IEEJ Outlook 2018

– Prospects and challenges until 2050 –

Energy, Environment and Economy

Executive summary

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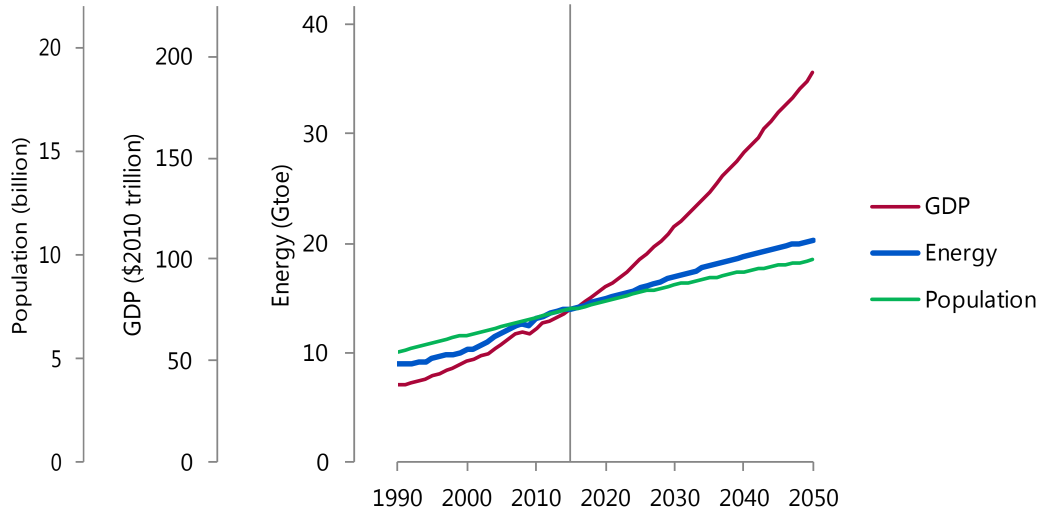
Executive summary

Global energy supply and demand outlook

Demand

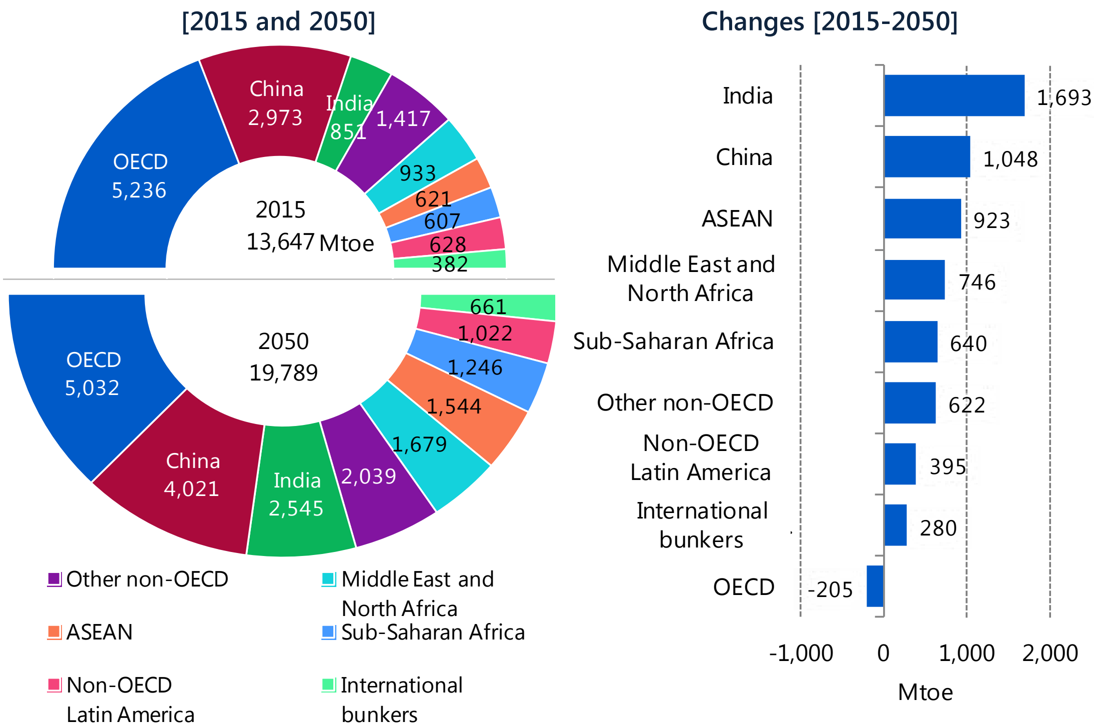
In the "Reference Scenario" which assumes that energy, environmental policies, etc. follow past trends, the world's population will be 1.3 times larger, the economy 2.5 times larger and energy consumption 1.5 times greater in 2050 than today (Figure 1). The energy needed to generate a single unit of gross domestic product (GDP) will decline at an annual rate of 1.6% due to energy efficiency improvements and will be a little more than half the current level in 2050. Although the increase in energy consumption continues as the economy grows, there is a significant difference in their pace of expansion. Nevertheless, the increase in energy consumption during the period – 6,142 Mtoe – is not a small amount, as the annual increase in demand is equivalent to the United Kingdom's consumption.

Figure 1 | World population, real GDP, primary energy consumption



The relationship between economic growth and energy consumption is not necessarily the same everywhere in the world. Despite economic growth, the energy consumption of the Organisation for Economic Co-operation and Development (OECD) member states combined will be less in 2050 than today (Figure 2). In other words, the future world increase in energy consumption will all occur outside the OECD. Among non-OECD countries, the significant increase in Asia – India, China and the Association of Southeast Asian Nations (ASEAN) – continues, and the Middle East, North Africa and Sub-Saharan Africa will also increase consumption largely due to rapid population and economic growth. Non-OECD's energy consumption that exceeded OECD in 2005, has since grown to 59% of the world today and will reach 71% in 2050. In other words, if non-OECD, including Asia, slows the increase in energy consumption due to more control or adjustment to their socioeconomic situation, the global energy supply and demand image can be greatly different.

Figure 2 | Primary energy consumption and changes (by region)

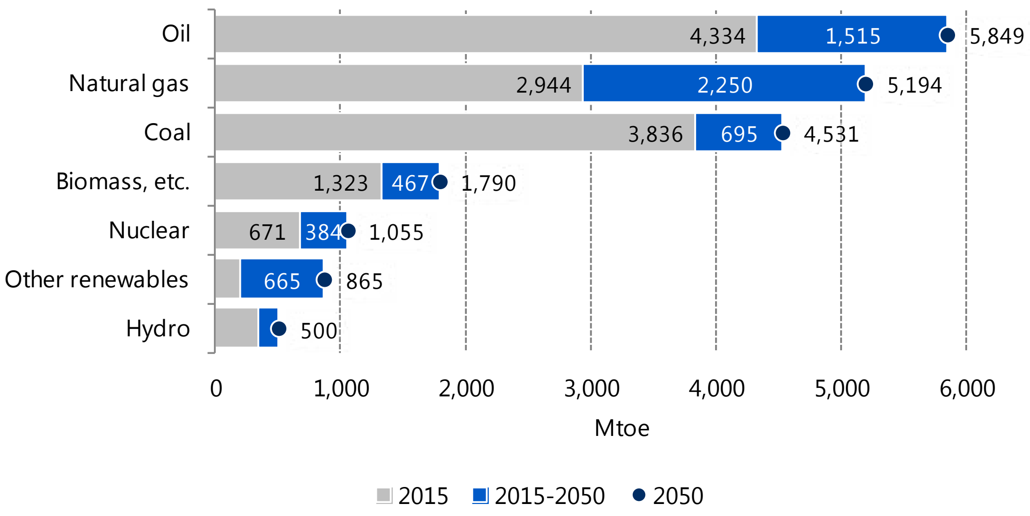


- Despite huge expectations from non-fossil energy, fossil fuels will meet most of the massive new demand (Figure 3). During the projection period, for each 1 toe of non-fossil energy increase, the fossil fuels will increase by 2.7 toes. The sum of all non-fossil fuels has yet to reach the total for coal, the least fossil fuel in 2050. Although non-fossil energy is expanding from 19%, its share is only 21% by the middle of this century.
- Oil remains the largest energy source, even in 2050, supporting 30% of global energy demand. Oil consumption peaked in OECD countries 10 years ago, and it continues to decline at an annual rate of 0.7%. The increase in global oil consumption from 90 million barrels per day (Mb/d) to 122 Mb/d is led by a vigorous consumption in non-OECD and international bunkers. China will be the world's largest oil consumer ahead of the United States in about 10 years. Its consumption will peak by the mid-2040s and decrease thereafter. India will become the second largest consumer prior to 2050, replacing the United States. India, the most populous country by 2022, is expected to become the largest consumer surpassing China in the mid-2050s.
- Natural gas shows increases larger than any other source of energy and overtakes coal as the second energy source by 2040. Both power generation and other uses contribute to an increase of more than 1,000 Mtoe. Of the 42 countries and regions that are listed in

IEEJ Outlook, only four countries, Japan, the United Kingdom, Italy and Germany, consume less natural gas in 2050 than today. Natural gas, the newest of the fossil fuels, exceeds oil and becomes the largest energy source in the United States around 2030 and in the European Union (EU) by 2040. Natural gas is currently the predominant energy source in 10 regions (13% of world energy coverage) but will be the leading fuel in 21 regions (36%) in 2050.

