Summary

Global energy supply and demand outlook to 2050

Energy demand will continue to rise until 2050 under current conditions.

- This Outlook analyses global energy supply and demand projections through 2050 under two scenarios. Under the Reference Scenario, which assumes current policy and technological trends continue, global primary energy consumption will continue to grow steadily, primarily driven by Emerging and Developing Economies, increasing by 14% by 2050 compared to 2023 levels.
- On the other hand, under the 'Advanced Technologies Scenario'—which assumes the maximum deployment of various energy technologies to advance energy security and decarbonisation—emissions peak around 2030 before gradually declining, reaching a 6% reduction by 2050 compared to 2023 levels.

Under the Advanced Technologies Scenario, global CO_2 emissions will be reduced by 59% of current levels.

- Projections for carbon dioxide (CO_2) emissions vary significantly between the scenarios. Under the Reference Scenario, global emissions remain largely unchanged from current levels until 2050. This is because emissions reductions in Advanced Economies are largely offset by increased emissions associated with economic growth in Emerging and Developing Economies.
- Meanwhile, under the Advanced Technologies Scenario, global CO_2 emissions in 2050 would be reduced by 59% compared to 2023 levels. However, electrification remains challenging in non-power sectors, particularly industry (high-temperature heat) and transport (long-distance haulage), making decarbonisation in these sectors a major hurdle towards overall net-zero. Hydrogen and synthetic fuels represent promising alternatives, but high costs remain a challenge. Further technological advancement and cost reduction are essential going forward.

Significant increase in electricity demand and challenges to stable supply

- Global electricity generation continues to increase substantially under both scenarios. The Reference Scenario projects a 66% increase compared to 2023 levels, while the Advanced Technologies Scenario anticipates nearly double the increase, driven by electrification and expanding demand for hydrogen and carbon capture and storage (CCS). This growth stems from the rapid expansion of data centres, currently attracting global attention, alongside industry sector growth centred on Emerging and Developing Economies and rising space heating and cooling demand in residential sector.
- To meet this substantial increase in demand and ensure stable electricity supply, securing sufficient power generation capacity is essential. Solar photovoltaics and wind are expected to account for a large proportion of the overall increase in electricity generated. However, from around 2030, constraints such as a shortage of suitable sites and rising integration costs to manage supply fluctuations will become apparent. Consequently, investment in other

power sources such as thermal, nuclear and other renewable energies will also be indispensable.

Fossil fuel demand varies considerably depending on the scenario.

- The future of fossil fuel demand is subject to significant uncertainty. Oil demand varies considerably depending on the extent of electric vehicle (EV) penetration and efficiency improvements. Under the Reference Scenario, it continues to increase until 2050, whereas under the Advanced Technologies Scenario, it declines substantially. Consequently, among the three fossil fuels, oil exhibits the greatest variation depending on the scenario.
- Natural gas demand remains robust under both scenarios, with demand levels in 2050 remaining comparable to current levels even under the Advanced Technologies Scenario.
- Coal primarily supports power generation demand in Emerging and Developing Economies, but demand could decline significantly if the expansion of renewables progresses.
- Nevertheless, fossil fuels will continue to account for the bulk of energy consumption. Even under the Advanced Technologies Scenario, fossil fuels will constitute 54% of global primary energy consumption. Therefore, ensuring a stable supply of fossil fuels remains a critical challenge even as the energy transition progresses.

India and ASEAN: surging demand and supply-side constraints

- As energy demand declines in Advanced Economies and China, Emerging and Developing Economies—notably India and the Association of Southeast Asian Nations (ASEAN)—will drive new growth. India's annual income per capita is projected to approach $10 000 by 2050, with final energy consumption expected to nearly double from current levels under the Reference Scenario. ASEAN countries will also see sustained consumption growth alongside rising incomes and industrialisation.
- In India, driven by expanding demand in buildings and industry sectors, the Reference Scenario projects that electricity generated will more than triple over the next 25 years. While solar photovoltaics deployment is expected to increase, competition with agricultural land poses a challenge, making it difficult for solar photovoltaics alone to meet all electricity demand. Furthermore, addressing the social issue of improving transmission and distribution losses is also required.
- In Malaysia, one of the ASEAN members, the Reference Scenario projects a roughly 2.5-fold increase in electricity generated by 2050, driven by factors such as expanding data centre demand. An increase in natural gas-fired power generation utilising domestic resources is anticipated. To reduce CO_2 emissions, strengthening the power grid interconnection between the densely populated Malay Peninsula and Borneo Island—where suitable sites for renewables are concentrated—will be key.

