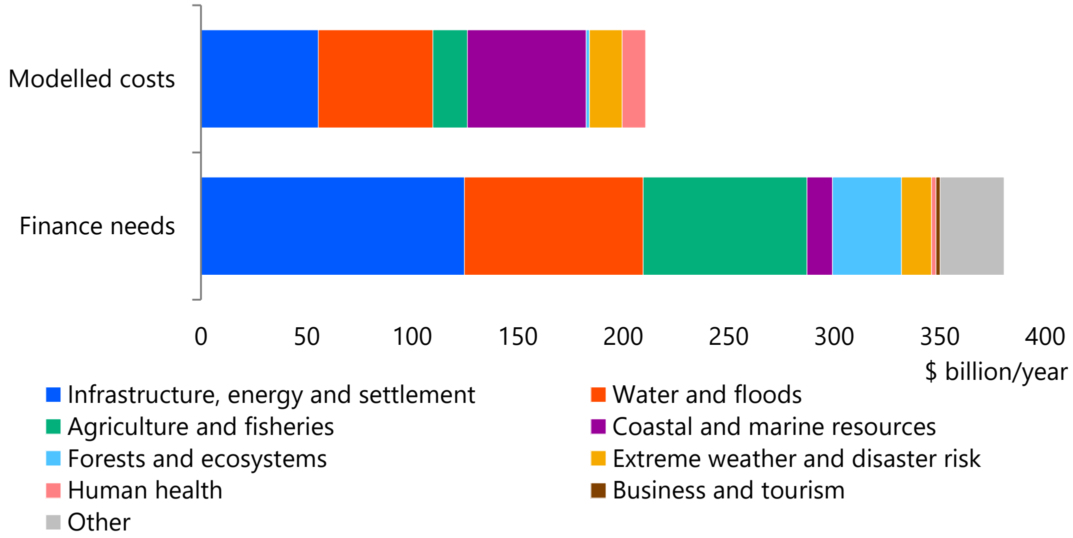
Table 9-3 | Key areas with adaptation needs

Area/sector	Description
Infrastructure, energy and settlement	Making infrastructure resilient in the energy and transportation subsectors
Water and floods	River flood protection (structures)
Agriculture and fisheries	Agricultural research and development, water management and infrastructure to address the impact of climate change on chronic hunger Addressing changes in fish catch potential, improving marine and coastal ecosystems (expanding marine protected areas) and safety at sea (responding to hazards from tropical windstorms, etc.)
Coastal and marine resources	Coastal protection (to address flood risks using dikes, etc.) and beach nourishment (to reduce erosion)
Forests and ecosystems	Expanding protected areas
Extreme weather and disaster risk	Weather and climate services (early warning systems, etc.) and social protection (funding for shock (climate extremes) response programs)
Human health	Disease control to address increase in malaria, dengue and diarrhoeal diseases, heat-alert schemes and supporting health sector responses to address increased heat-related mortality, disease surveillance and making future water, sanitation and hygiene (WASH) investment resilient

Source: Created based on UNEP (2023) Adaptation Gap Report 2023.

The key adaptation areas with high financing needs are 'agriculture and fisheries', 'water and floods' and 'infrastructure, energy and settlement', while those with high modelled costs are 'water and floods', 'infrastructure, energy and settlement' and 'coastal and marine resources' (Figure 9-8). Other areas that make up a large portion are 'forests and ecosystems' in terms of high financing needs and 'human health' with high modelled costs. It is necessary to consider which areas to prioritise for adaptation based on actual and future needs.

Figure 9-8 | Finance needs and modelled costs



Source: Created based on UNEP (2023/2024) Adaptation Gap Report 2023 and 2024.

10. Future of artificial intelligence and energy demand

The close interrelationship between artificial intelligence (AI) and energy is at the centre of global attention. As a symbolic example, in recent years, the growth in the use of generative AI and digitalisation has triggered a major increase in the number of data centres, raising concerns that electricity supply facilities may fail to keep up with the pace of data centre construction in some places in the future.

There are also high expectations for AI to bring significant benefits to energy-use-related demand sectors. AI has the potential to transform energy use itself by improving productivity and saving energy in industry, transport and buildings. AI is expected to enable optimal plant operation by forecasting demand, improving productivity, and thereby enhancing the energy efficiency of plants. In the transport sector, AI will save energy through autonomous driving, namely by improving fuel efficiency through optimising the spacing between cars and route selection, and by shortening travel distances. For buildings, AI will save energy by optimising air-conditioning operations while maintaining comfort. In this way, the futures of AI and energy are closely interconnected.

This chapter provides an overview of the relationship between AI and energy, examines the energy savings potential of data centres, and assesses the current status and provides a future outlook, focusing on the role that AI can play in energy saving.

10.1 Relationship between AI and energy

Factors behind the soaring electricity consumption of data centres in recent years

AI is an area of computer science that refers to technologies for building machines and computers capable of simulating the cognitive functions associated with human intelligence. There are various types of AI, but when we focus on analytical techniques, they can be classified into 'rule-based AI', 'machine learning', 'deep learning' and 'generative AI'.

- **Rule-based AI**: AIs operate based on the rules given by humans.
- **Machine learning**: This is a method that enables computers to realise a mechanism equivalent to human learning. Based on a certain algorithm, the computer discovers patterns and rules from input data, and it applies these patterns to new data to identify and predict what they are.
- **Deep learning**: Machine learning performed using multi-layer artificial neural networks. An artificial neural network simulates the neural network of the human brain and enables higher accuracy than machine learning.
- **Generative AI**: Based on deep learning technology, generative AI generates new content using massive amounts of learning data.

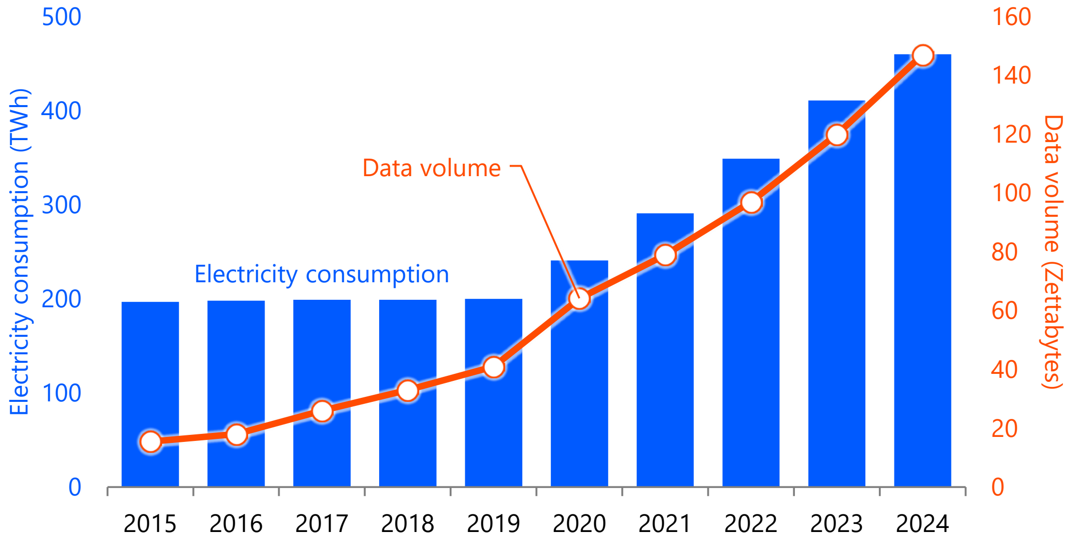
With the advent of generative AI in recent years, increases in data centres and their electricity consumption are raising the risk of local capacity constraints in transmission networks and electricity supply shortages at peak demand.

Currently, AI-related workload is estimated to account for 14% of the electricity consumption of data centres worldwide, cloud computing 54%, and conventional business-related workload from email and storage 32%[52]. AI uses significant amounts of electricity during the training and inference processes.

Meanwhile, if we look at the historical trends of data centres, electricity consumption remained mostly unchanged from 2015 through 2019, while the global data volume increased by a factor of 2.6 from 15.5 zettabytes. This was due to 1/ improved efficiency of servers, storage, networking, infrastructure and other devices; 2/ the transition from small-scale data centres to large-scale cloud and hyperscale data centres; and 3/ improved efficiency of the graphics processing unit (GPU) that processes images and videos.

However, global electricity consumption of data centres, which had previously remained stable, increased by 70% in the three years between 2020 and 2023. The factors behind it included the expansion in the use of generative AI and progress in digitalisation, the spread of remote work and workation during the pandemic, and the full-fledged development of the fifth-generation mobile communication system (5G) including in regions previously without coverage[53]. All these factors spread faster than improvements in the efficiency of data centre equipment and facilities.

Figure 10-1 | Global electricity consumption and data volume of data centres



Sources: Masanet et al. (2020), Cisco, International Energy Agency, Goldman Sachs Research

Improving the hardware and software efficiency of AI

In looking at the relationship between AI and energy, it is necessary to consider both the hardware and software aspects for future efficiency improvements. Specifically, 1/ the hardware aspects represent the performance of data centre information and communication technology (ICT) equipment that conducts computational tasks, and that of auxiliary facilities such as cooling; and 2/ the software aspects include differences in electricity consumption between computational methods and improvements in the efficiency of AI models.

