The 436th Forum on Research Work

IEEJ Outlook 2021

Energy transition in the post corona world

Energy, Environment and Economy

Tokyo, 16 October 2020

The Institute of Energy Economics, Japan

Energy Outlook toward 2050 and Post Corona Scenario

Summary of Reference Scenario

Reference Scenario

The scenario reflects past trends with technology progress and current energy policies.

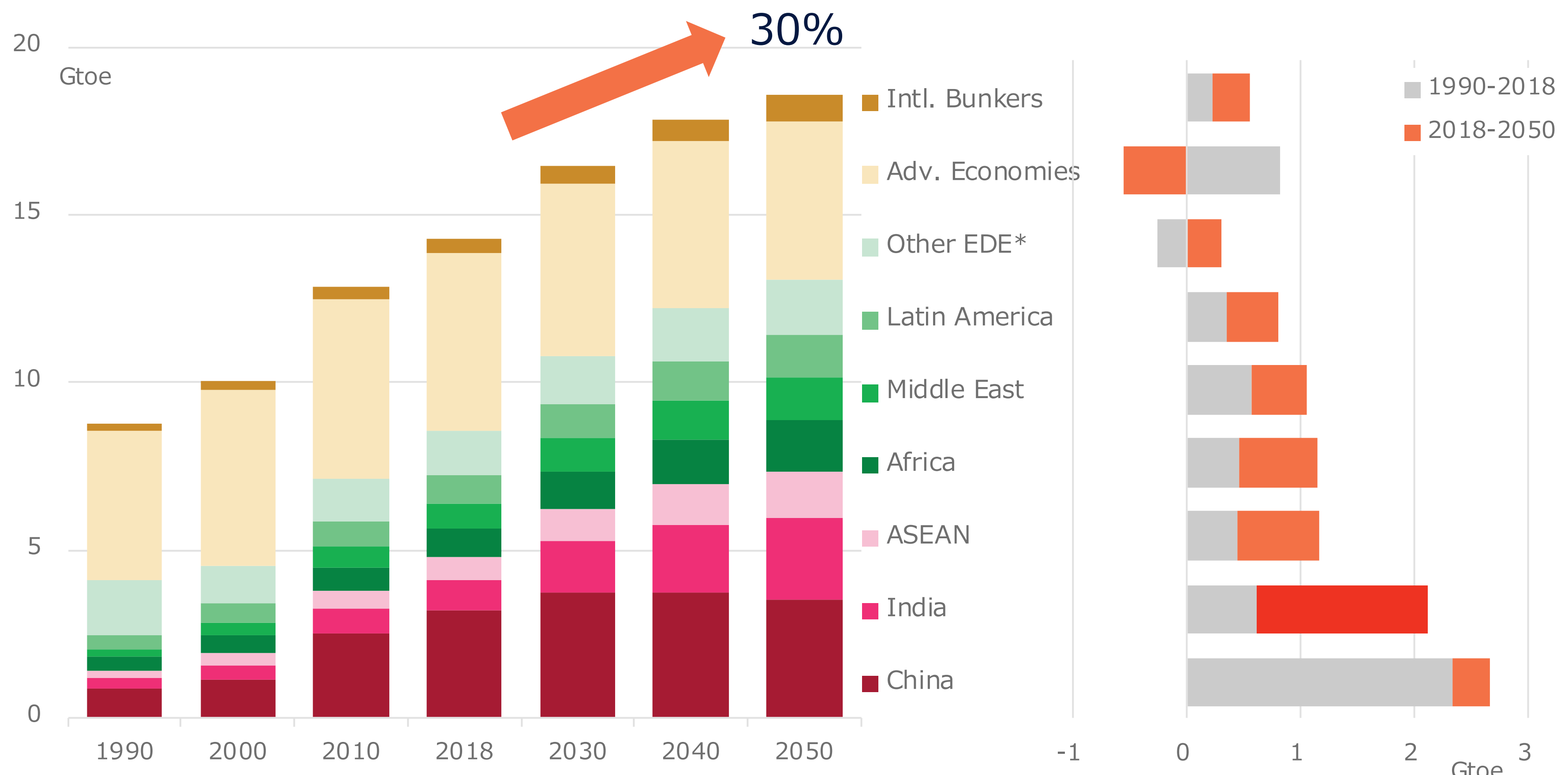
- Global energy demand increases, especially in Asia. The center of global energy demand shifts to Asia.
- Within Asia, demand increases mainly in India and Southeast Asia.
- Natural gas increases significantly, oil increases moderately while coal peaks out. The overall share of fossil fuels stays at 80%, even in 2050.
- With an increase in energy demand centered on fossil fuels in Asia, energy security and environmental issues become more serious in the future.
- It is important to respond to the decline in self-sufficiency and the increase impact on the environment, especially in Asia.