Rising import dependence in Asia and its impact on the international energy market

- Increased domestic demand in India and ASEAN will heighten dependence on oil and natural gas imports. Furthermore, by 2050, 85% of crude oil interregional trade will be destined for Asia, with over half of this destined for South and Southeast Asia. Consequently, Asia will further enhance its presence in international energy trade.
- The CO_2 emissions reduction potential (the difference in emissions under the Reference and Advanced Technologies Scenarios) for India, ASEAN and other Emerging and Developing Asia combined is comparable to that of all Advanced Economies or China. The investment

required to realise reductions in these three regions amounts to approximately $240 billion annually. This represents 80% of the total funding target for all emerging and developing countries agreed at the 29th Conference of the Parties to the United Nations Framework Convention on Climate Change (COP29) ($300 billion per annum). Mobilising private capital is essential to achieve investment on this scale.

The potential of variable renewable electricity considering integration costs

Expectations and challenges for variable renewable energy

- Significant increases in carbon-free energy sources are required to achieve decarbonisation. Expectations are particularly high for the continued expansion of variable renewable energy (VRE) sources such as solar photovoltaics and wind, which have seen substantial growth until recently. The IEEJ Outlook 2026 projects that under the Reference Scenario, VRE power generation will increase approximately fivefold from current levels to 2050, rising to approximately sevenfold under the Advanced Technologies Scenario.
- As the output of VRE fluctuates significantly depending on natural conditions such as solar radiation and wind speed, the expansion of VRE will have a major impact on the stability of the electricity supply-demand balance. For instance, as already observed in some countries and regions (such as the Kyushu region in Japan), instances occur where output from some generation facilities is curtailed during periods of surplus electricity supply from VRE. Furthermore, when VRE power generation suddenly drops due to natural conditions, and if the thermal power plants serving as backup experience unplanned outages, instances of tight electricity supply and demand are also frequently observed.
- With the expansion of VRE certain to continue into the future, it is essential to build a power system capable of responding to VRE fluctuations. This requires not only accurate forecasting of VRE power generation but also flexible operation of power generation facilities, the introduction of storage batteries and grid enhancement.

Volume of VRE deployment and integration costs

- As a cost assessment for the energy transition era premised on the expansion of VRE, analysis focusing on the overall costs of the energy (particularly electricity) system is gaining attention. This analysis considers the costs required for grid integration to accommodate the supply fluctuations of VRE (integration costs).
- In analysing integration costs, emphasis is placed on comprehensively and holistically assessing the expenses required for introducing the necessary technologies for the new energy transition. This is achieved by considering factors such as the costs of introducing new equipment like storage batteries and grid upgrades, as well as the costs associated with flexible facility operation (such as maintaining and operating thermal power plants as backup).
- As an example of analysis concerning integrated costs in Japan, the Agency for Natural Resources and Energy's Working Group on Power Generation Cost Verification has conducted a factor decomposition of the difference between the levelised cost of electricity (LCOE) and the levelised cost of electricity adjusted for some integrated costs (LCOE*). This analysis indicates that charging and discharging losses and the impact of output curtailment

are significant factors. Furthermore, the analysis of the energy mix (power generation mix) for fiscal year 2040 within the Seventh Strategic Energy Plan also incorporates considerations of integrated costs.

Changes in system costs according to VRE deployment levels (ASEAN analysis example)

- IEEJ Outlook 2026 analysed the deployment volume and integration costs of VRE up to 2060 for ASEAN, as an analysis considering integration costs.
- This analysis indicates that for ASEAN, the VRE share minimising energy system costs will be approximately 30% in 2060. Increasing VRE beyond this cost-minimising share leads to the replacement of conventional power generation sources such as thermal. This reduces the capital costs and fuel expenses associated with conventional power generation. Conversely, the costs associated with introducing VRE increase, alongside rising integration costs for measures such as battery storage. These additional costs exceed the savings from conventional power generation, resulting in an overall increase in total costs.
- In ASEAN, if the share of VRE in electricity generated reaches approximately 80%, this would result in cumulative additional costs of around $1.3 trillion between 2030 and 2060, compared to the cost-minimising share of approximately 30%.
- Regarding the promotion of energy transition towards decarbonisation in ASEAN, strengthening national efforts alongside collaboration and cooperation at the ASEAN level is essential. On the other hand, concerning enhanced measures through the expansion of VRE, it is necessary to note that additional costs may vary significantly between countries. This stems from differences in geographical and natural conditions, as well as the state of infrastructure development, meaning the scope for additional VRE varies considerably across ASEAN countries.
- Furthermore, the capacity to bear additional costs varies depending on economic circumstances and national scale. To further utilise VRE, transnational cooperation is essential, alongside diverse decarbonisation pathways tailored to each country's specific circumstances.