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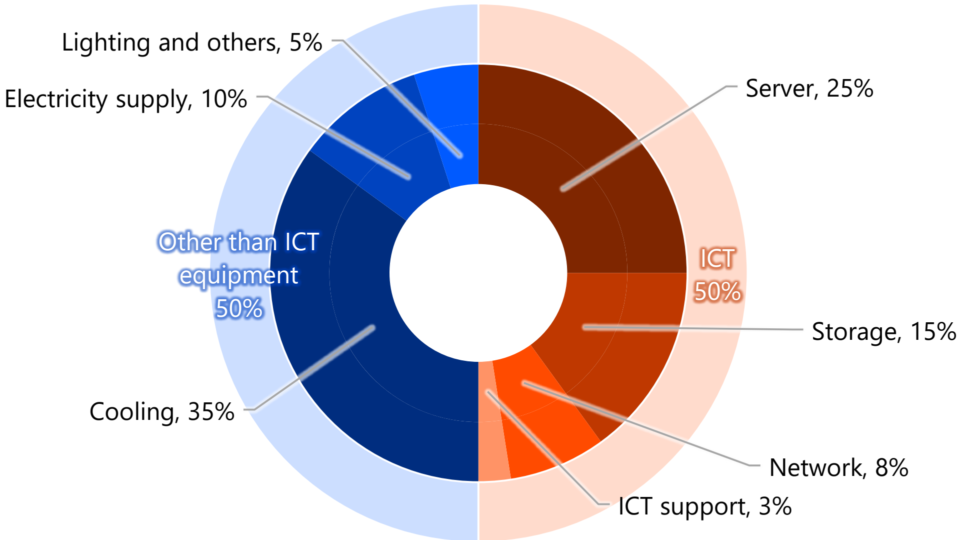
52 https://www.goldmansachs.com/insights/articles/ai-to-drive-165-increase-in-data-center-power-demand-by-2030

53 https://www.jaif.or.jp/en/news/7022#:~:text=Among%20other%20things%2C%20it%20showed,/%20floor%20area)%20as%20parameters

Data centre efficiency performance is often measured by power usage effectiveness (PUE). PUE is obtained by dividing the total electricity consumption of a data centre by the electricity consumption of its ICT equipment, and the energy efficiency is higher the closer the PUE is to 1. Data centre performance varies greatly depending on the scale, but the global average PUE is around 1.5. When PUE is 2, ICT equipment accounts for 50% of the total electricity consumption, followed by cooling, which accounts for around 35% (Figure 10-2). Often located near cities, data centres are experiencing rising ICT equipment density per rack for efficient land use. In some cases, efficiency is deteriorating due to operating air conditioners at full capacity to cool the heat emitted from ICT equipment.

Figure 10-2 | Breakdown of data centre electricity consumption (when PUE=2)



Source: Hongyu Zhu et. Al. (2023) "Future data center energy-conservation and emission-reduction technologies in the context of smart and low-carbon city construction. Sustainable Cities and Society" | VOL 89 | 2023 |

A generative AI system must conduct massive amounts of computation depending on the model (such as a large language model [LLM]) and data volume (several billion web pages). Learning is conducted over several weeks using supercomputers installed in data centres, sometimes with massive energy consumption.

According to an analysis of electricity demand for generative AI use by Dutch researcher Alex de Vries, ChatGPT may consume 564 MWh of electricity per day to operate. According to the analysis, if Google were to use AI to conduct about 9 billion searches a day, 29.2 TWh of electricity would be needed per year, which is equivalent to the annual electricity consumption of Ireland.

Meanwhile, the generative AI tool Gemini, which Google released in 2025, consumes just 0.24 Wh per prompt, which is almost the same as the electricity consumption of a common search. Considering that a generative AI search was said to be 10 times as electricity intensive as a common search, electricity savings have made rapid progress.

Table 10-1 | Relationship between data centres, AI and energy: present and future

		Present	Future
Hardware (data centre)	ICT equipment Server, storage and ICT auxiliary equipment	ICT equipment is the most electricity-intensive and accounts for 50% of the total data centre electricity consumption. Often located near cities, data centres are seeing rising ICT equipment density per rack for efficient land use. In some cases, efficiency is deteriorating due to putting air conditioners in full operation for cooling.	Optimise rack layout. Shift from company data centres to hyperscalers. Migrate to edge computing for some purposes. Optimal use of servers such as shifting from GPU to CPU. Improve the efficiency of integrated circuits and storage.
	Auxiliary facilities Cooling, backup electricity supplies, lighting, etc.	Cooling demand is rising as computation volume soars and ICT equipment density rises. Cooling-related electricity consumption accounts for around 35% of the total.	Improve efficiency by switching from air cooling to rear door cooling, liquid cooling and immersion cooling.
Software	Computation Generative AI, Data processing, Software	Computation by generative AI consumes 10 times as much electricity as common search operations. However, a search operation by the latest generative AI only consumes almost as much electricity as a common search operation.	Reduce energy demand per task through innovative algorithms. Models are 'optimised in scale' to match different tasks.

10.2 Efforts of tech firms

Hyperscalers that own many large-scale data centres necessary for using artificial intelligence (AI) are setting ambitious net-zero targets (Table 10-2). Among the efforts to reach those targets, all companies set energy efficiency improvements that directly affect operating costs as their priority and are implementing various unique initiatives.

Table 10-2 | Efforts of tech firms

Hyperscaler	Net-zero target	Efforts to achieve net-zero		
		Data centre efficiency improvement	Supply chain decarbonisation	Electricity source development and support, carbon dioxide removal (CDR)
Amazon (Amazon Web Services)	2040 (Amazon as a whole)	Improve power usage effectiveness (PUE) by introducing efficient cooling systems. Develop efficient semiconductor chips.	Use low-carbon construction materials (steel, concrete). Utilise low-carbon fuels (sustainable aviation fuels (SAFs), renewable diesel).	Invest in renewable energies; electricity purchase agreements (PPAs). PPAs with battery systems, actively utilise proprietary systems. Nuclear power generation PPAs, support for the development of small modular reactors (SMRs).
Microsoft (Microsoft Azure)	2030 (Microsoft as a whole; hourly matching)	Use of energy-saving operations such as standby mode. Develop advanced cooling technologies.	Use low-carbon construction materials (steel, concrete, wood, etc.) Utilise low-carbon fuels (SAFs, renewable diesel). Cooperation with suppliers (requiring the use of decarbonised electricity).	Invest in renewable energies; PPAs. Nuclear PPAs (including nuclear restarts). Provide support for implementing decarbonised energies using proprietary technologies.
Google (Google Cloud Platform)	2030 (Google as a whole; hourly matching)	Optimise cooling systems by utilising machine learning. DR through task shifting. Optimise data centre design.	Cooperation with suppliers (requiring the use of decarbonised electricity). Utilise low-carbon construction materials.	Invest in renewable energies; PPAs. Provide support for implementation of decarbonised energies using proprietary technologies.
Meta	2030	Monitor workload and optimise electricity profile. Highly energy-efficient hardware design. Improve cooling efficiency using outdoor air and direct evaporative cooling.	Cooperation with suppliers (aim to have at least two-thirds of all suppliers set emission targets by 2026). Utilise decarbonised fuels (SAFs, biofuels)	Invest in renewable energies and batteries; PPAs. Provide support for developing CDR technologies.

Efforts to achieve net-zero (cross-company efforts)
iMasons Climate Accord (ICA): a framework to decarbonise the digital infrastructure run by industrial group iMasons, which consists of digital infrastructure firms, mainly big tech firms.
Semiconductor Climate Consortium (SCC): a framework for decarbonising the semiconductor industry.
ZEROgrid: A framework consisting mainly of large-scale users to decarbonise electricity grids and improve their reliability.

To lower the power usage effectiveness (PUE) by improving the efficiency of non-information and communication technology (ICT) equipment such as cooling systems and the facilities as a whole, efforts to raise operating temperatures to reduce the amount of necessary cooling are in progress, alongside efforts to improve cooling systems using innovative technologies and AI. Improvements in data centre efficiency through data centre design optimisation, strengthened workload monitoring, and AI utilisation are also underway. In addition, measures to improve data centre flexibility, such as task shifting, though not directly linked to improving the energy intensity, are receiving attention as they contribute to demand response (in which electricity consumption is adjusted depending on the balance between grid electricity supply and demand), and in turn help decarbonise the grid.

To improve the efficiency of central processing units (CPUs), graphics processing units (GPUs) and other ICT equipment that perform computations, alongside efforts such as offloading CPU computations and energy-saving operations such as a standby mode, big tech companies are developing their own AI-specific semiconductor chips, such as Amazon Web Services' Trainium, Google's TPU, Meta's MTIA and Microsoft's Maia 100.