Reference

Demand growth shifts from China to India

❖ Primary Energy Demand

❖ Growth (1990-2050)



*EDE: Emerging and Developing Economies

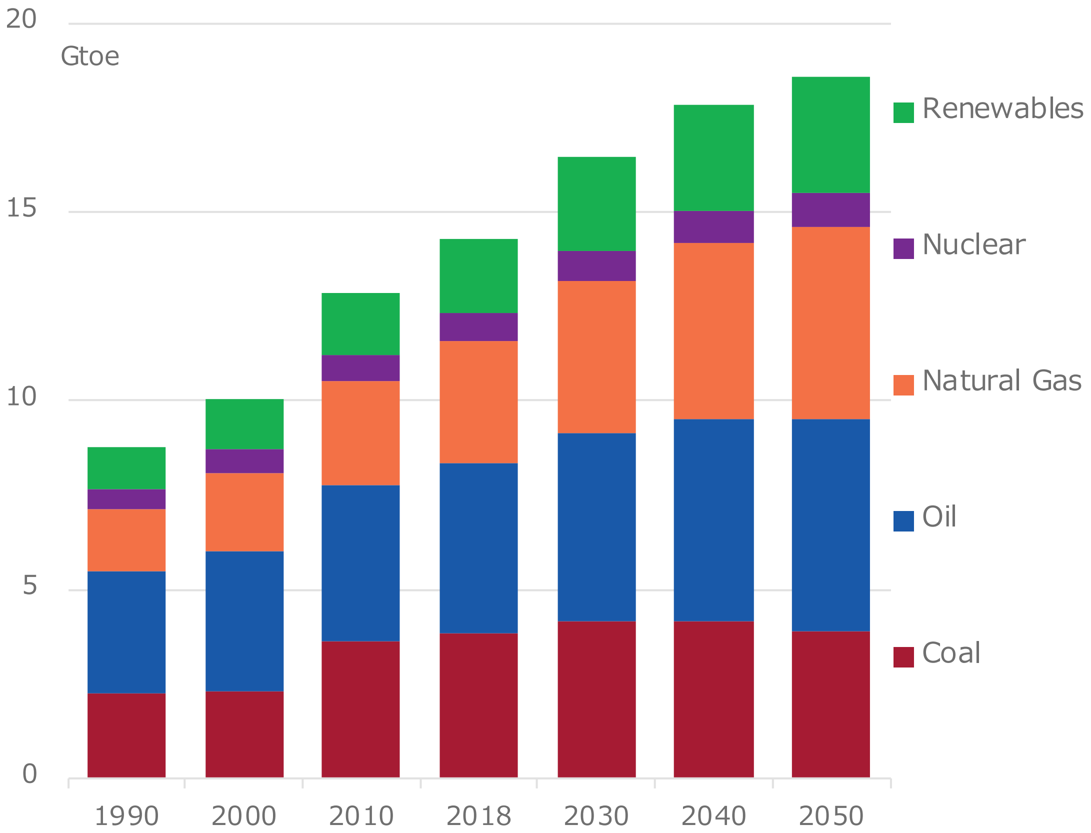
Energy demand in emerging and developing countries increases by more than 50%, while that in advanced economies decreases by about 10%.

The global energy demand growth changes from China to India. More than one-third of the global demand growth comes from India, while China's demand peaks in the late 2030s.