- Coal has grown significantly to cover half the world's energy consumption increase over the first 10 years of this century. However, the momentum has slowed down substantially, and this new trend continues in the future. Individual aspects, however, vary considerably from region to region. OECD continues to reduce its consumption and China, which tripled its coal consumption from 2000 to 2015, will turn down its needs after a slight increase by 2040. On the other hand, India and ASEAN provide much of the energy demand for coal, and the dependence on coal in 2050 will be as much as or more than today. As coal continues to be indispensable, it is strongly recommended to develop highly efficient and clean technology for its use.

Figure 3 | World primary energy consumption (by energy source)



- Final energy consumption, which represents the actual consumption by end-users, increases in all sectors (buildings, transport, industry, non-energy use, etc.) reaching 13,675 Mtoe in 2050, 46% more than today (Figure 4). As for primary energy consumption, the increase is attributable to non-OECD and international bunkers.

- Electricity consumption increases regardless of the economic development stage of each country and region (Figure 5). The share of electricity in the total final energy consumption will rise from 19% today to 24% in 2050. A particularly notable increase in electricity consumption comes from the non-OECD upper-middle-income economies. As non-OECD's lower-middle and low-income economies also increase their electricity consumption by more than four times, total non-OECD's demand increases by 15.7 PWh, well above the current and projected OECD consumption of 9.3 PWh and 12.1 PWh.

Figure 4 | Changes in final energy consumption [2015 – 2050]

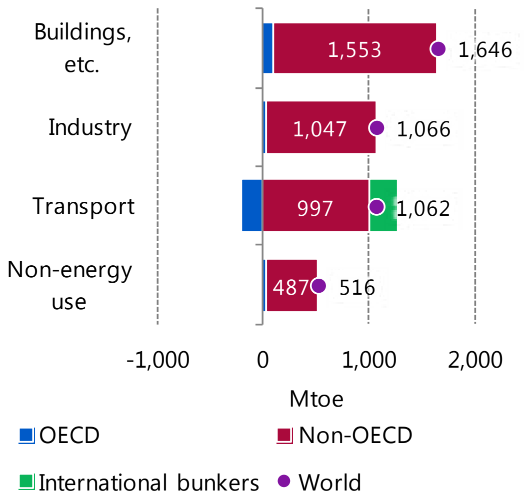
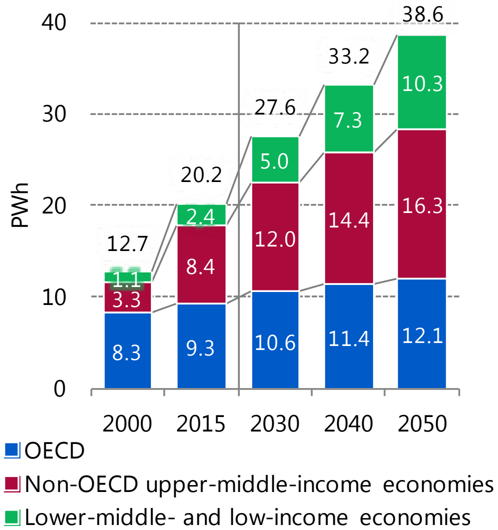


Figure 5 | Final electricity consumption



Note: Lower-middle- and low-income economies are countries and regions with nominal GDP per capita of $4,000 or less as of 2015.

The world electricity supply (electricity generation) is also increasing to meet the rapid growth pace in consumption. Energy used for power generation was 34% of the total primary energy consumption in 2000; it will represent 41% in 2050. The ratio will be 44% in OECD, where electrification is more advanced.

Supply

As a result of higher oil products demand, the supply of oil from both OPEC and non-OPEC will increase (Figure 6). Over 80% of the production increase until 2050 comes from Middle East OPEC, and North and Latin Americas. In North America, investments in exploration and development sectors will improve, backed by a moderate oil price recovery – $95/bbl and $125/bbl (real in $2016) in 2030 and in 2050, respectively. Unconventional oil, such as shale oil and oil sands, will steer the production increase. Production in Latin America, mainly driven by the Brazilian pre-salt development, will also play an important part of the increase in non-OPEC supplies. Non-OPEC production shares, however, will decline gradually from 58% in 2015 to 53% in 2050, due to the production decline in Asia and the peak of Europe and Eurasia around 2030.

Although demand for oil is increasing, the supply until the middle of the century can be met from already proven reserves, which are resources that can be produced in the current technology and economy (Figure 7). As such, the possibility of a supply constraint due to early depletion of resources is small because technological advances will also lead to the discovery of reserves and unconfirmed resources. The concern is that excessive risk avoidance, which is due to the volatility of oil prices and environmental constraints, will hinder adequate supply investment.

Figure 6 | Crude oil production in selected regions

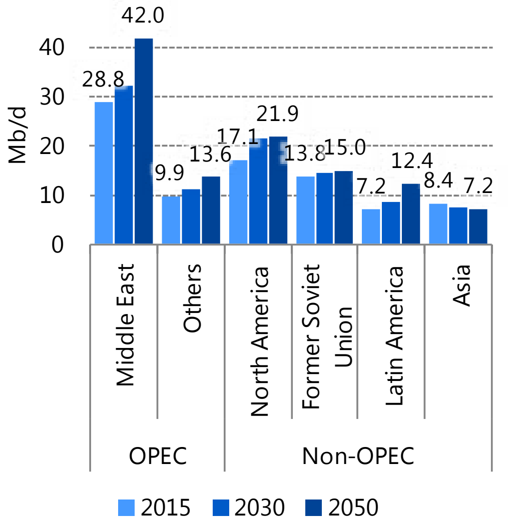
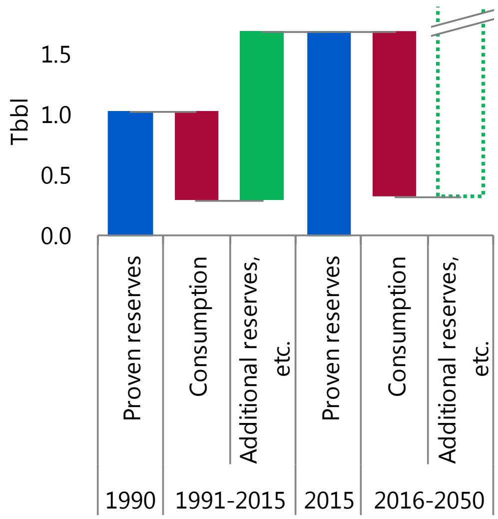
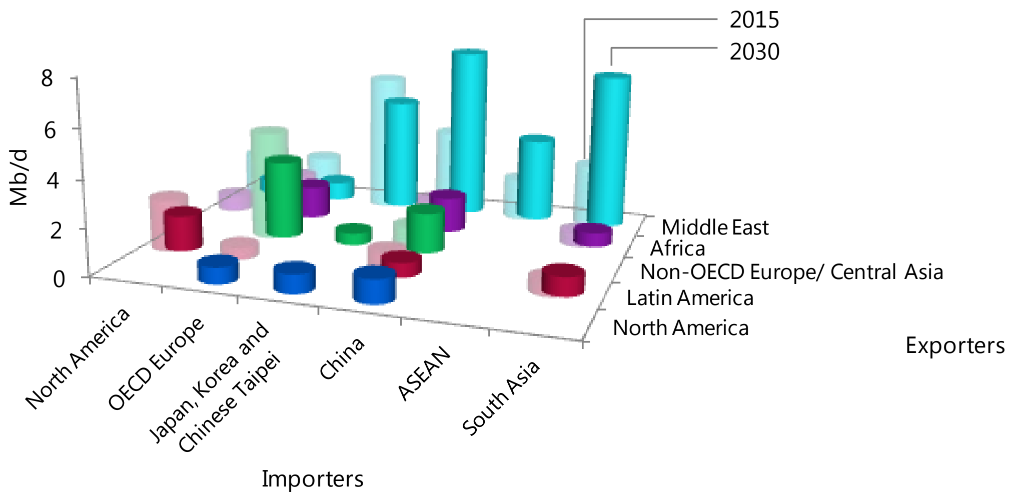


Figure 7 | World crude oil reserves and cumulative consumption



Crude oil trade between the selected regions increases to 43 Mb/d in 2030 (Figure 8). There will be fewer imports in the OECD, as demand declines and production increases in North America, but imports in emerging Asian economies will increase overall trade volume. In Asia, despite some diversification, oil supply from the Middle East and Africa accounts for 80% as of 2030. North American imports from Latin America and the Middle East will remain, but decline substantially. Non-OECD Europe / Central Asia, Africa, and the Middle East will compete in Europe as the region's imports decline. Non-OECD Europe / Central Asia and the Middle East will intensify their exports to Asia where demand increases, deepening the interdependence in crude oil trade between the Middle East and Asia.