The importance of climate change targets and adaptation grounded in reality

Recent developments concerning the 1.5°C target

- The Paris Agreement (2015) stipulates the global temperature rise mitigation target as well below 2°C and to pursue efforts to limit the increase to 1.5°C. Subsequently, driven by successive net-zero declarations from major nations around 2020, the pursuit of the 1.5°C target and the associated goal of net-zero greenhouse gas (GHG) emissions became the global trend. However, in reality, global GHG emissions continue to rise, making the prospects for achieving the 1.5°C target increasingly challenging. Against this backdrop, new realities illustrating the difficulty of realising the 1.5°C target are becoming apparent worldwide.
- For example, the Group of Seven (G7) excluding Japan and the European Union (EU) are currently exceeding the emissions pathway required to achieve net zero by 2050 from current levels. Furthermore, Canada's new 2035 Nationally Determined Contribution (NDC) target exceeds the emissions pathway required to achieve net zero by 2050 from current levels.

- Coal-fired power generation trends in China and India also merit attention. In China, final investment decisions (FID) were made for 100 GW of new coal-fired power plants in 2024 alone. This represents the largest scale in the past decade. Meanwhile, coal-fired power plant decommissioning over the past five years averaged just 4.7 GW annually. Similarly, India saw FIDs for 15 GW of new coal-fired power plants in 2024, again the largest scale in the past decade. The current reality presents a challenging situation for achieving net-zero GHG emissions.

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

- The remaining carbon budget[1] required to limit global temperature rise to 1.5°C with a 50% probability is rapidly diminishing with each year's emissions. Specifically, the Synthesis Report of the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report had estimated this budget at 500 $GtCO_2$ after 2020. However, the latest assessment by Indicators of Global Climate Change (IGCC) shows a significant reduction to 130 $GtCO_2$ after 2025. This figure represents less than four years' worth of current emissions. Under a simple calculation assuming linear emissions reductions, this implies the world would need to achieve net-zero by 2032. Given the latest remaining carbon budget assessment, the 1.5°C target can be considered effectively unattainable. Consequently, setting a 2°C target appears realistic as a goal consistent with the Paris Agreement. This does not necessarily signify a retreat but rather a return to the original objective of the Paris Agreement.
- The overall CO_2 emissions pathway estimated based on energy-related CO_2 emissions up to 2050 from the IEEJ Outlook 2026 Advanced Technologies Scenario achieves net zero in 2073. Furthermore, the cumulative emissions from 2025 onwards until net-zero is achieved would total 906 $GtCO_2$, a level comparable to the latest remaining carbon budget (1 050–1 110 $GtCO_2$) and sufficient to limit global temperature rise to 2°C with 50% probability. However, to meet the 2°C target with the highest possible probability, it remains crucial to explore and pursue reduction potentials exceeding those of the Advanced Technologies Scenario.

Adaptation

- Climate change countermeasures are broadly categorised into 'mitigation' and 'adaptation'. 'Mitigation' involves reducing GHG emissions and expanding sinks to prevent increased GHG emissions from exacerbating climate change. Adaptation, on the other hand, refers to the processes of adjustment and response to climate change and its impacts, aimed at reducing the effects and damage caused by climate change. The primary approach is to mitigate the impacts of climate change through mitigation; if this proves difficult, it becomes crucial to combine it with adaptation. With the 1.5°C target now effectively unattainable, the importance of adaptation will only continue to grow.
- However, according to the United Nations Environment Programme's "Adaptation Gap Report 2024", there is an 8 to 14-fold gap between the finances required for adaptation and the current level of finance provision. The adaptation finance gap is substantial, and closing this gap is a priority.
- Breaking down the climate finance provided and mobilised by advanced economies reveals that mitigation finance accounted for 72% of the total in 2016 and 60% in 2022. Meanwhile, the proportion allocated to adaptation has increased, rising from 17% in 2016 to 28% in 2022.

[1] The total amount of CO_2 emissions permitted globally going forward to achieve a target

Article 9, paragraph 4 of the Paris Agreement aims for a 'balance' between adaptation and mitigation finances, which can be understood as striving for a ratio close to one-to-one between adaptation and mitigation finances. However, the current situation remains far from balanced, necessitating efforts to achieve equilibrium between adaptation and mitigation finances.

- When examining the primary areas of adaptation in terms of finance requirements and modelled costs, the sectors with the highest finance needs are 'agriculture and fisheries', 'water and floods' and 'infrastructure, energy and settlement'. Other important sectors include 'coastal and marine resources', 'forests and ecosystems' and 'human health'. It is necessary to consider which areas of adaptation should be prioritised, considering both current and future needs.

The future of AI and energy demand

The relationship between AI and energy

- The close interrelationship between artificial intelligence (AI) and energy is attracting global attention. A symbolic example of this is the recent expansion in the use of generative AI and advances in digitalisation, which have led to a significant increase in data centres. Locally, this has raised future concerns that the pace of constructing power supply facilities may not keep up with the pace of building data centres.