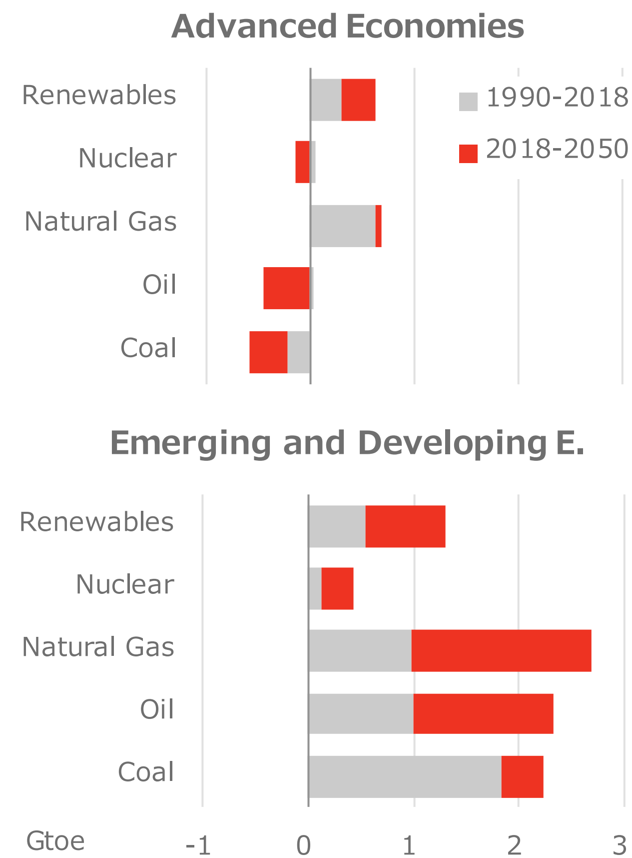
Reference

Coal peaks out, NG increases significantly, Oil continues to increase

❖ Primary Energy Demand



❖ Growth (1990-2050)



Natural gas increases the most, especially in the power generation sector, making it the second largest energy source after oil. The growth in oil consumption in emerging and developing countries by far counter-balances the decrease in advanced economies. Coal demand peaks in the mid-2030s due to a decline in advanced economies and China.

Analyzing "Post Corona World Transformation Scenario"

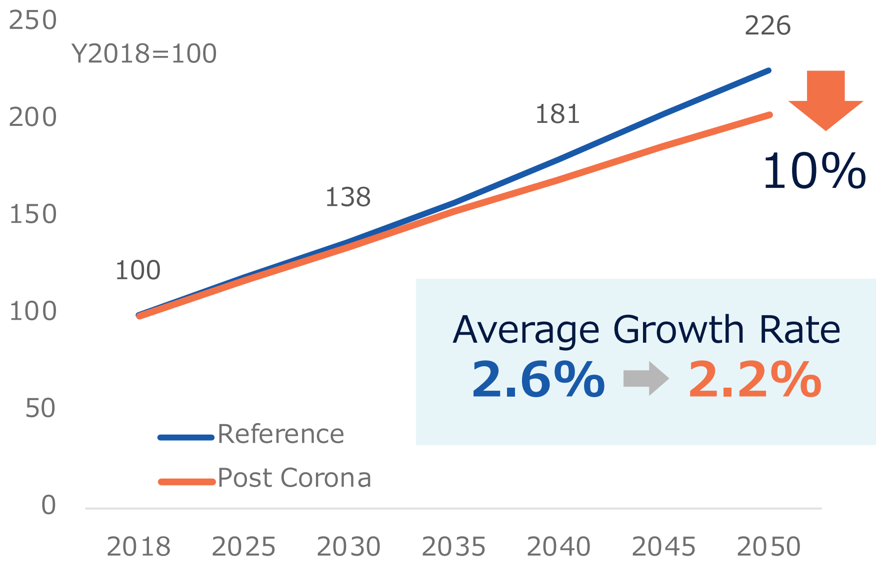
Reference Scenario	Reflects past trends with technology progress and current energy policies.	
Post Corona World Transformation Scenario	A world in which the coronavirus pandemic causes transformation and changes in politics, economy and society. Strengthening climate measures continues, but the extent of efforts differs in each country/region.	
	Emphasis on security	**Progress of digitization**
Changes in consciousness and behavior	・Ensuring the safety and health of people, including measures against infection. ・Reviewing supply chains, including the extent of self-sufficiency.	・Increasing remote activities by refraining people's movements and personal contacts. ・As society avoids denseness, migration from large cities to rural areas is emerging.
Changes are accelerating	・The worsening of US-China relations ignites relatively high political tensions between nations. ・Nationalism and alliedism leading to withdraws from the free trade system.	・Accelerating ICT to support and establish remote economic activities. ・Refraining from foreign travel, transportation demand stagnated.
Consequences of the changes	・Global economy slowing down. Manufacturing base shifts from China to India /ASEAN. ・Strengthening efforts to diversify energy supply and improve self-sufficiency. Competition for energy technology hegemony.	・As society becomes more digital, electricity demand increases. ・Significant drop in oil demand, especially for transportation fuels .