Figure 8 | Crude oil trade between selected regions [2015 and 2030]



- The volume of natural gas production in the world increases by 80% from 2015 to 2050 (Figure 9). The largest increase in production comes from the Middle East with the annual addition of 589 billion m^3 (Bcm). Iran, which has the largest proven reserves in the world, will continue to maintain its position as the largest producer in the region meeting demand for petrochemical feedstocks and pipeline gas to neighbouring countries after 2030. The United States will continue to increase production using its accumulated knowledge on development and will expand exports of liquefied natural gas (LNG) from the Gulf Coast. The former Soviet Union follows these two regions. In Russia, East Siberia and Sakhalin will contribute to production increases after 2030, adding to the Yamal Peninsula, which is currently under development.
- The amount of natural gas trade between the selected regions of the world as of 2016 was 544 Bcm. Most of it was pipeline trade, especially from Russia to Europe. Trade will continue to expand to 825 Bcm in 2030, increasing Asia's LNG imports and North America's exports. Oceania and North America are the largest growing export regions, in which many LNG projects are planned to start operation between 2020 and 2025. On the other hand, the largest importer is China, importing 108 Bcm by pipeline and vessels (LNG) from Russia and Central Asia.
- Demand for LNG increases faster than the market for natural gas due to the quantitative and regional expansion of the use of natural gas. The balance of supply and demand is now relaxed. It, however, will reach a balance of about 400 million tonnes (Mt) in the mid-2020s if the additional supply capacity is limited to projects with final investment decision (FID) or under construction (Figure 10). On the other hand, about 370 Mt of projects are currently under plan, and there will be no shortage of supply if (part of) these stand up. It is important to develop a favourable environment to attract sufficient investment.

Figure 9 | Natural gas production in selected regions

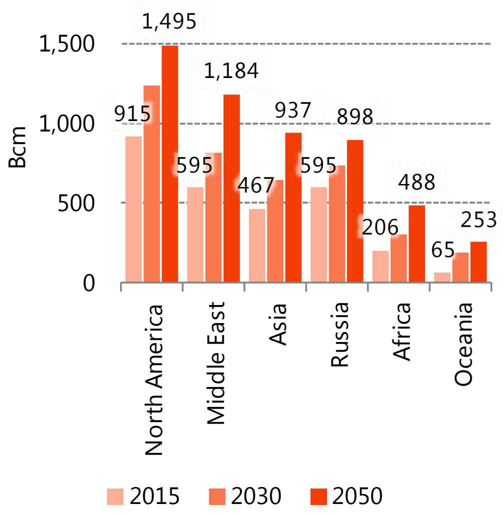
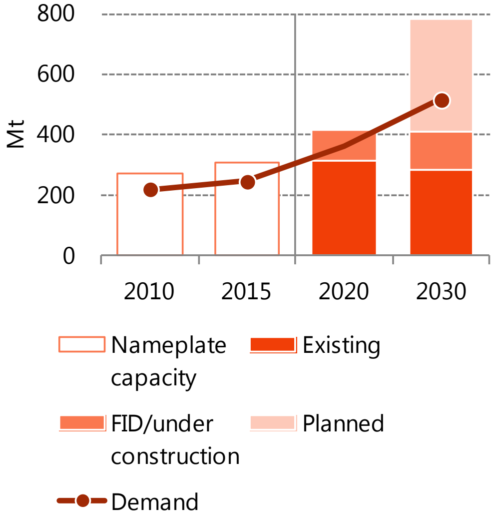


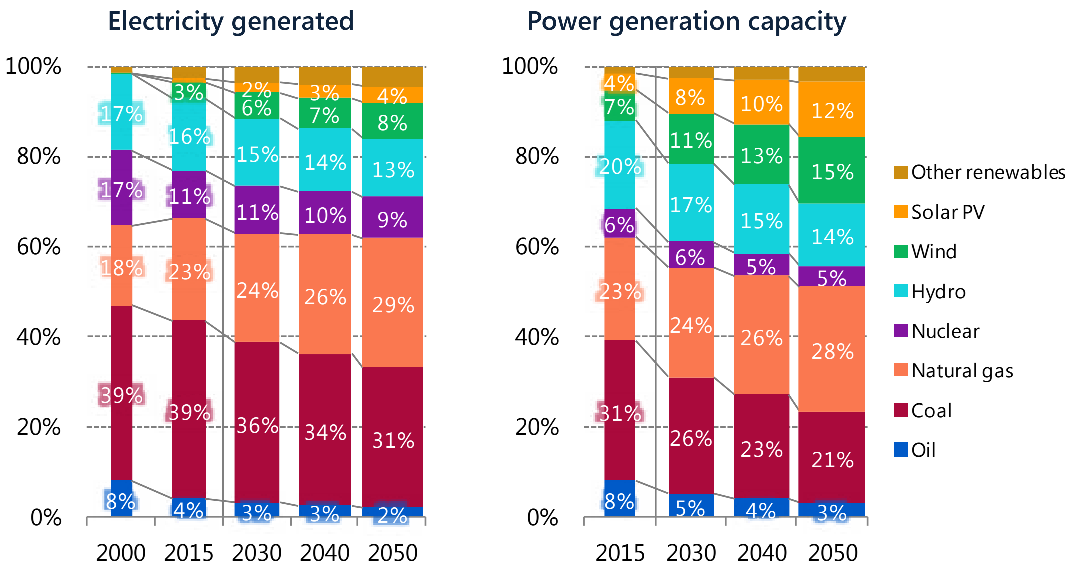
Figure 10 | World LNG supply capacity and demand



Coal production will increase from 7,727 Mt in 2015 to 9,283 Mt in 2050, with increasing demand for non-OECD countries, mainly in Asia and others such as Latin America and Africa. Steam coal increases from 5,835 Mt in 2015 to 7,710 Mt in 2050, 1.32 times, to largely meet increasing demand for power generation. Coking coal decreases from 1,081 Mt in 2015 to 1,004 Mt in 2050 due to shrinking crude steel production, and lignite decreases from 811 Mt in 2015 to 570 Mt in 2050 due to a decline in demand for this type of coal in power generation.

Although renewable energy is attracting attention in power generation, thermal power will remain dominant in the electricity generation sector (Figure 11). However, only natural gas-fired with high efficiency, with low carbon dioxide (CO_2) emissions and with excellent load-following will increase its share as thermal power generation. While coal continues to be the largest power source, its share will drop by 8% points to 31%, due to a decline in Europe and America.

Figure 11 | World power generation



Note: Bar width is proportional to total electricity generated

Note: Bar width is proportional to total power generation capacity

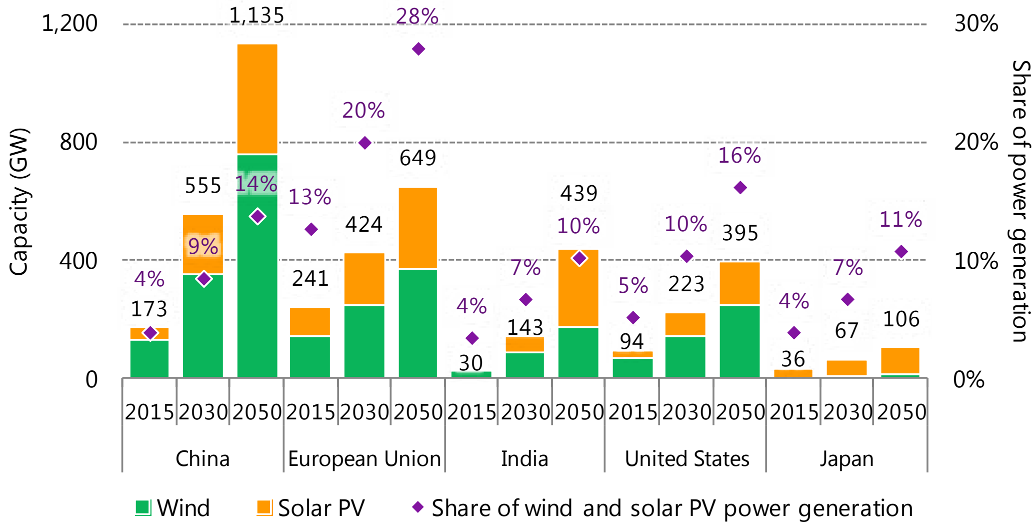
Nuclear power generation increases from 2,571 TWh in 2015 to 4,047 TWh in 2050. It, however, does not grow as rapidly as the total power generation, and its share will shrink by 2% points. The capacity will decrease in nine countries and regions, including Japan and Germany, which will stop in the 2020s. On the other hand, 12 countries will introduce new plants and 20 countries will increase capacities. The global capacity will increase from 406 GW in 2016 to 577 GW in 2050.