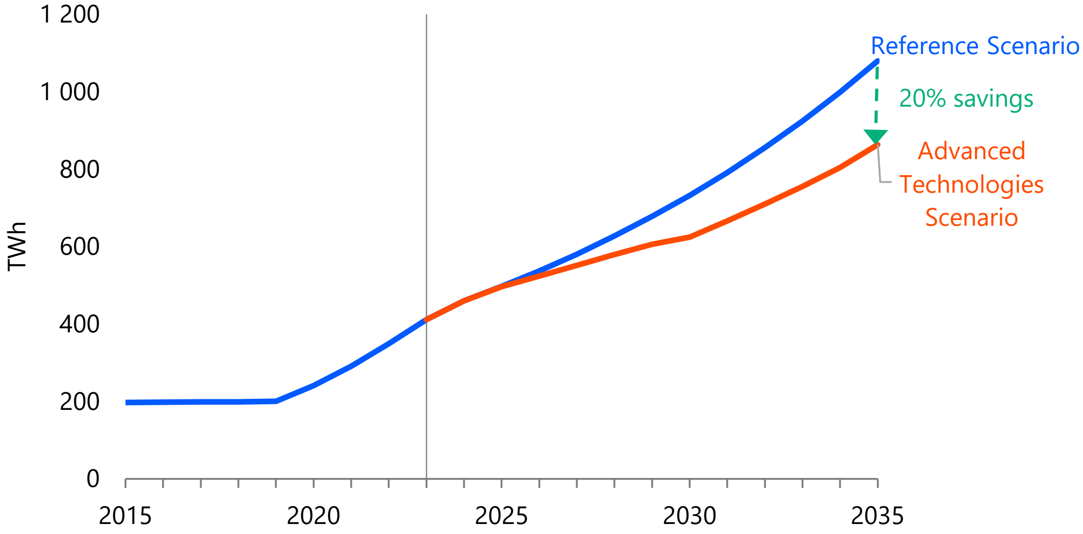
10.3 Electricity demand and energy savings potential of data centres

Based on the Reference Scenario, the electricity demand of data centres worldwide will increase by 2.1 times from 497 TWh in 2025 to 1 080 TWh in 2035 (Figure 10-3). The amount of data will grow by 2.9 times from 230 zettabytes (ZB) to 660 ZB in the same period.

The growth is driven by electricity consumption for artificial intelligence (AI) computations at data centres, which will double from the current 14% to 30% of the data centre total in 2035. Meanwhile, the pace of increase in data centre electricity consumption will ease somewhat from 17.5% per year in 2020–2024 to 8.1% in 2025–2035. Recently, electricity consumption soared as AI learned new data from scratch over weeks for large language models. However, as AI systems will learn more efficiently by shifting to differential learning and only learning updates, or by updating only some parameters, the increase in data centre electricity consumption is expected to ease in the future.

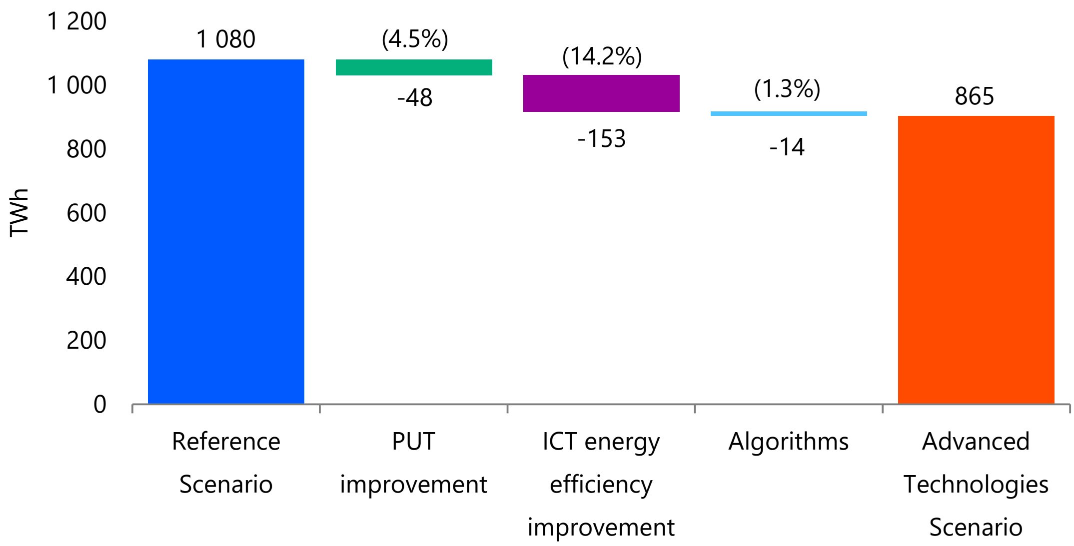
Based on the Advanced Technologies Scenario, data centre electricity consumption will be 20% lower than that of the Reference Scenario in 2035. This saving is due to improvements in power usage effectiveness (PUE) through the introduction of high-efficiency cooling technologies in new data centres, and improvements in the efficiency of information and communication technology (ICT) equipment and computations.

Figure 10-3 | Electricity demand and energy savings potential of data centres



The current average global PUE of data centres is estimated to be 1.5. This will improve to 1.38 in 2035 based on the Reference Scenario, and further to 1.28 based on the Advanced Technologies Scenario thanks to the wider adoption of liquid cooling and immersion cooling (an electricity saving of 4.5% from the Reference Scenario). ICT has an even greater energy savings potential, and the Advanced Technologies Scenario can save 14.2% more electricity than the Reference Scenario. Efficiency is improved by various technological factors such as more efficient central processing units (CPUs) and graphics processing units (GPUs), non-von Neumann computers, more efficient storage equipment, shorter transmission pathways between memory and processors, and the replacement of some volatile memory functions with non-volatile memory (that can retain data when electricity is cut off).

Figure 10-4 | Electricity demand and energy savings potential of data centres (comparison with the Reference Scenario) [Advanced Technologies Scenario, 2035]



An electricity saving of about 1.3% can be expected from improvements in computation efficiency (by 2035). The number of searches by generative AI is expected to more than double by 2035 from the current 3 trillion searches a year, but higher-efficiency models are likely to be adopted to some extent.

10.4 Energy saving using artificial intelligence (current state analysis)

Overview

There are concerns that the widespread use of artificial intelligence (AI) will drive up data centre electricity consumption and trigger national, regional and local electricity supply shortages. Meanwhile, AI is also expected to bring various benefits to the energy sector, such as an expanded use of renewables through weather forecasts, optimal electricity grid operation, energy savings and efficiency improvements in other demand sectors and the development of new materials. As demand sectors have greater energy consumption than data centres, the application of AI to these sectors can result in greater net energy savings overall.

AI can play various roles in the demand sectors. These roles can be summarised based on four keywords: 'detection', 'prediction', 'simulation' and 'optimisation'.

One possible application is to optimise the processes from sourcing to production, not for one manufacturing plant but for the whole company or even several companies, thus optimising and planning the production for the entire supply chain. Weather forecasting by electricity retailers and the optimal supply of renewable energy have been put into practice. It is also possible to guide users to control the timing of heat storage by heat pumps and the discharge of electric vehicles (EVs) to match the supply of variable renewable electricity.

The following sections focus on AI's contribution to energy savings in each sector, provide an overview of its roles, discuss the potential and challenges, and forecast the future.

Industry

The use of AI technology is already underway in the industry sector for applications such as failure detection, production management and demand forecasting. For example, it can forecast optimal production capacity while allowing for demand fluctuations and optimise energy consumption across entire supply chains.

AI also plays an essential role in energy saving. It can produce additional energy savings of a few percent in the industry sector without special facility upgrades. Facility upgrades are needed, however, if further energy savings are to be explored. The industry sector is a so-called 'hard-to-abate' sector, and even a contribution of a few percent from AI would be valuable for reducing remaining heat demand, as well as supporting electrification.

Conventional digital control was performed based on the difference between the target and actual values. For example, when controlling the heat temperature in a factory, control operations stop when a target temperature is reached. This causes a gradual deviation from the target temperature over time and the need for a correction.