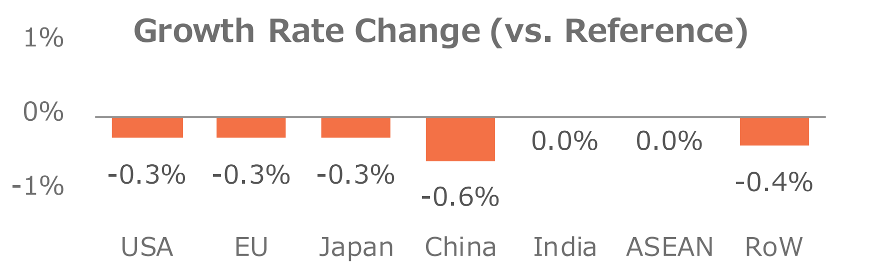
Post-Corona

Economic growth slows and energy demand curtails

IEE JAPAN

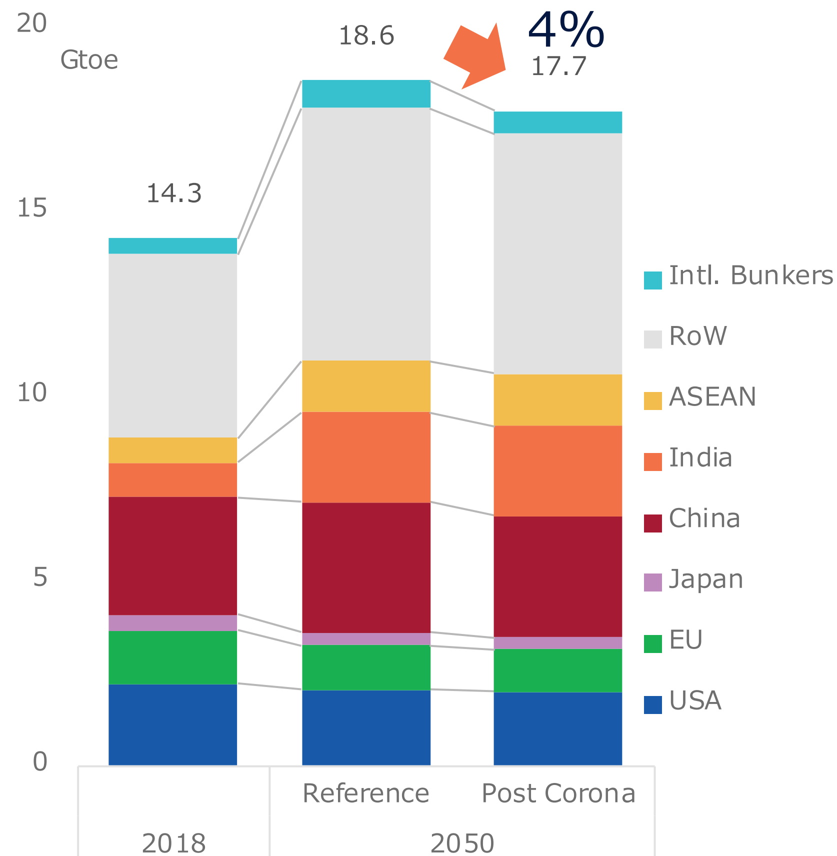
GDP





Ref.) During the Great Depression of 1929, about 10% of GDP was lost in three years.

Primary Energy Demand



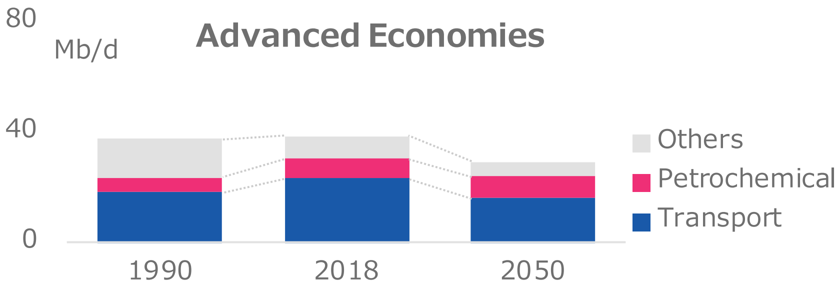
Note) The EU (European Union) does not include the United Kingdom. The same shall apply hereafter. RoW: Rest of the world