Electricity generated by wind and solar photovoltaic (PV), etc. increases 2.5 times from 1,111 TWh in 2015 to 2,778 TWh in 2030, and will double to 5,637 TWh in the following two decades. It accounts for 13% of total power generation in 2050. The required capacity for such generation is 1,865 GW of wind (4.5 times the current capacity) and

1,519 GW of solar PV, (6.8 times the current capacity) accounting for 27% – more than double the share of electricity generated – of total capacity of 12,547 GW.

The major introduction areas of wind and solar PV are now China, Europe and the United States, but India will be joining in the future (Figure 12). The introduction will expand as a region where those power generation costs decline. Behind the cost reduction, there are various factors, such as the low system price and cost of construction, the blessed solar radiation conditions, wind conditions, land acquisition, and the low barriers related to environmental assessment. Efforts to resolve problems are required in countries where system prices and construction costs are high.

Figure 12 | Capacity and power generation ratio of wind and solar PV in selected regions



Oil Demand Peak Case

Demand

Oil consumption continues to increase for automobiles until 2050 (Figure 13). However, the current movement to shift from conventional gasoline- or diesel oil-fuelled vehicles to electric vehicles has been particularly active in the context of air pollution countermeasures (Table 1). Some predict that oil consumption will peak in the not too distant future from the demand side as a response to climate change issues and not resource constraints.

Figure 13 | World oil consumption

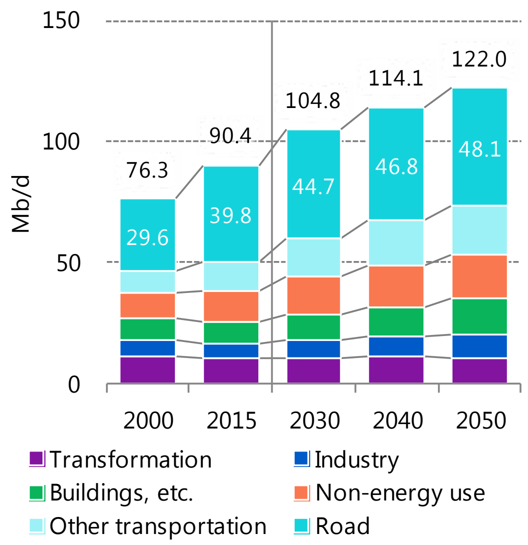


Table 1 | Major movement toward vehicle electrification

Germany	A resolution to ban conventional car sales in the European Union by 2030 was passed by the Bundesrat of Germany (2016)
Norway	The ruling and opposition parties proposed the abolition of conventional vehicles by 2025 (2016)
France	The Government announced that it would ban conventional car sales by 2040 (2017)
United Kingdom	The Government announced that it would ban conventional car sales by 2040 (2017)
India	Minister said that all new car sales after 2030 would be electric vehicles (2017)
China	Deputy Minister mentioned that the ban on the sale of conventional vehicles was under investigation (2017)

Future images are different from the Reference Scenario if all new vehicle (passenger and freight) sales in the world become zero emission vehicles (ZEV)[1] in 2050. In this “Peak Oil Demand Case,” oil consumption turns to a decline after peaking at 98 Mb/d; the vertex occurs around 2030 (Figure 14). The reduction from the Reference Scenario widens to 7 Mb/d in 2030 and 33 Mb/d in 2050.

The impact of the increase in electricity demand by ZEVs is not small (Figure 15). Electricity consumption for automobiles increased by 409 Mtoe in 2050 from the Reference Scenario, raising the final consumption of electricity by 12%. If the increased demand is met by thermal power generation, the primary consumption of natural gas and coal is increased by 572 Mtoe and 432 Mtoe, respectively. As a result, natural gas and coal exceed oil by the end of the 2030s, and then natural gas becomes the largest energy source. Biofuels for automobiles decrease with the reduction of vehicles with an internal combustion engine.

Total CO_2 emissions are reduced by 1.8 Gt in 2050 from the Reference Scenario, or 5.9% reduction from 2010. The highest reduction rates are seen in the countries and regions that have low carbon intensity of electricity with a large amount of hydro, including New Zealand, Canada and Latin America. In contrast, Iraq’s CO_2 emissions will rather increase by 7%.

[1] In this Outlook, plug-in hybrid vehicles, electric vehicles, and fuel cell vehicles

Figure 14 | World oil consumption and changes

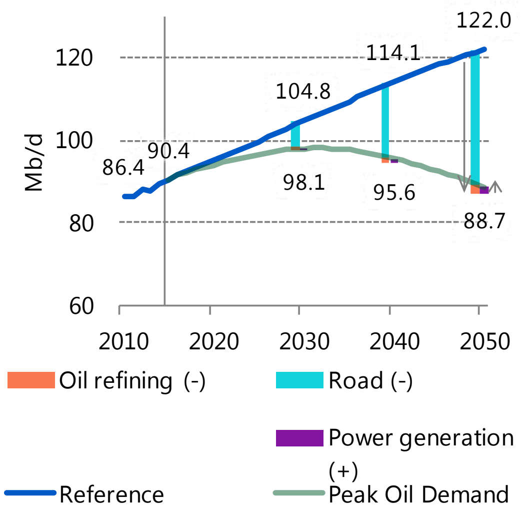
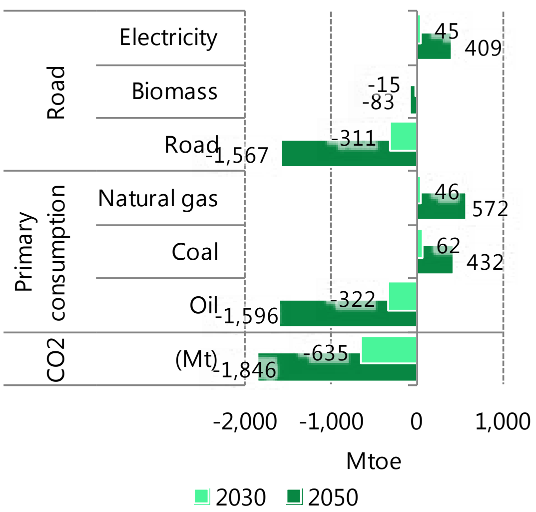


Figure 15 | Changes in world energy consumption (from Reference Scenario) [Peak Oil Demand Case]

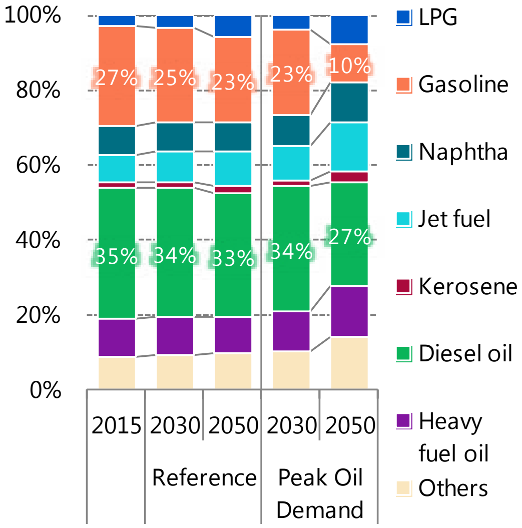


Supply

- These changes also spread to supply and demand by petroleum products (Figure 16). Gasoline's share of petroleum product consumption falls to just 10% in 2050. Since diesel oil is used in industry and other sectors, its share is not as small as gasoline, but it is reduced by 6% points from the Reference Scenario. The oil refining industry facing this situation needs to change drastically its operations. This could have implications for competitiveness due to the difference in secondary refining facilities and the difference in crude oil prices.

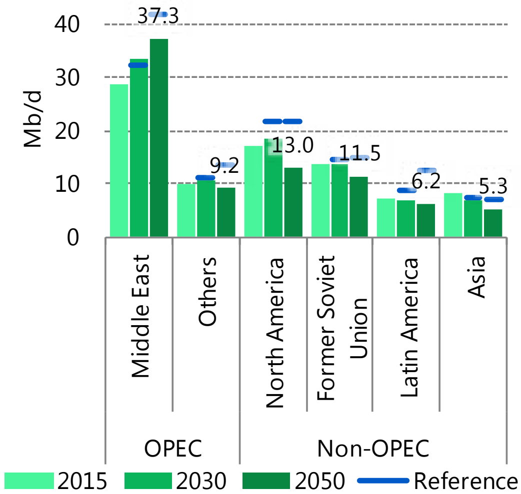
- The decline in oil consumption will have significant impacts on crude oil production (Figure 17). In view of the fact that oil demand in the world continues to increase in the future due to the conventional oil price assumption, the peaking of oil demand in the world becomes a kind of game changer, and oil prices may fall due to the relaxation of the supply and demand pressure and change in the market sentiment. Prices are assumed in this Case at $65/bbl in 2030 and $50/bbl in 2050 while $95/bbl in 2030 and $125/bbl in 2050 were assumed in the Reference Scenario (in 2016 prices). Assuming this significant price decline, regions with lower production costs should have an advantage and, as such, the Middle East is the only region to produce more in 2050 than today. OPEC's production share rose from 42% in 2015 to 46% in 2030 and continues to expand. In contrast, North American production is 13 Mb/d in 2050, 40% less than the Reference Scenario.