Figure 10-5 | Energy saving using AI in the industry sector

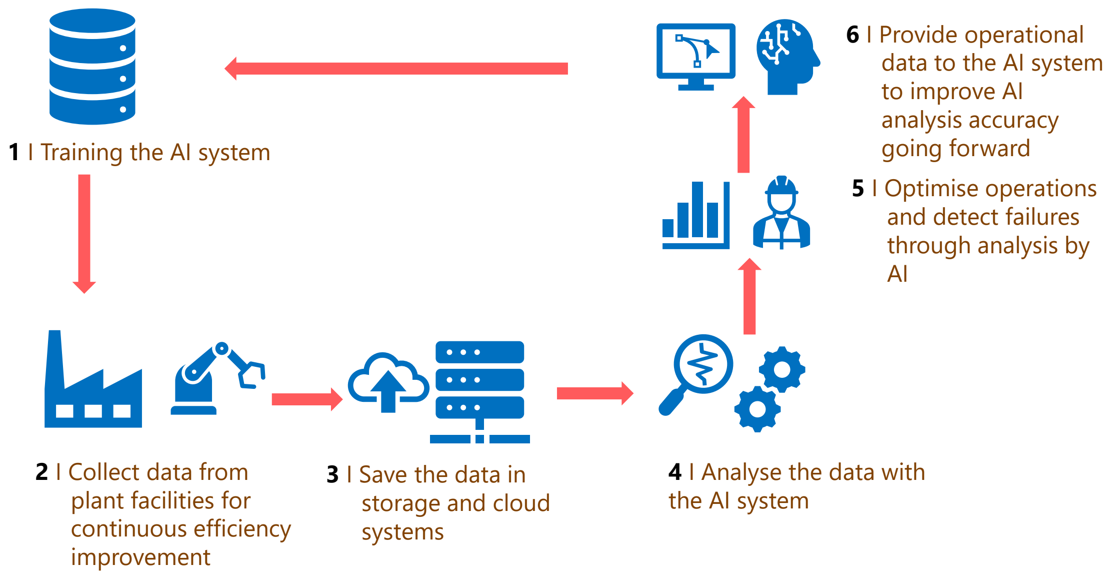
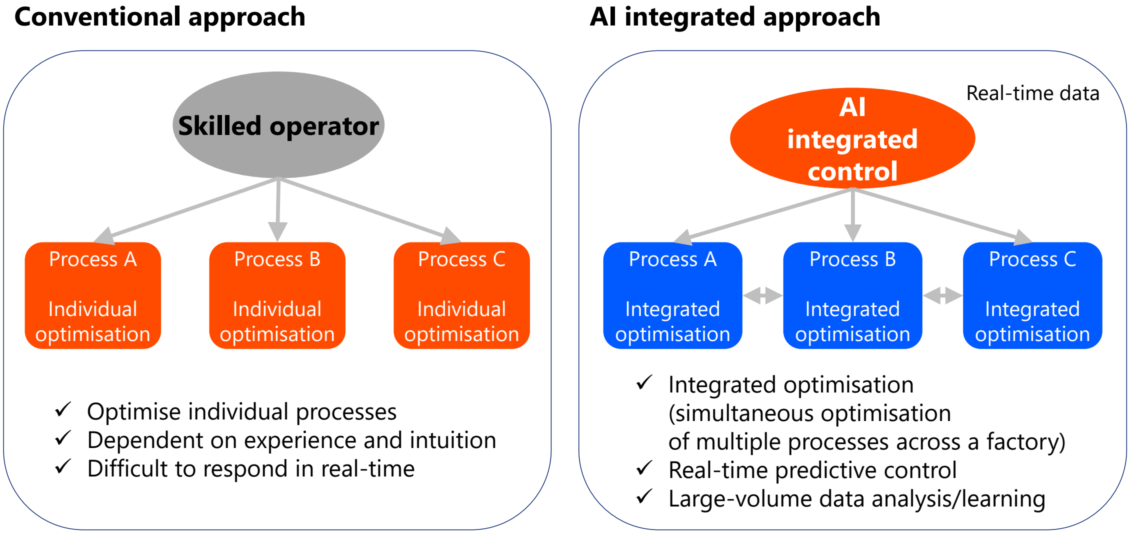


Figure 10-6 | Energy saving in the industry sector: Comparison between the conventional approach and AI integration approach



AI control learns from past operational data and performs a control operation before a deviation occurs. For heat temperature control, once the target temperature is reached, control is performed focusing on 'what kind of control is needed to avoid deviating from the target value'.

AI can achieve greater energy savings as it is capable of not only optimising the operations of a single facility but also optimising multiple processes simultaneously across a factory, performing dynamic control based on real-time forecasts, deriving optimal solutions from large amounts of data, and coordinating approaches among several factories.

One example of energy saving using AI is the case of Toshiba. There are multiple boilers, turbines, generators and chillers operating in one factory, and it is necessary to supply electricity, steam and cold and hot water. Toshiba provides a digital platform for optimising plant operations and minimising costs by using a mathematical model, which is built based on demand forecasts generated by AI using outdoor temperatures and production plans[54].

Azbil Corporation provides technologies for updating models for factory control[55]. The accuracy of advanced factory control depends on how accurately plant operations are modelled. Meanwhile, a model's error can widen after implementation due to changes in the plant's operational characteristics, such as ageing, facility repairs and modifications, and can affect the model's performance related to control and optimal operation. The company provides technologies for updating models so that models remain up to date with changes in the plant.

Iron and steel

The iron and steel industry is an energy-intensive sector that accounts for 8% of the world's final energy consumption and 7% of the carbon dioxide (CO_2) emissions of the energy sector, and its production processes are hard to decarbonise[56]. By collecting and analysing data using AI, benefits can be expected, including improving product quality, reducing raw material costs and enabling preventive maintenance of equipment, which in turn leads to reduced energy use and lower CO_2 emissions, as well as improving production efficiency.

The major European steel company ArcelorMittal is working on saving energy at its plants using Energiency's industrial energy performance software. This software platform evaluates the energy performance of plants in real-time using AI algorithms. With the help of Energiency, Luxembourg's Belval plant has reduced its energy consumption by 9 GWh, saving 150 000 euros or over 3% in electricity tariffs[57]. Belgium's Geel plant is also aiming to cut its annual energy consumption by at least 5%[58].

Japan's JFE Steel has built a cyber-physical system (CPS) that reproduces the status of the steel mills' blast furnaces in virtual space. CPS visualises the status of blast furnaces using real-time image data from inside the furnaces, in addition to temperature and pressure data collected with sensors. Optimal controls are performed by forecasting the future using AI and conducting analysis with various models[59]. Digital twin technology is a core component of CPS and is being used to optimise incineration in parts of the furnaces. This technology has been implemented at the company's West Japan Works and has reduced fuel use by 5% and CO_2 emissions by 6 600 t/year compared with previous levels[60].

Cement

The cement industry is an energy-intensive sector that accounts for 8% of the global CO_2 emissions and 4.5% those of Japan[61]. The uses of AI related to cement proposed to date include

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[54] "Optimisation of private power generation facilities": Toshiba Energy Systems & Solutions Corporation (2021) https://www.global.toshiba/jp/company/energy/topics/digital-transformation/dx008-210324.html

[55] "Plant model automatic update technology using parameter probability distribution": Azbil Corporation, https://www.azbil.com/jp/corporate/pr/library/review/pdf/Review2025_05.pdf

[56] https://www.iea.org/reports/iron-and-steel-technology-roadmap, https://unece.org/climate-change/press/cop27-un-report-shows-pathways-carbon-neutrality-energy-intensive-steel

[57] https://innoenergy.com/uploads/2023/01/success-story-arcelormittal-energiency-eng.pdf

[58] https://belgium.arcelormittal.com/en/arcelormittal-chooses-energiencys-artificial-intelligence-to-save-energy-in-steel-coils-processing/

[59] https://www.jfe-steel.co.jp/products/solution/data-science/01-blast-furnace.html

[60] https://www.jfe-steel.co.jp/release/2023/07/230710.html

[61] Takafumi Noguchi 'The Challenge of Concrete for Achieving Carbon Neutrality by 2050', Japan Institute of Country-ology and Engineering, September 2022

heat optimisation using sensors during clinker production[62] and optimising concrete mixes (ratio of cement, sand, water, fly ash, etc.)[63].

Carbon Re, a venture from Cambridge University, is optimising the heat of plant operations during clinker production. The company creates a high-accuracy digital twin based on cement plant operation data to realise real-time process optimisation and reduce fuel use in the preheater and kiln (baking) processes. The digital twin technology can be added to existing plants and can be linked with advanced process control (APC) systems such as ABB's Expert Optimizer and FLSmidth's ECS/ProcessExpert, allowing operations to be adjusted automatically by AI. The Mokra plant of Heidelberg Materials has reduced its energy-related CO2 emissions by 2% by introducing this AI on a trial basis.

Paper

The paper industry mainly produces paper and paperboard using wood (pulp) and recycled paper as raw materials and is an energy-intensive sector that requires large amounts of electricity and heat from steam during the manufacturing process. The manufacturing process is divided into the pulping process for producing the raw materials and the papermaking process, in which pulp is processed into paper.

Paper and paperboard production requires substantial amounts of steam heat and electricity. Paper mills around the world are starting to introduce AI to reduce energy consumption and CO_2 emissions. AI is expected to be used in a variety of areas such as improving the efficiency of drying processes, optimising shipping plans for raw material purchases and predictive maintenance.

One best-practice example in the paper industry shows that electricity costs were cut by 5% per year and CO_2 emissions by 20 kt by switching to load-levelling operations suggested by AI[64].

Chemicals

The chemicals industry is divided largely into the petrochemical, polymer chemical and inorganic chemical industries. Among these, the petrochemical industry is particularly energy-intensive, as it involves high-temperature processes such as thermal cracking using naphtha obtained from crude oil as feedstock. Energy consumption in chemical processes occurs mainly in the reaction (such as thermal decomposition), separation and purification (such as distillation), drying and concentration, transport and mixing and other processes (such as auxiliary facilities), and the reaction and separation and purification processes are particularly energy-intensive. For example, the decomposition furnace, which is the core facility of an ethylene plant, accounts for the majority of the total energy consumption[65, 66].