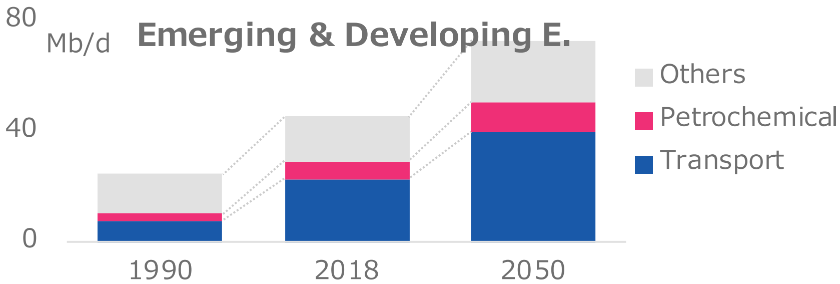
In the Reference scenario (RS), energy demand increases by 30%, with more than 60% of the increase coming from the Asian region.

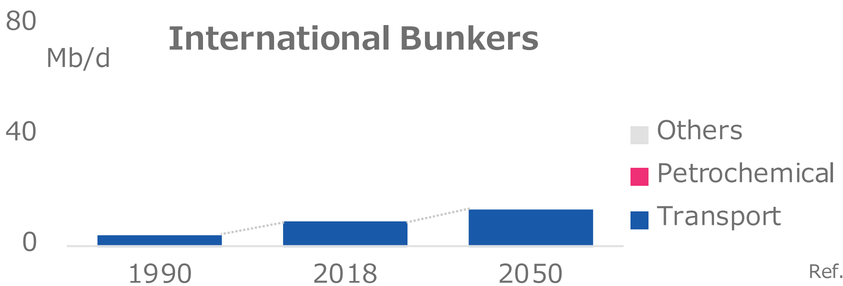
In the Post Corona scenario (PCS), stagnation in free trade causes the world economy to shrink 10% by 2050. With leakages in production bases, China's economy significantly slows down. Global energy demand shrinks by 4%, but concentration in Asia remains unchanged.

Oil demand peaks due to stagnation in transportation

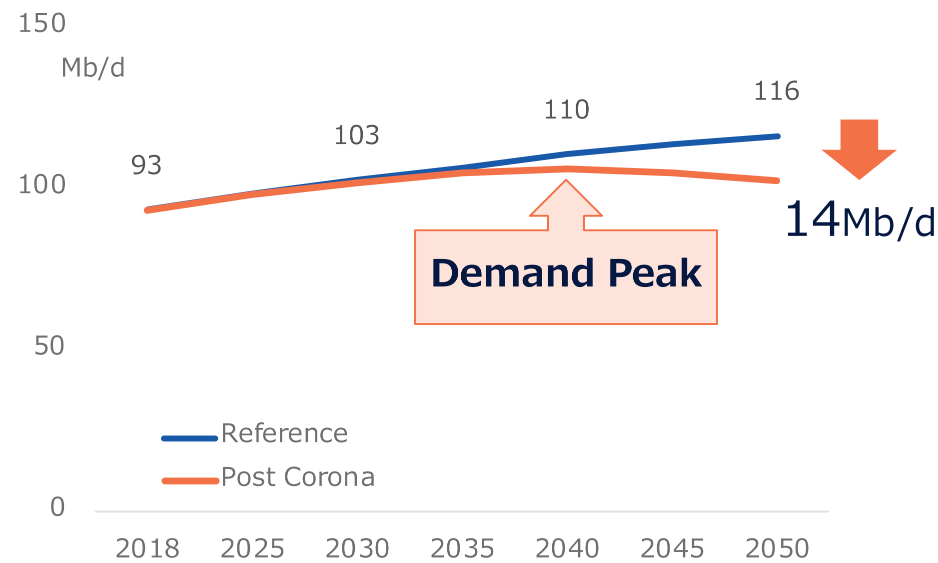
❖ Oil Demand by Sector (Reference)