Figure 16 | World petroleum product consumption structure



Note: Excluding own use

Figure 17 | Crude oil production in selected regions [Peak Oil Demand Case]

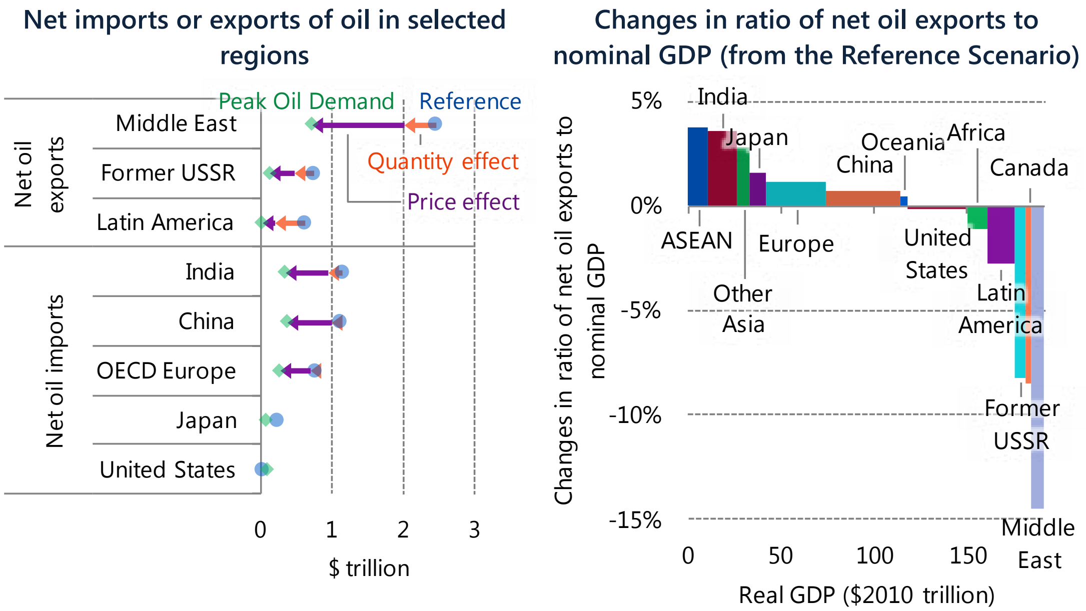


Impact on economic, environment and energy security

The resulting economic downturn, however, works not only in regions with lower crude oil production share but also in Middle East oil-producing countries (Figure 18). The decrease in net oil exports from the Middle East reaches $1.6 trillion in 2050, equivalent to 13% of its nominal GDP. In oil-producing countries, preparations for economic diversification that do not rely solely on oil are urgently required, and such “buds” are seen in the drawing of the “Saudi Vision 2030” by Saudi Arabia. On the other hand, the country most benefiting from the reduction of net oil imports is India, which will become the second largest oil consumer and poor in domestic reserve. India will be followed by China, which has the world’s largest automobile fleet.

The decline in oil demand may result in a decrease in tax revenues in developed countries where an excise tax is imposed on gasoline and diesel oil for automobiles. The amount of the tax is estimated at about $370 billion today, but it will drop to about $80 billion or one fifth of today in 2050 in the Peak Oil Demand Case if the tax regime is unchanged. On the other hand, in the current system, it is almost impossible to separate the amount of electricity used for automobiles from other uses and tax. It is possible that financial resources will be a major issue in combination with subsidies during the promotion of ZEVs.

Figure 18 | Net imports and exports of oil [Peak Oil Demand Case, 2050]



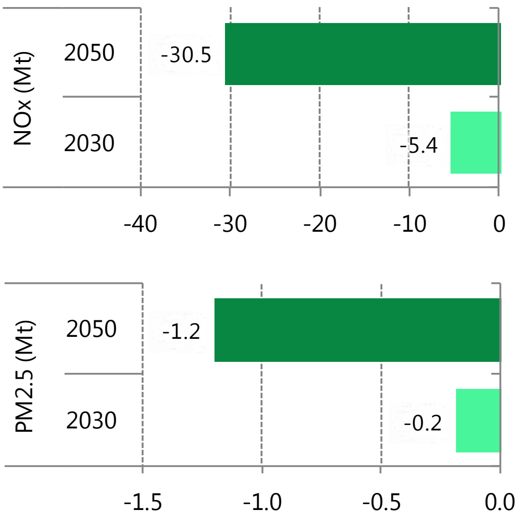
Note: Europe excludes the former Soviet Union

- The emissions of air pollutants, one of the main drivers for the promotion of the ZEVs, are reduced by 30 Mt for nitrogen oxides (NO_x) and 1.2 Mt for particulate matter ($PM_{2.5}$) from the Reference Scenario, or 27% and 3% of total emissions in 2010, respectively (Figure 19). These reductions exclude future improvements in emission control performance of conventional vehicles[2]. Contributions are expected to improve air quality in urban areas.

- The oil self-sufficiency rate of oil importing regions may deteriorate from the Reference Scenario despite the decrease in consumption (Figure 20). This is because oil price fall becomes a headwind against oil production in these high-cost areas as abovementioned.

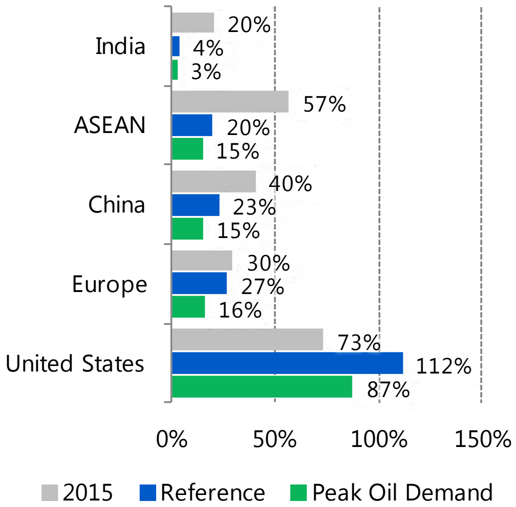
[2] Electricity demand for ZEVs can increase air pollutants from power generation. However, emission measures at power plants are easier to introduce than those for automobiles. Appropriate management is important to avoid increasing emissions.

Figure 19 | Changes in world NO_x and $PM_{2.5}$ emissions (from the Reference Scenario) [Peak Oil Demand Case]



Note: Excluding future improvements in emission control.

Figure 20 | Oil self-sufficiency ratio in selected regions [2050]



Note: Europe excludes the former Soviet Union

How do we recognise the rapid de-oiling?

- The Peak Oil Demand Case has shown that oil consumption can turn into a decline in the not too distant future under some circumstances. However, the feasibility of this Case can be said to be extremely challenging because the penetration of ZEVs is far greater than that in the "Advanced Technologies Scenario," in which a bottom-up approach to the maximum implementation of advanced technologies is adopted (described later). Rather, it can be interpreted that oil consumption may not be easily reduced. Also, it should not be overlooked that oil is required even in 2050 in the Peak Oil Demand Case on a scale that does not differ from today. It is natural for suppliers to worry about and necessary to prepare for demand peaks. However, if the supply investment is neglected, due to excessive pessimism in the future, it can trigger the switching from oil to other energy sources threatening energy security.

- The rising dependence on Middle East crude oil will increase geopolitical risk for stable supply. With the discord between Saudi Arabia and Iran, the rupture of diplomatic relations with Qatar, and the possibility of the proliferation of terrorist attacks while capture of "Islamic State" progresses, the situation in the Middle East is volatile with no sign of stability in the short term. In the Middle East oil-producing countries, the fiscal balance will be difficult to achieve given the low oil prices assumed in this Case. Although it is reasonable to cut public investment and subsidies to reduce budget deficits, it is difficult to deny the possibility of increasing social anxiety and worsening situation not only in oil-producing countries in the Middle East but also in the whole of the region.