In the petrochemical industry, energy-saving initiatives including catalyst improvements to increase low-temperature activity and selectivity, waste heat recovery and reuse, heat integration, and high-efficiency furnaces and distillation columns have been implemented. Previously, operations used to be based mainly on static optimisation assuming an as-designed, steady state and rely on the experience and knowledge of skilled operators. However, combining operations

[62] Carbon Re, https://carbonre.com/. Retrieved 19 August 2025
[63] Meta, 16 July 2025. https://engineering.fb.com/2025/07/16/data-center-engineering/ai-make-lower-carbon-faster-curing-concrete/
[64] https://newji.ai/supplier/manufacturing-industry/paper-industry-dx-strategies-and-ai-iot-application-examples/
[65] https://research-portal.uu.nl/files/691692/NWS-E-2006-3.pdf
[66] https://www.sciencedirect.com/science/article/abs/pii/S0360544218309083

with AI has made possible an integrated approach that can optimise multiple processes simultaneously across a factory, dynamic control based on real-time forecasting and data-driven operation that derives the optimal solution from vast amounts of data, raising the likelihood of simultaneously achieving stable quality and higher yield while saving energy.

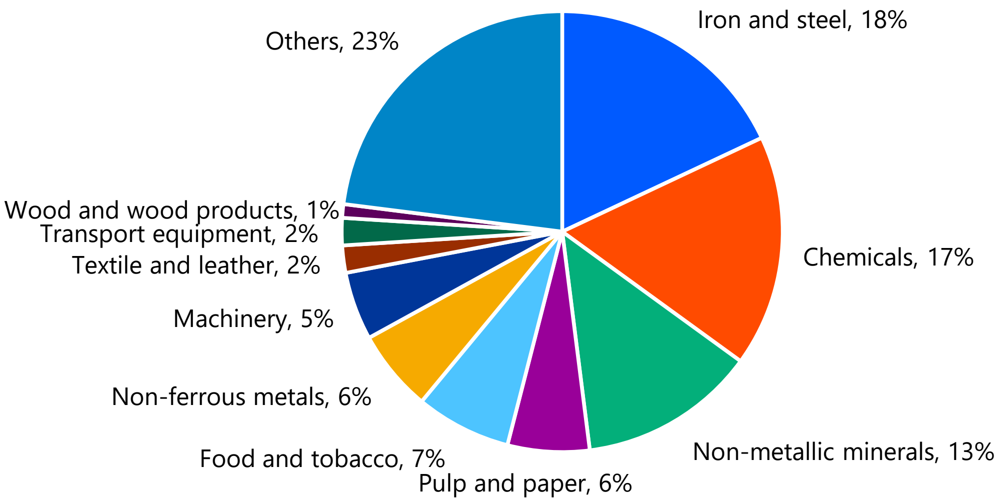
Published case studies report energy savings of a few percent[67] through unit-to-plant optimisation, with certain units (such as rotary kilns) indicating savings in the high double digits (for example, 4%[68] fuel savings for chemical manufacturers and 15%–30%[69] fuel savings for rotary kilns). However, the effect varies significantly depending on the scope of introduction, operational conditions, and the baseline. While this is a limited case, a petrochemical ethylene plant has reported a 40% reduction in fuel consumption through visualisation and optimal control achieved by combining internet of things (IoT) sensors with AI[70].

Other industries

So far, we have discussed energy-intensive industries such as steel, cement, paper and petrochemicals. Meanwhile, there are also other industries that consume significant amounts of energy. Among such industries are food and tobacco, non-ferrous metals and machinery manufacturing[71].

In the final energy consumption of the manufacturing sector, electricity accounts for 30%, while heat and other uses account for 70%[72].

Figure 10-7 | Final energy consumption of the global manufacturing sector



Source: International Energy Agency (2024) "World Energy Balances"

67 https://www.mckinsey.com/industries/metals-and-mining/our-insights/the-potential-of-advanced-process-controls-in-energy-and-materials
68 https://c3.ai/wp-content/uploads/2024/05/C3-AI-Case-Study-Chemical-Manufacturer-Energy-Efficiency.pdf
69 https://imubit.com/oxbow-case-study/
70 Yokogawa Electric Corporation, https://www.yokogawa.co.jp/news/press-releases/2023/2023-03-30-ja/
71 International Energy Agency (2024) "World Energy Balances"
72 International Energy Agency (2024) "World Energy Balances"

As an example of the energy-saving effects of AI utilisation in factories, Yokogawa Electric reduced energy consumption by 3.3%. This was done by using a manufacturing data analysis AI to establish energy-saving metrics, then combining these with a general-purpose AI that performs optimisation and control[73]. Fuji Electric states that by utilising AI to optimise the operation of electricity and heat supply equipment, energy savings of 5% to 7% can be expected[74, 75]. Similar initiatives are underway at overseas companies; Schneider Electric Industries SAS says that by employing AI for analysis and proposal generation, energy consumption in the utilities sector can be reduced by 10% to 15%[76].

Residential

Energy savings using AI are achieved in the residential sector by having AI learn and analyse each household's energy usage patterns and human activity levels, so that appliances and devices can operate with optimal energy efficiency. By using AI controls to conduct upward and downward demand response (DR) based on the electricity prices and the share of renewable electricity sources, it is possible to use the resources within the residential sector as grid-balancing capacities. Various cases of AI use in the residential sector include savings of 14% for air conditioning[77], 15% to 35% for water heating[78] and 21% for washing and drying[79].

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73 Agency for Natural Resources and Energy (Yokogawa Digital Corporation), "The hearing materials in Document 4 for the 48th Energy Efficiency and Conservation Subcommittee of the Committee on Energy Efficiency and Renewable Energy, Advisory Committee for Natural Resources and Energy", https://www.meti.go.jp/shingikai/enecho/shoene_shinene/sho_energy/pdf/048_04_00.pdf

74 Kyushu Renewable Energy and Environmental Industry Promotion Association (2024), "148th Eco School: Energy-saving solutions that create competitiveness: Introducing an energy management system that utilises DX and AI technologies (Fuji Electric Co., Ltd.)", https://k-rip.gr.jp/wp/wp-content/uploads/2024/06/3e78a0a6d967afb90ef0174efdcd55c7.pdf

75 Fuji Electric Co., Ltd., "AI Technology Solutions List", https://www.fujielectric.co.jp/products/blue_navigation/energy_conservation/solution_list_energy_conservation_ai.html

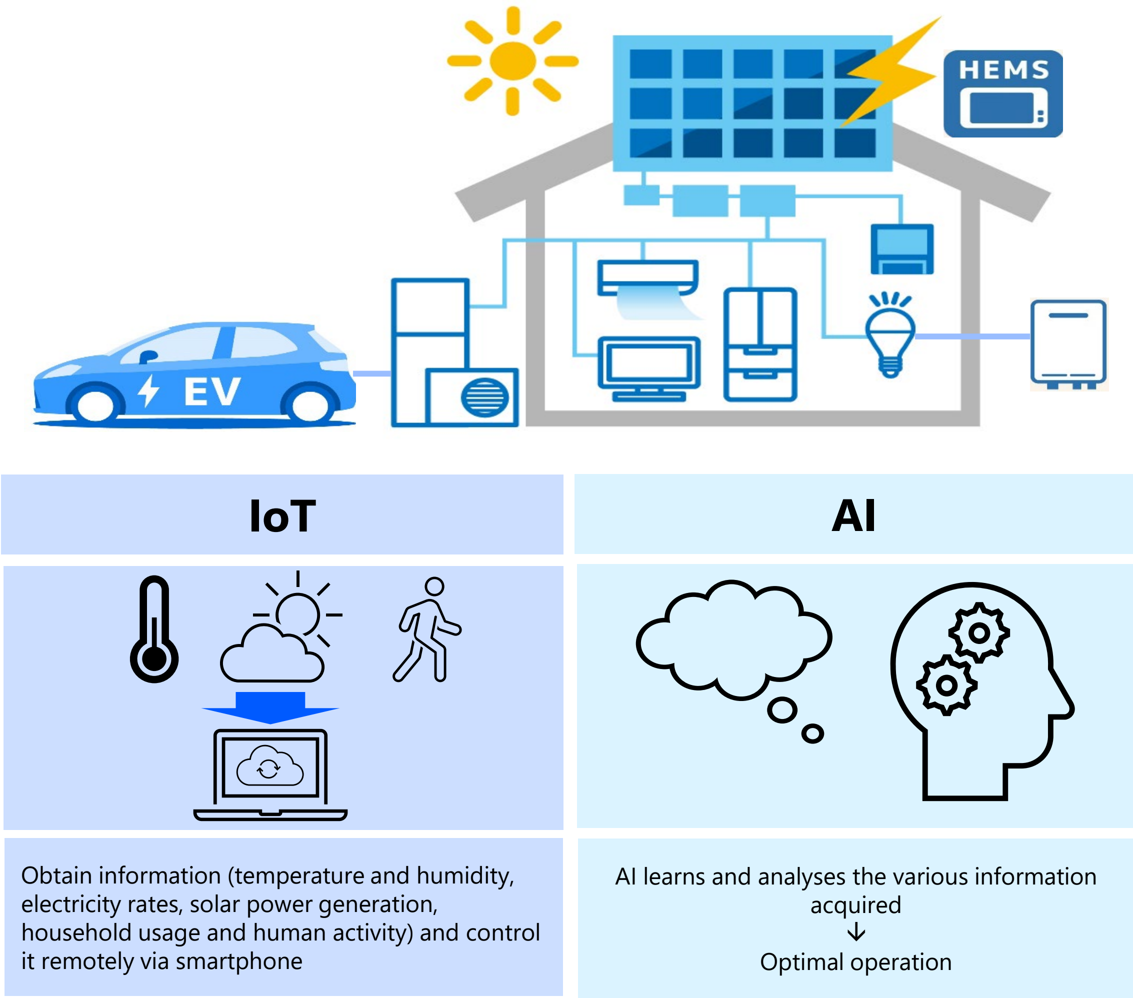
76 Schneider Electric Industries SAS (2024) "EcoStruxureTM Industrial Advisor - Predictive Energy", https://download.schneider-electric.com/files?p_Doc_Ref=PEB_99823549329&p_enDocType=Brochure&p_File_Name=EcoStruxure+Industrial+Advisor+-+Predictive+Energy+e-brochure.pdf