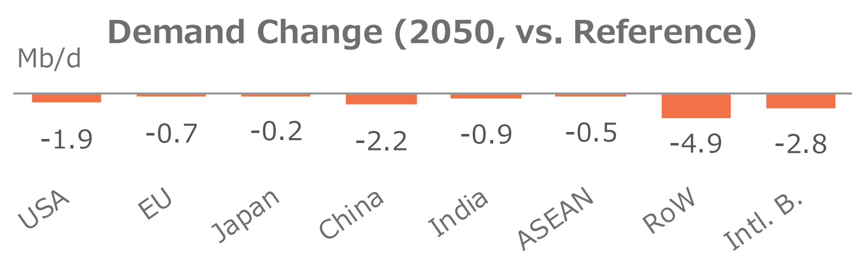






❖ Oil Demand in Post-Corona





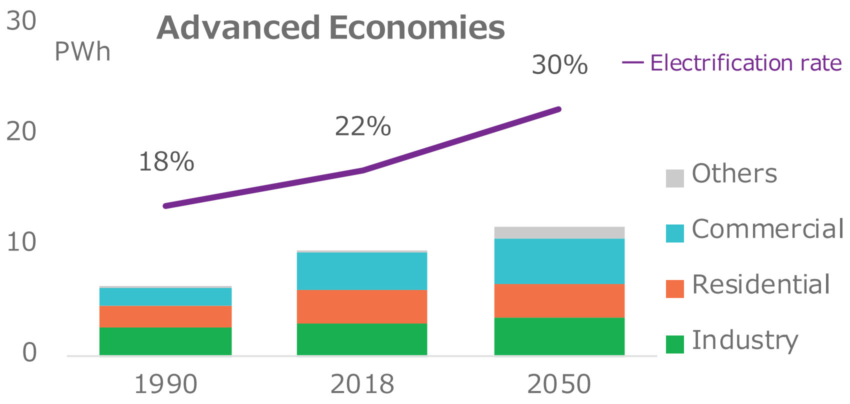
Ref.) It is estimated that if the electrification of automobiles progresses rapidly, it will reach its peak around 2030 (IEEJ Outlook 2018).

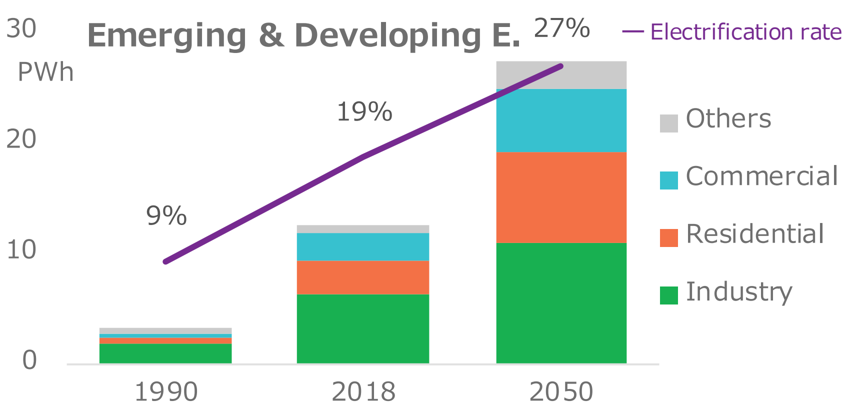
In the RS, global oil demand grows primarily because of transportation fuels and petrochemical feedstocks. In advanced economies, however, demand for transportation fuels is declining.

In the PCS, oil demand peaks around 2040. Fuel demand for automobiles, aviation, and ships declines due to economic slowdown and associated lower transportation requirements.