Addressing climate change issues

Advanced Technologies Scenario

- In the Advanced Technologies Scenario, it is expected that the use of energy conservation and low-carbon technologies will be maximised in all countries of the world, based on applicable opportunities and acceptability by society to ensure stable energy supply and climate change objectives. In this Scenario, energy consumption in 2050 is reduced by 2,570 Mtoe or 13% from the Reference Scenario and the future increment is suppressed by 42% (Figure 21).
- In 2050, 23% of the energy savings required for the transition from the Reference Scenario to the Advanced Technologies Scenario is from 35 OECD countries; China and India are showing contributions of 24% and 15%, respectively (Figure 22). The world in the future depends on the success of a wide range of energy conservation and low carbonisation in developing countries offering plenty of potential for technological advances.

Figure 21 | World primary energy consumption

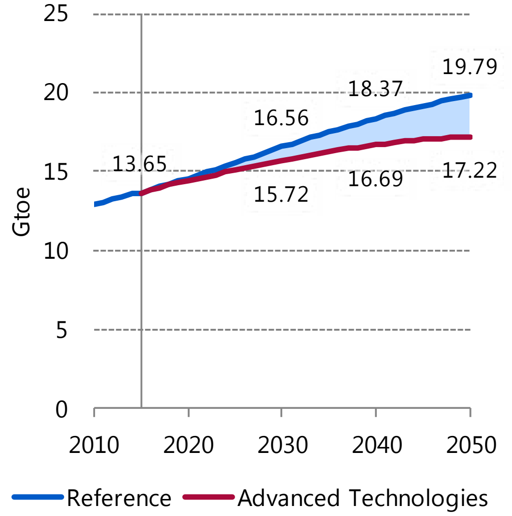
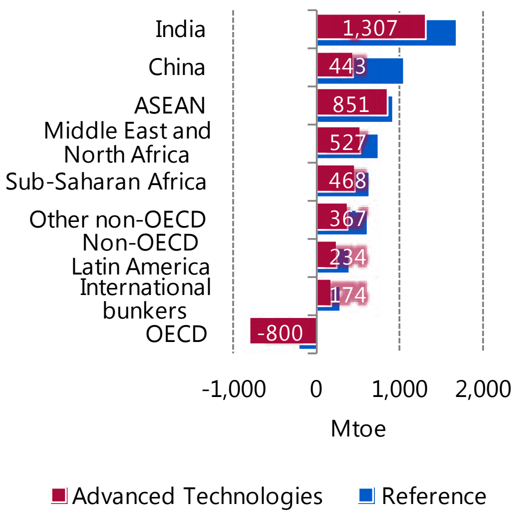
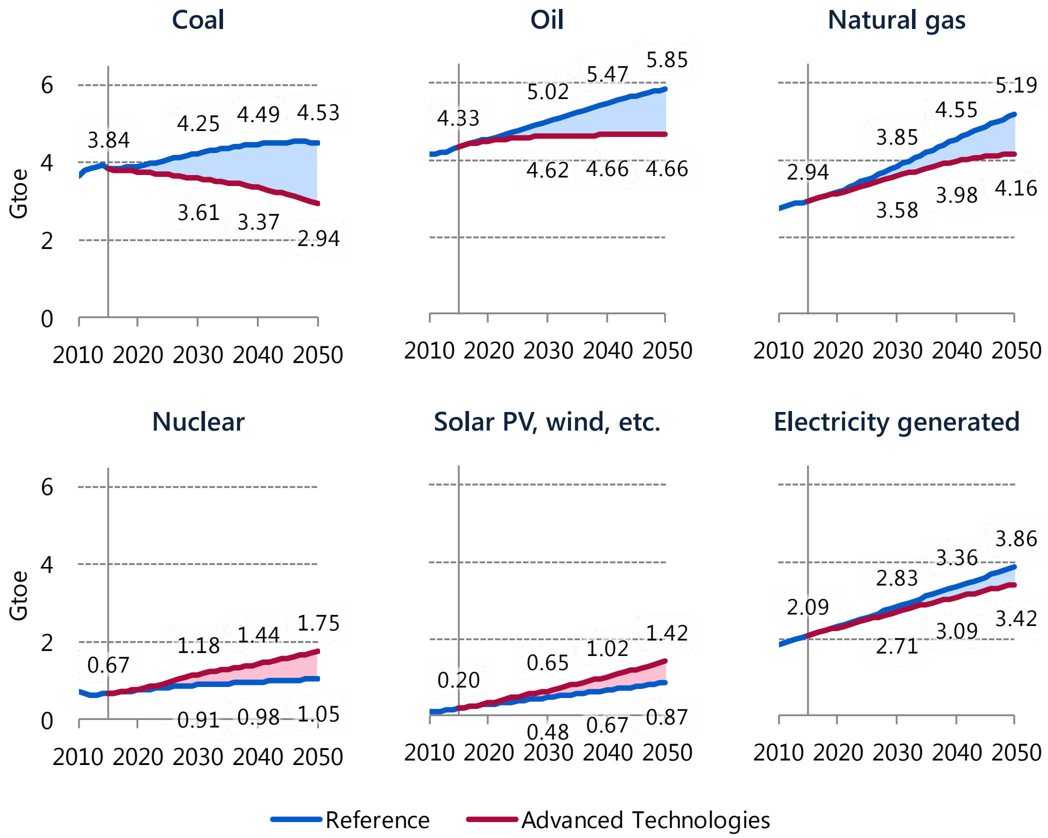


Figure 22 | Changes in primary energy consumption [2015-2050]



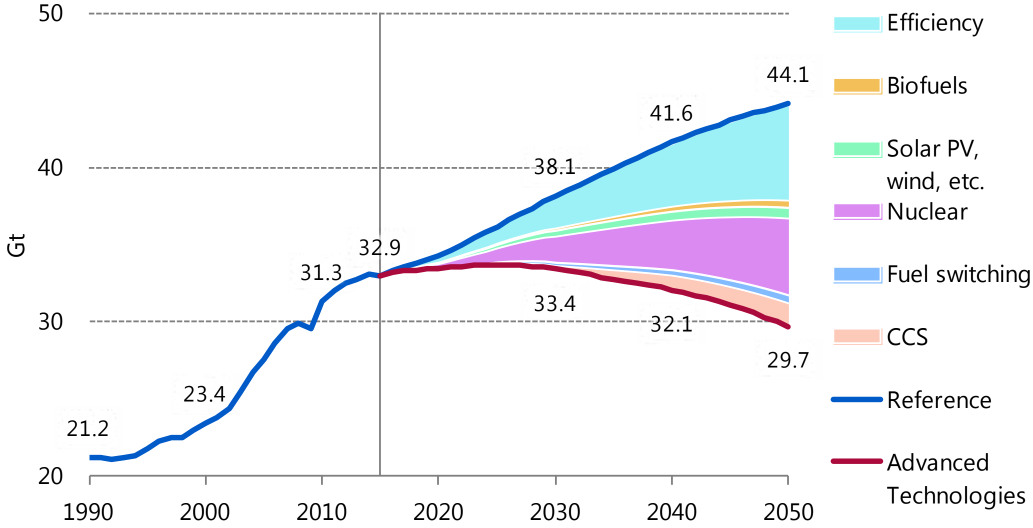
- The most significant change in the energy sources is seen in coal, which is mainly reduced for power generation, the result of lower electricity consumption, improved power generation efficiency, and switching to other energies (Figure 23). Oil reached a peak around 2040 and is 1,193 Mtoe below the Reference Scenario in 2050. Unlike coal and oil, natural gas will continue to increase for the next 35 years. While fossil fuels are reduced by 3,825 Mtoe from the Reference Scenario, nuclear is 699 Mtoe more and renewables are increased by 555 Mtoe, mainly wind and solar PV. As a result, the share of fossil fuels falls from 81% in 2015 to 68% in 2050.

Figure 23 | World primary energy consumption and power generation



▍ Energy-related CO_2 emissions of the world begin to decline gradually in around 2025, and reach 29.7 Gt in 2050, 1.6 Gt or 5% less than in 2010 (Figure 24). It is far from the "sharing with all parties to the UNFCCC the upper end of the latest IPCC recommendation of 40 to 70% reductions (of greenhouse gases [GHGs]) by 2050 compared to 2010" supported at the 2015 G7 Summit 2015 in Schloss Elmau. Nevertheless, the reduction of 14.4 Gt from the Reference Scenario is equivalent to 46% of the world's emissions in 2010, and the cumulative reduction of 227 Gt by 2050 is equivalent to 7.2 years of the world's current emissions. By region, OECD will be halved in 2050 compared to 2010. Although non-OECD emissions will peak in 2040, the overall increase by 2050 will be 23% compared to 2010.