77 When comparing the power consumption of Sharp air conditioners with and without AIoT control. Sharp Corporation 'More energy savings with AIoT!' https://jp.sharp/aircon/aiot-saving/ (Accessed on 13 August 2025)

78 Case studies featuring Panasonic's AI EcoNavi-equipped water heaters and wood pellet water heaters from ÖkoFEN (Austria). 'AI EcoNavi' by Panasonic https://sumai.panasonic.jp/hp/2point/2_11.html (Accessed on 13 August 2025), ÖkoFEN (2025) "Product catalogue pellet heating" https://www.oekofen.com/assets/download/DeutschMA/Drucksorten/Drucksorten_aktuell_EN/oekofen_catalogue_pellets_2025.pdf (Accessed on 13 August 2025)

79 Case studies featuring Panasonic's AI EcoNavi-equipped washing machine. 'AI EcoNavi' by Panasonic https://panasonic.jp/wash/feature/LX/econavi.html (Accessed on 13 August 2025)

Figure 10-8 | An illustrative example of AI-driven energy savings in the residential sector



With air conditioners, AI assesses factors such as lifestyle and ambient temperature to automatically regulate settings, maintaining comfort while achieving energy savings. For instance, by learning the time to wake up or to come home, as well as the room thermal characteristics, the air conditioner learns to start up gradually, reducing the electricity consumption during startup. It can also reduce electricity consumption by automatically adjusting the temperature based on when occupants are leaving the house and proactively controlling the temperature based on weather information collected by AI. These AI-based controls reduce electricity consumption by 14% compared to systems without AI.

For water heaters, energy can be saved mainly by detecting people entering and leaving the bathroom when the bath is in automatic reheating mode and by reducing the energy consumption for automatic reheating when no one is bathing. Furthermore, by learning bathing patterns, AI can heat bath water at the optimal time. This can save energy by up to 35% compared with systems without AI.

Washing machines and laundry dryers can save energy by having AI determine the optimal operating conditions based on the water temperature, load size and fabric type detected by sensors. For instance, when the water temperature is high or the load size is small, the washing time is automatically shortened to save energy. When drying, the drying time is reduced to save electricity when there are many items that dry quickly. There are reports that AI control has reduced electricity consumption by up to 8% for washing alone and by up to 21% for the combined washing and drying cycle.

AI can be utilised not only in individual appliances but also in Home Energy Management Systems (HEMS) to reduce energy consumption. This mechanism involves using AI to predict solar photovoltaic power generation and electricity usage, control appliances within the home, and thereby reduce electricity consumption.

By connecting to the internet, IoT appliances support functions such as remote on/off switching via smartphone, remote monitoring of usage status and operation according to preset schedules, temperatures and other parameters. AI-equipped appliances learn from collected data and optimise operations more autonomously.

For example, they can perform more precise control by collecting past usage data using the sensors in the IoT appliances, transferring the data to the cloud or servers for storage, and then having AI learn and analyse this data by cross-referencing it with weather data and other information.

However, while these AI-equipped appliances and devices are technically capable of saving energy, their widespread adoption remains a challenge. AI-equipped devices tend to be more expensive than conventional products, which can be a barrier to adoption.

Commercial

Energy conservation in the commercial sector primarily focuses on improving the efficiency of installed equipment, and the energy savings effect can be limited depending on the actual operating conditions after installation. However, a combination of factors, including recent progress in AI technology, the falling costs of networked sensors and cloud computing, and innovations in construction and building materials, could drive a significant improvement in energy conservation in the commercial sector.

Energy efficiency in the commercial sector should be approached in stages. First, at the building design stage, with AI technology, it will be possible to utilise large amounts of historical data to create more efficient designs, beyond just fulfilling the current energy efficiency standards. At the operation stage, it will be possible to optimise lighting, air conditioning and power control using data on the flow of people and the weather collected via sensors, and to simultaneously achieve efficient energy use and comfort for the whole building. Furthermore, through integration with the surrounding buildings, energy savings can be expected at the community level.

There are several instances of AI-driven energy-saving initiatives like these. First, Daikin Industries implemented an initiative in which it used a Building Energy Management System (BEMS) to visualise the energy usage of a Yamaha office building, and it then used AI to analyse the accumulated data and save energy by 21% through optimisation[80]. In a similar example, NTT

[80] Daikin Industries (2025) "Achieving energy savings in air conditioning through artificial intelligence (AI) | Automatic energy tuning using heat load prediction" https://www.daikin.co.jp/tic/topics/feature/2025/20250507#:~:text=%E2%80%95%E2%80%95%E3%83%A4%E3%83%9E%E3%83%8F%E6%A7%98%E3%81%A7%E3%81%AF21%EF%BC%85%E3%80%81BMW%EF%BC%88%E3%82%BF%E3%82%A4%EF%BC%89%E6%A7%98%E3%81%A7%E3%81%AF16%EF%BC%85%E3%81%AE%E7%9C%81%E3%82%A8%E3%83%8D%E6%80%A7%E8%83%BD%E3%82%92%20%E7%99%BA%E6%8F%AE (Accessed on 13 August 2025)

Data (2025) applied NTT's computing technology for optimal air conditioning control scenarios to the office lobby of JR Shinjuku Miraina Tower and demonstrated a 50% reduction in energy consumption in the summer[81]. Additionally, Zhao et al. (2023) have demonstrated that the winter heating energy consumption of the Osaka University campus can be reduced by at least 30% through automatic air-conditioning control using AI. Similarly, outside of Japan, Vattenfall (2023) has demonstrated a 30% reduction in the energy consumption of residential buildings by using AI to analyse their energy consumption and optimise their operation[82].

Even when a building energy-saving plan is created, it is difficult to adjust the discrepancy between the target and actual results daily. Mitsubishi Electric's system uses AI-based control to achieve planned targets, saving energy without the involvement of building managers[83]. The key point of this system is that it uses machine learning to analyse the incoming electricity and energy demand patterns for air conditioning, estimate energy-saving effects, and on that basis, sets targets and manages energy savings.

Even with AI control, results for air-conditioning temperature can deviate from targets depending on weather conditions; any such deviations are carried over to the next day's target to achieve annual performance targets. Compared with the electricity consumption of the previous year, energy savings of 1% to 5% have been achieved.

AI control can contribute to the energy management of not only individual buildings but also entire regions. Taisei Corporation is developing a cloud-based Community Energy Management System (CEMS)[84]. In this system, AI creates optimal operation plans based on weather forecasts, building usage and past operational data. The system is deployed through the installation of data collection devices in buildings. Furthermore, because it can control multiple buildings, it can be used not only to save energy but also as a grid-balancing capacity, such as by shifting demand to another building depending on the grid's supply-demand balance.

Meanwhile, digitising buildings for higher efficiency may not produce results that match the anticipated savings potential because of the installation of numerous networked sensors, higher on-site energy consumption for processing the collected data, or increased demand for data centres. Responses to possible sensor failures and events such as electricity outages must also be considered.

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[81] NTT DATA Japan Corporation (2021) "Demonstrating the simultaneous achievement of energy savings and comfortable environments through feedforward AI air conditioning control using small-scale learning" https://www.nttdata.com/global/ja/news/release/2021/110100/ (Accessed on 13 August 2025)
[82] Vattenfall (2023) "Yes, AI will improve energy efficiency—Essentially all buildings can benefit from this technology" https://group.vattenfall.com/press-and-media/newsroom/2023/yes-ai-will-improve-energy-efficiency--essentially-all-buildings-can-benefit-from-this-technology#:~:text=The%20properties%27%20heating%20system%20is,total%20of%20about%2030%20percent (Accessed on 13 August 2025)
https://www.taisei.co.jp/about_us/wn/2025/250711_10553.html
[83] Mitsubishi Electric Corporation (2023) 'An automated energy-saving solution for building air-conditioning systems "Smart Energy-Saving Assist"'
https://www.giho.mitsubishielectric.co.jp/giho/pdf/2023/2311106.pdf
[84] "Japan's first introduction of cloud-based CEMS utilising AI in an existing high-rise complex.": Taisei Corporation (2025)

Transport

Road

One area where AI can improve energy efficiency in road transport is the optimisation of services such as parcel delivery, where large volumes of packages are delivered using numerous trucks. The issue is route optimisation, in other words, how multiple delivery operations should be connected and what routes should be taken to maximise energy efficiency for delivering packages from an unspecified number of senders to their respective receivers. This is a complex problem, particularly in urban areas with well-developed road networks, where numerous options exist; using AI increases the likelihood of selecting a better route. By considering factors such as traffic congestion predictions, in addition to the length and slope of the road and the speed limit, an optimal route with a greater energy-saving impact can be selected. Such efforts to use AI to improve the efficiency of truck transport networks are already underway in Japan by Yamato Transport[85] and other companies.