- Meanwhile, AI is anticipated to deliver significant benefits within the energy demand sector. It holds the potential to fundamentally transform energy usage itself by enhancing productivity and enabling energy savings across industry, transport and buildings. Through demand forecasting, AI can guide optimal factory operations, thereby improve productivity and enhance ultimately the energy efficiency of facilities such as factories. In transport, autonomous driving achieves energy savings through improved fuel efficiency via optimised vehicle spacing and route selection, alongside reduced travel distances. In buildings, energy savings are realised by optimising the operation of air conditioning and other systems while maintaining comfort levels. Thus, the future of AI and energy will be closely intertwined.

Data centre electricity demand and energy saving potential

- Global data centre electricity demand is projected to expand by a factor of 2.1, rising from 497 TWh in 2025 to 1 080 TWh in 2035 under the IEEJ Outlook 2026 Reference Scenario. Data volumes over the same period are expected to increase by a factor of 2.9, growing from 230 Zettabytes (ZB) in 2025 to 660 ZB in 2035. AI computation-related electricity consumption in data centres will drive this increase in electricity demand, with its share doubling from the current 14% to 30% by 2035. Meanwhile, the pace of growth in data centre electricity consumption, which averaged 17.5% annually between 2020 and 2024, will moderate slightly to 8.1% between 2025 and 2035.

- Global data centre electricity demand could potentially be saved by approximately 20% by 2035 compared to the Reference Scenario under the Advanced Technologies Scenario, indicating significant energy-saving potential. Contributing factors include improvements in power usage effectiveness (PUE) through the adoption of high-efficiency cooling technologies in new data centres (4.5% savings), efficiency enhancements in information and communication technology (ICT) equipment (14.2% savings) and computational efficiency gains (1.3% savings). How to achieve this represents a key challenge for the future.

- In any case, how to supply the increasing demand for electricity under the new information revolution in a stable manner and at competitive prices will become one of the most critical issues in the world's energy challenges.

AI-based energy savings potential in the demand side

- AI is expected to deliver significant energy savings through its application in the demand sector. This study estimated the additional energy-saving potential achievable beyond the Advanced Technologies Scenario through AI-driven optimisation. In the industry sector, an additional 2% to 6% energy-saving potential is projected for 2035 compared to the Advanced Technologies Scenario. In the short to medium term (2025–2035), the primary focus will be on retrofitting existing equipment with AI for optimisation and efficiency improvements. By sector, the greatest benefits are expected from non-energy-intensive industries, including machinery manufacturing, yielding 68 million tonnes of oil equivalent (Mtoe). This is followed by chemicals at 26 Mtoe and steel at 21 Mtoe.
- By 2035, the additional energy-saving potential from AI-enabled autonomous driving for passenger cars, buses and lorries will amount to 36.5 Mtoe. In Advanced Economies, the additional energy-saving potential from the Advanced Technologies Scenario is approximately 2.9%, while China's is 2.6%. Conversely, the adoption of autonomous driving in other Emerging and Developing Economies will not progress significantly; consequently, the additional energy-saving potential from the Advanced Technologies Scenario will be around 0.9% to 1.8%.
- The additional energy-saving potential for space cooling and heating, ventilation and lighting in the commercial sector in 2035 amounts to 8.8 Mtoe (102 TWh) compared to the Advanced Technologies Scenario. This is equivalent to reducing the electricity demand of data centres in 2035 by approximately 10%. The energy-saving potential of AI in Advanced Economies in 2035 is 4.3 Mtoe, while China's is 2.6 Mtoe.
- The additional energy-saving potential of AI-equipped space heating and cooling and water heating appliances in the residential sector is estimated at 1.5 Mtoe in Advanced Economies (a 2.3% reduction compared to the Advanced Technologies Scenario) and 0.9 Mtoe in Emerging and Developing Economies (a 1.5% reduction) by 2035.

Towards future expansion and adoption

- The utilisation of AI on the demand side holds significant energy-saving potential. However, various challenges exist in achieving its widespread adoption and realising these savings. The primary issues include a shortage of personnel capable of leveraging AI and insufficient awareness of its benefits. Furthermore, to realise AI's full potential, data standardisation and the establishment of input rules are necessary. Additionally, operational considerations such as ensuring cybersecurity are required during AI deployment.
- The energy-saving potential of data centres is significantly influenced by improvements in ICT efficiency. Consequently, alongside the traditional focus on enhancing cooling efficiency, measures and strategies aimed at improving the efficiency of ICT equipment are required. This necessitates additional metrics for evaluating data centre energy savings, such as ICT efficiency (beyond PUE). Furthermore, collaboration is vital not only by data centre operators but also with diverse stakeholders, including semiconductor manufacturers and IT-related equipment manufacturers.