Figure 24 | World energy-related CO_2 emissions and reduction contribution

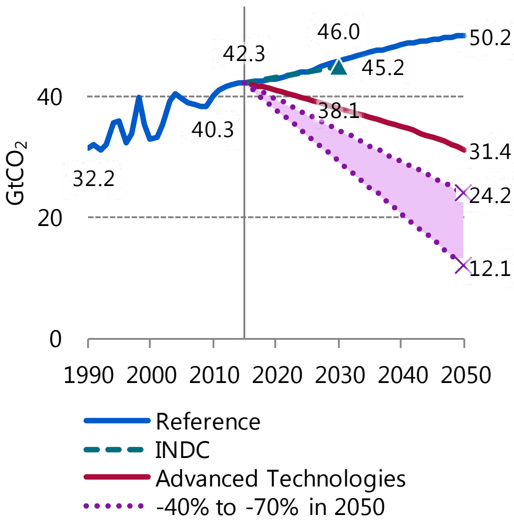


Intended Nationally Determined Contributions under the Paris Agreement

World GHG emissions estimated based on Intended Nationally Determined Contributions[3] (INDC) of the Paris Agreement are 45.2 $GtCO_2$ in 2030, an increase from today (Figure 25). They are lower compared to past trends and the differences from the Reference Scenario are not significant since the emissions of the past few years have been restrained. It is far from the abovementioned 40% to 70% reduction in 2050, or from the long-term goals of the Paris Agreement – peaking of greenhouse gas emissions as soon as possible, and making it virtually zero in the second half of this century. In order to approach the long-term goals, it is desirable for each country to reduce emissions to the extent of the Advanced Technologies Scenario. The penetration of low-carbon technologies in developing countries is particularly important.

[3] On 4 August 2017, the United States submitted a notice to the United Nations that it will withdraw from the Paris Agreement, but it is included in analysis for as the country can withdraw from the Paris Agreement on 4 November 2020 as earliest.

Figure 25 | World GHG emissions



Note: Estimates based on G-20's INDC under the Paris Agreement

Table 2 | Long-term goals of the Paris Agreement

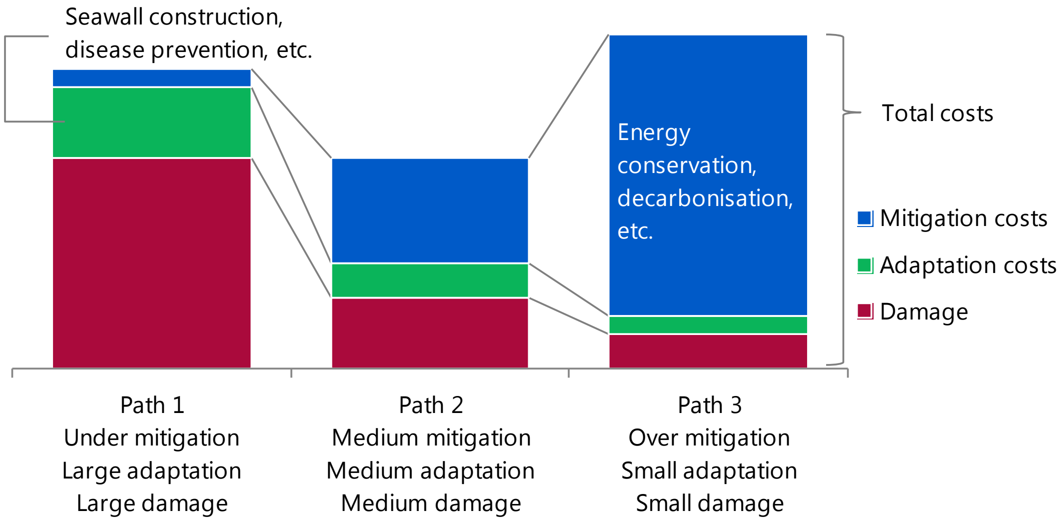
Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change. – Article 2
In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible, recognizing that peaking will take longer for developing country Parties, and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity, and in the context of sustainable development and efforts to eradicate poverty. – Article 4

Source: United Nations

Ultra long-term climate change paths

The climate change issue is a long-term challenge that will involve a wide range of areas over numerous generations. When and how specific measures should be taken and what measures should be implemented must be considered carefully. From the viewpoint of balance and sustainability, a combination of measures to minimise the total costs covering mitigation, adaptation and damage is evaluated (Figure 26). For example, an attempt to spend $1,000 on cutting emissions and building seawalls to prevent $100 in damage would be very difficult to justify and would risk failure.

Figure 26 | Image of the total costs of mitigation, adaptation and damage



- In "Minimising Cost Path" in which cumulative total cost is minimised, energy-related CO_2 emissions in 2050 is reduced to as much as in the Advanced Technologies Scenario. It, however, is not necessary to cut by half the emissions from today (Figure 27). GHG emissions continue to decline moderately after 2050 and fall by 52% from today in 2100. The atmospheric GHG concentration[4] will continue to rise slowly until around 2100 and fall to 550 ppm in 2150. Temperatures increase by 2.4°C and 2.6°C in 2100 and in 2150, respectively, compared to the latter half of the 19th century. That is, the Minimising Cost Path is different from a path of achieving the very ambitious long-term goals of the Paris Agreement.

- It, however, is dependent on assumptions. For example, although the Minimising Cost Path delays mitigation measures, the temperature rise will still be about 2°C if the climate sensitivity[5] is 1.9°C instead of 3.0°C. A simple calculation results in a difference of about 0.5°C in the temperature of 2200 due to the difference in climate sensitivity of 1°C. In addition, if the average discount rate of the period until 2300 is 1.1%, instead of 2.5%[6], future costs would be higher, so the path for earlier mitigation would be considered as optimal, with a temperature rise of 2°C around 2100 and then decreasing. By simple calculation, a difference of 1% point of the discount rate results in a temperature difference of about 0.5°C in 2200.

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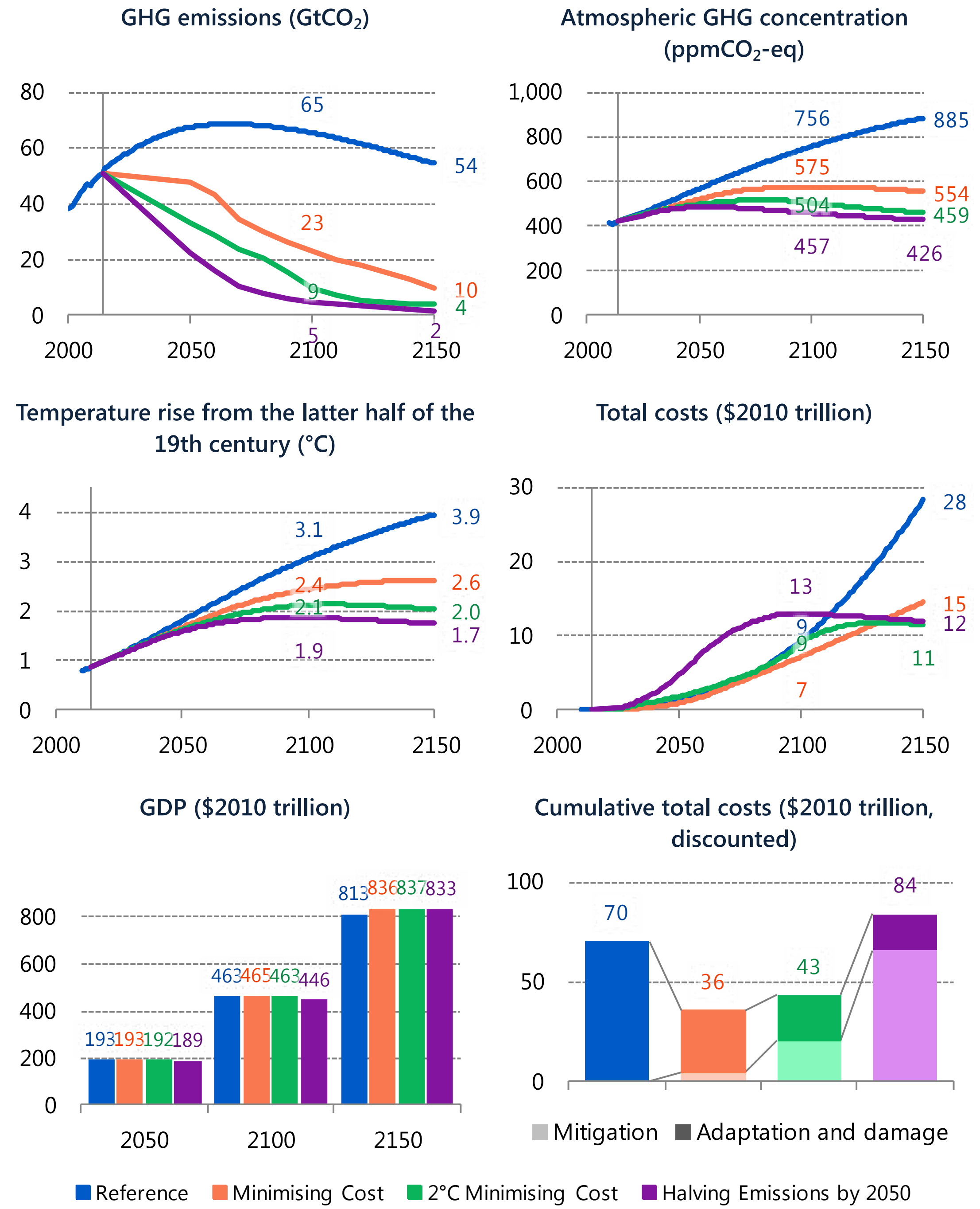
[4] CO_2 equivalent. Include aerosols, etc.