Furthermore, for long-distance truck transport, fuel consumption is an issue not only during delivery but also when empty trucks travel after delivery. For higher energy efficiency, it is desirable for trucks to carry loads on both outbound and return trips, to reduce the number of empty trucks and increase delivery efficiency. Energy efficiency can also be improved by loading as many packages as possible to minimise empty spaces in the loading compartment while trucks are in transit. It is desirable to combine multiple delivery jobs with overlapping or nearby delivery routes and transport them together on a single truck. Such energy-saving efforts are already underway at companies such as Kao[86] and Lion[87]. In addition, the New Energy and Industrial Technology Development Organization (NEDO) is working on a programme called 'Program to Develop and Promote the Commercialization of Energy Conservation Technologies to Realize a Decarbonized Society', in which the Air Business Club and the University of Shiga Prefecture are studying ways to improve transportation efficiency using AI, including mixed-load trucks[88].

The above are examples related to planning freight transport, but AI can also optimise the operation of individual vehicles, that is, enabling eco-driving. For example, new types of 'connected and automated vehicles' (CAVs) that can communicate with surrounding vehicles and nearby traffic lights are being proposed and considered. CAVs monitor the surrounding road conditions through communications and use this information to optimise their driving speed and adjust the electricity distribution of their drivetrain (for example, adjusting the balance between the engine and motor). This reduces energy consumption and achieves eco-driving. Not all control technologies installed in CAVs are AI applications, but the knowledge and algorithms obtained through machine learning are expected to be useful, for example, when incorporating traffic light conditions into vehicle control[89].

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[85] Yamato Transport Co., Ltd., https://www.yamato-hd.co.jp/news/2021/newsrelease_20210803_1.html
[86] Kao Corporation, https://www.kao.com/jp/newsroom/news/release/2025/20250122-001/
[87] Lion Corporation, https://doc.lion.co.jp/uploads/tmg_block_page_image/file/10377/20241225_02.pdf
[88] NEDO, https://www.nedo.go.jp/koubo/DA3_100318.html
[89] Paper on CAV, https://doi.org/10.1016/j.rser.2023.114025

Table 10-3 | Energy saving in the road sector using AI

Purpose	Energy conservation through AI in the road sector
Demand forecast	The loading efficiency and passenger efficiency of cargo trucks, taxis, etc. are improved based on weather and traffic information.
Route decision	Through machine learning, AI suggests optimal routes considering the driver's travel preferences and, for cargo trucks, delivery efficiency.
Maintain distance between vehicles	By keeping a constant distance between vehicles through autonomous driving, vehicles can move without congestion, improving fuel efficiency. Platooning also reduces air resistance, contributing to improved fuel efficiency.

Aviation, shipping and railways

Air, sea and rail transport face challenges similar to road transport. First, they must reduce the energy consumption of aircraft, ships and vehicles during flight, navigation and operation—in other words, optimise their operation, akin to eco-driving in automobiles. Furthermore, airlines and shipping companies with large fleets operating air and sea transport networks need to combine operations and develop plans for efficient transport across multiple airports and ports. This problem is structurally similar to that of vehicle transport, and AI is expected to improve efficiency. In fact, in the aviation industry, Alaska Airlines is using AI to optimise flight routes[90], and in the shipping industry, Cosmo Oil is using AI to plan domestic vessel allocations, reducing fuel consumption[91].

10.5 Scenario analysis related to energy savings using artificial intelligence

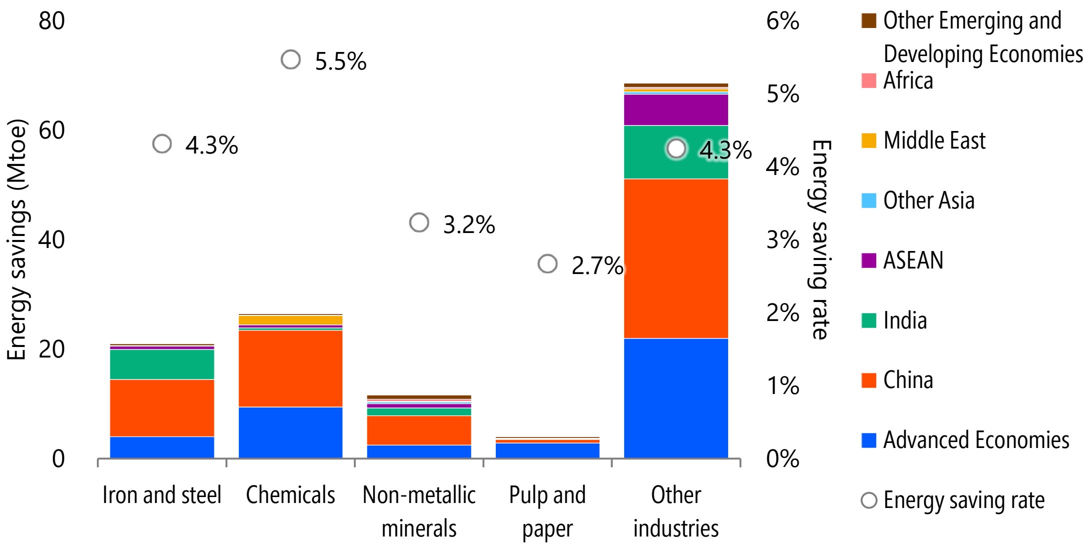
Energy savings potential of artificial intelligence in the industry sector

The energy savings potential of artificial intelligence (AI) in the industry sector will be equivalent to 2% to 6% under the Advanced Technologies Scenario in 2035 (Figure 10-9). In the short to medium term (2025 to 2035), the introduction of AI will be primarily focused on retrofitting existing facilities to optimise operations and improve efficiency.

By industry, the energy savings in the chemical industry will be the largest at 26 Mtoe, followed by the steel, cement and paper industries at 21 Mtoe, 11.5 Mtoe and 4 Mtoe, respectively. In addition to these, there will be a 68 Mtoe effect in non-energy-intensive industries such as the machinery industry.

[90] Alaska Airlines, https://www.alaskakouku.com/2021/06/airspace-intelligenceai.html
[91] Cosmo Oil Co., Ltd., https://www.cosmo-energy.co.jp/ja/information/press/2025/250415-01.html

Figure 10-9 | Energy savings potential of using AI in the industry sector (compared with the Advanced Technologies Scenario) [2035]



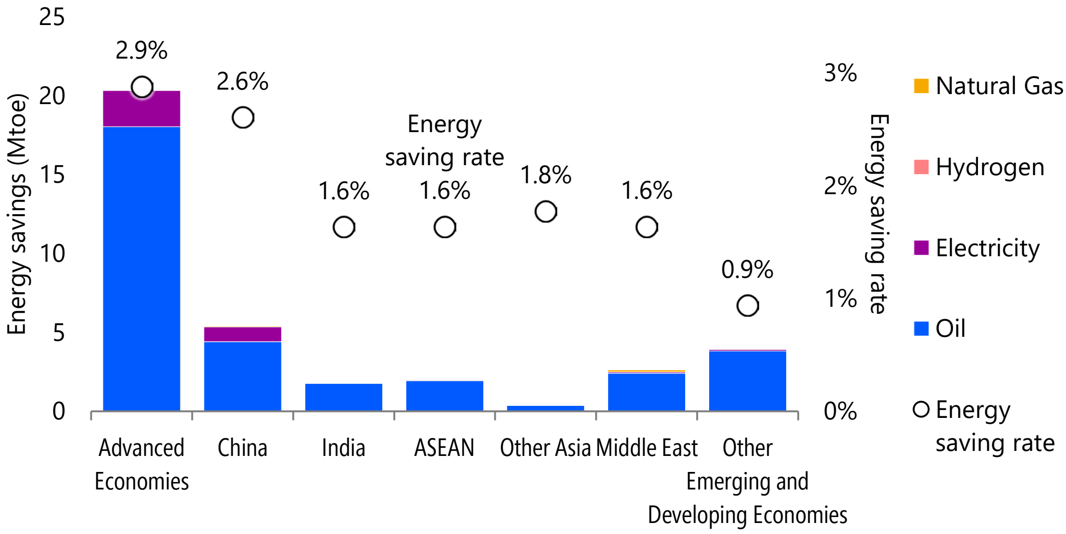
By region, AI will be adopted from early on in the Organisation for Economic Co-operation and Development (OECD) countries thanks to their abundant capital and digital infrastructure. China will see a high rate of AI adoption from the early stages, driven by its national strategy to actively promote digitalisation, as well as new builds and large-scale expansions. India, the Association of Southeast Asian Nations (ASEAN), other Asian countries, Africa and other Emerging and Developing Economies will initially lag behind, but adoption will accelerate due to rapid industrial development and the need to improve cost competitiveness. From 2035 onwards, they are expected to benefit from their late-comer advantage and introduce the latest AI more efficiently when expanding facilities or building new ones.

Energy savings potential of AI for road transport

The energy savings achieved by autonomous driving using AI in passenger cars, buses and trucks will reach 36.5 Mtoe in 2035 (Figure 10-10). The energy savings effect will be around 2.9% higher than that under the Advanced Technologies Scenario in Advanced Economies and 2.6% in China. Meanwhile, in other Emerging and Developing Economies, autonomous driving will not see significant progress in the short to medium term (2025 to 2035), and the energy savings will be around 0.9% to 1.8%.

Autonomous driving technology is not limited to electric vehicles (EVs) and can be applied to internal combustion engine vehicles (ICVs) as well. There are expectations that autonomous driving will spread to trucks, buses, taxis and other commercial vehicles, for which EVs are considered more difficult to deploy widely. This can lead to energy savings by improving loading efficiency and passenger efficiency based on weather and traffic information. Furthermore, transportation distances will be shortened by avoiding traffic congestion and selecting optimal routes. Autonomous driving will also improve fuel efficiency by maintaining a consistent distance between vehicles.

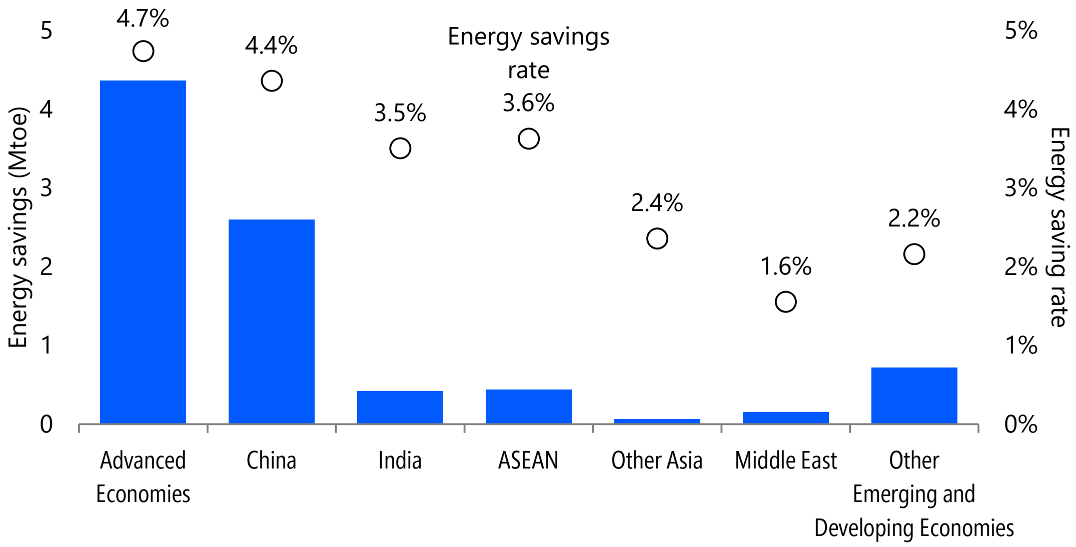
Figure 10-10 | Energy savings potential of AI for road transport (compared with the Advanced Technologies Scenario) [2035]



Energy savings potential of AI in the commercial sector

The energy savings potential of AI for heating, cooling, ventilation and lighting in 2035 is 8.8 Mtoe (102 TWh) compared with the Advanced Technologies Scenario (Figure 10-11). This is roughly a 10% reduction in data centre electricity demand in 2035. The energy savings potential of AI is 4.3 Mtoe in Advanced Economies and 2.6 Mtoe in China. In Emerging and Developing Economies, the adoption of AI will be limited to the latest buildings in the short to medium term.

Figure 10-11 | Energy savings potential of AI in the commercial sector (compared with the Advanced Technologies Scenario) [2035]

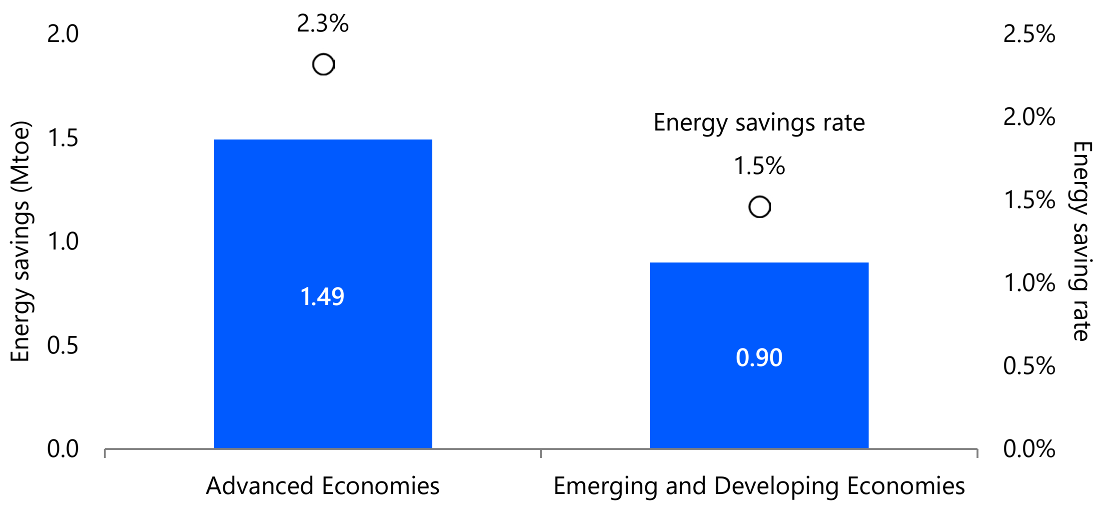


In Advanced Economies, digital control using Building Energy Management System (BEMS) has already become standard in large buildings of over 10 000 m². BEMS manages a building's energy based on predefined rules. By adding AI learning and prediction functions to this mechanism, more autonomous management of a building's energy will be possible. AI can improve the energy efficiency of an entire building without upgrading existing equipment, namely by installing sensors to collect data on the movement of people, temperature, and so on, and maintaining comfort through optimal control of lighting, air conditioning and power. In Emerging and Developing Economies, AI is expected to spread in the long run (after 2035), after first going through a stage of digitalisation.

Energy savings potential of AI in the residential sector

The energy savings potential of AI-equipped air conditioners and water heaters is 1.5 Mtoe compared with the Advanced Technologies Scenario (a 2.3% saving) for Advanced Economies and 0.9 Mtoe (a 1.5% reduction) for Emerging and Developing Economies in 2035 (Figure 10-12). Since AI-enabled technologies are high-end products that require a high initial investment, their adoption rate will be relatively low compared with that in other sectors in the short to medium term. AI air conditioners, for example, can save energy while maintaining comfort by performing proactive control that takes weather forecasts and human behaviour into account. For wider adoption of AI, it is necessary to promote understanding of its benefits.

Figure 10-12 | Energy savings potential of AI in the residential sector (compared with the Advanced Technologies Scenario) [2035]



For further widespread adoption

The use of AI on the demand side has many possibilities, including improving productivity and achieving energy savings in the industry sector, improving fuel efficiency and reducing travel distances for automobiles, and improving energy efficiency while maintaining comfort in the buildings sector. By 2035, an additional energy savings potential of several percent compared with the Advanced Technologies Scenario can be expected.

However, there are many obstacles to the introduction of AI in the energy demand sectors. First is the shortage of skilled personnel who can utilise AI in the industrial, commercial, road and other sectors. For example, factory equipment operators often rely on their experience. It is essential to raise awareness among factory workers about what AI can do.

Another issue is the lack of data that can be used. The more data there is, the higher the accuracy of predictions, which in turn enables more efficient operations. In other words, data preparation is essential before AI can be put into operation.

On the other hand, we must be careful of rebound effects, such as increases in energy consumption due to higher productivity. Efforts are currently underway to mitigate the rebound effects by having AI learn human behaviour and energy use patterns and apply predictive control. Sharing efforts like these is also important to promote the use of AI in the demand sectors.

Policy measures that need to be taken include sharing best practices to develop human resources and raise awareness and providing incentives to promote widespread adoption. To maximise the impact of AI, it is also necessary to standardise data and establish rules for data input and interoperability. Measures must also be implemented during the operation of AI, such as ensuring cybersecurity.

The energy savings potential of data centres depends significantly on improvements in information and communication technology (ICT) efficiency. Therefore, in addition to improving cooling efficiency, which has traditionally been the focus, measures and strategies to improve the efficiency of ICT equipment are needed. This will require additional evaluation of ICT efficiency as an indicator of data centre energy efficiency (in addition to power usage effectiveness [PUE]). It will also be important to cooperate not only with data centre operators but also with various stakeholders such as semiconductor manufacturers and ICT-related manufacturers.