[5] Average temperature increase when the atmospheric GHG concentration as CO_2 equivalent concentration is doubled (°C).

[6] The average of 2.5% is equivalent to the pure time preference rate $\delta = 0.5\%$ in the Ramsey rule and the elasticity of the marginal utility of consumption $\eta = 2$. The average of 1.1% is $\delta = 0.1\%$ and $\eta = 1$.

Figure 27 | Ultra long-term paths



Note: Atmospheric GHG concentrations include aerosols, etc. Cumulative total cost is 2015 to 2500.

It is also useful to consider a path that is stronger to curb the temperature rise than the abovementioned Minimising Cost Path, respecting the "2°C Target" in international political and negotiation arenas. For example, in order to keep the cumulative total cost as small as possible and to reduce the temperature rise range in 2150 to 2°C, additional reductions are required to the Minimising Cost Path. GHG emissions under this "2°C Minimising Cost Path" decrease by 31% and by 80% in 2050 and in 2100, respectively, compared to 2010.

- The development and diffusion of innovative technologies is essential for the realisation of the 2°C Minimising Cost Path. The reduction of energy-related CO_2 required for the transition from the Advanced Technologies Scenario to the 2°C Minimising Cost Path is 11.1 Gt in 2050. If this 11.1 Gt is realised by using hydrogen, for example, 3,000 GW of hydrogen-fired power generation and 1 billion fuel cell vehicles are required (Table 3). All innovative technologies, including other options, have challenges in development and social acceptability today. International cooperation is important to overcome these challenges for individual technology development.

- In addition, the costs of technologies must be sufficiently lowered. The highest implicit CO_2 reduction costs (in 2010 prices) for the 2°C Minimising Cost Path are $85/t$CO_2$ in 2050 and $503/t$CO_2$ in 2100 (Figure 28). The Minimising Cost Path provided by the principle of reducing cumulative total cost will not introduce a technology unless its cost falls below these CO_2 reduction costs. In addition, unless it is cheaper than other competitive technologies, the technology will not be selected economically if the potential for introducing competitive technology is not limited. Innovative technologies also need "innovative" ways to reduce their costs. The target costs for those technologies, such as BECCS, hydrogen-fired power generation, FCV, very-high-temperature reactor, and solar power satellite are almost within the range of the CO_2 reduction costs; the 2°C Target can be achieved with the use of these technologies.

Table 3 | Example of innovative technologies introduced to transition to the 2°C Minimising Cost Path

[1] Zero emission technologies: amount required for CO_2 reduction (10.4 Gt) in the power generation sector

Substitution of approximately 2,800 GW of thermal power generation capacity without CCS in 2050

Thermal power generation with CCS (aquifer storage)	Approximately 2,800 GW (a maximum reduction of 9.4 Gt assuming CO_2 recovery rate of 90%) CO_2 storage potential is estimated at 7,000 Gt or more	Either
Hydrogen-fired power generation (CO_2 free hydrogen)	Approximately 3,000 GW ≈ 1 GW of turbine × approximately 3,000 units Hydrogen required: 650 Mt/year (three times as much as current LNG demand)	
Solar power satellite	Approximately 3,000 GW ≈ 1.3 GW of equipment (2 km × 2 km) × approximately 2,300 units	
Very-high-temperature reactor	Approximately 2,400 GW ≈ 0.275 GW of plant × approximately 8,700 units	
Nuclear fusion	Approximately 2,200 GW ≈ 0.5 GW (ITER equivalent) of plant × approximately 4,500 units	

[2] Zero emission technologies: amount required for CO_2 reduction (remaining 0.7 Gt) outside the power generation sector

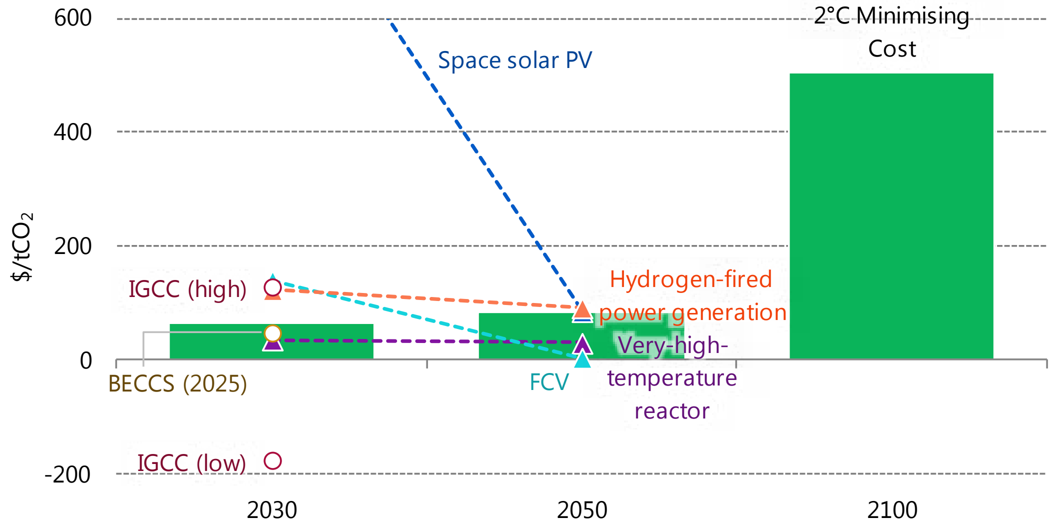
CCS in manufacturing	Laying CCS in 16% of iron and steel, cement, chemical, paper and pulp, petroleum refining, and GTL/CTL production facilities	Either
Fuel cell vehicle (CO_2 free hydrogen)	Approximately 1 billion units (2.6 billion vehicles are on road in 2050) Hydrogen required: 150 Mt/year (equivalent to 60% of current LNG demand)	

[3] Negative emission technologies: amount required for CO_2 reduction in the power generation sector (11.1 Gt)

Biomass-fired power generation with CCS (BECCS)	Approximately 1,400 GW ≈ 0.5 GW turbine × approximately 2,800 units Biomass required: 2,000 Mtoe/year. As much as 2.85 million km^2 of land, larger than Argentina (2.78 million km^2), is required for the supply

Note: Stock volume and usage as of 2050. Addition from the Advanced Technologies Scenario. One from each of [1] and [2], or [3] is equivalent to 11.1 Gt reduction.

Figure 28 | CO_2 reduction costs



Note: The 2°C Minimising Cost Path is the highest CO_2 reduction cost among the technologies adopted at each time of the Path (carbon price) and in 2010 prices. The assumptions and ambition of the goal and estimates are different in each technology.

Key assumptions for calculation:

[Very-high-temperature reactor] With reference to the Nuclear Science and Technology Commission "Development of future research and development related to the very-high-temperature reactor technology (draft)," the construction cost of a 0.3 GW reactor is assumed at about $500 million.

[Integrated coal gasification combined cycle (IGCC)] With reference to OECD/NEA "Projected Costs of Generating Electricity, 2015 Edition," the construction cost is assumed $1,200/kW - $2,900/kW and power generation efficiency is assumed 50% - 52%.

[Fuel cell vehicle (FCV)] With reference to the Hydrogen and Fuel Cell Strategy Council "Hydrogen and Fuel Cell Strategy Roadmap," assumed that vehicle price in 2050 is $25,000 (same as conventional vehicle), fuel economy is 115 km/kg (fuel efficiency of 31 km/Lge) and hydrogen retail price is $0.5/Nm^3$.

[Hydrogen-fired power generation] With reference to the Hydrogen and Fuel Cell Strategy Council "Hydrogen and Fuel Cell Strategy Roadmap" and IEA "Technology Roadmap: Hydrogen and Fuel Cells," assumed that plant delivery price of hydrogen in 2050 is $0.15/Nm^3$, construction cost is $1,200/kW, and power generation efficiency is 57%.

[Solar power satellite] With reference to the Space System Development Promotion Organization "Integrated Space Solar Power Generation System 2006 Model Research and Development Roadmap, Revised version 2016," $100/MWh as the target unit price for power generation in 2050 is used.

[Biomass power generation with CCS (BECCS)] With reference to IRENA "Renewable Power Generation Costs in 2014" and the IPCC "Special Report on CCS," estimated based on power generation cost of $130/MWh and CO_2 recovery and storage cost of $70/tCO_2$.

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