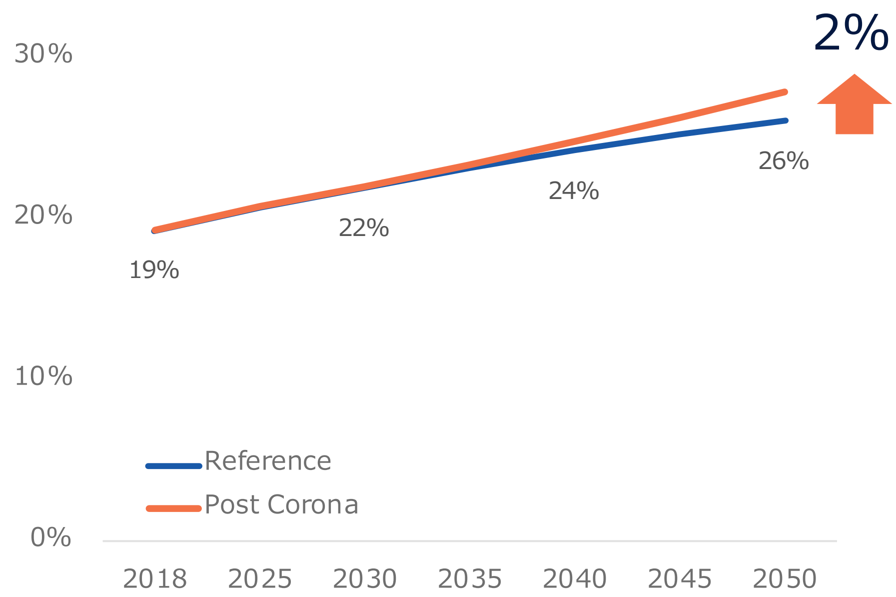
Digital transformation(DX) raises electrification rate

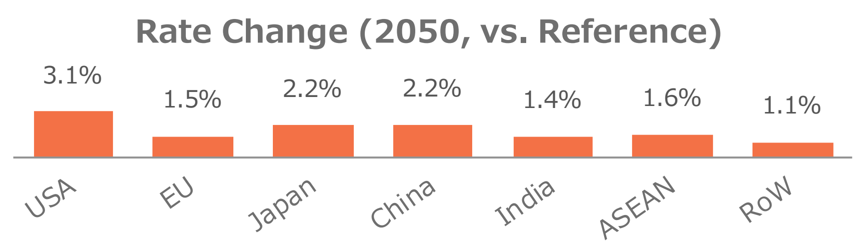
❖ Final Electricity Demand (Reference)





❖ Electrification Rate in Post-Corona



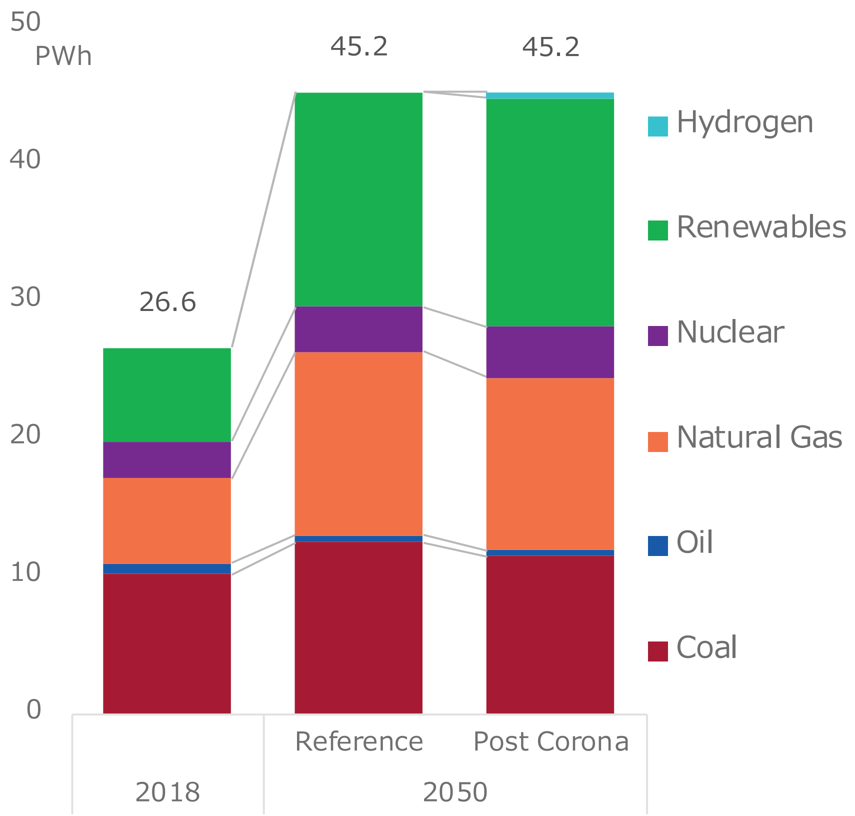


In the RS, electricity demand in the industry and building sectors surged along with the economic development of developing countries. Energy demand becomes more electrified.

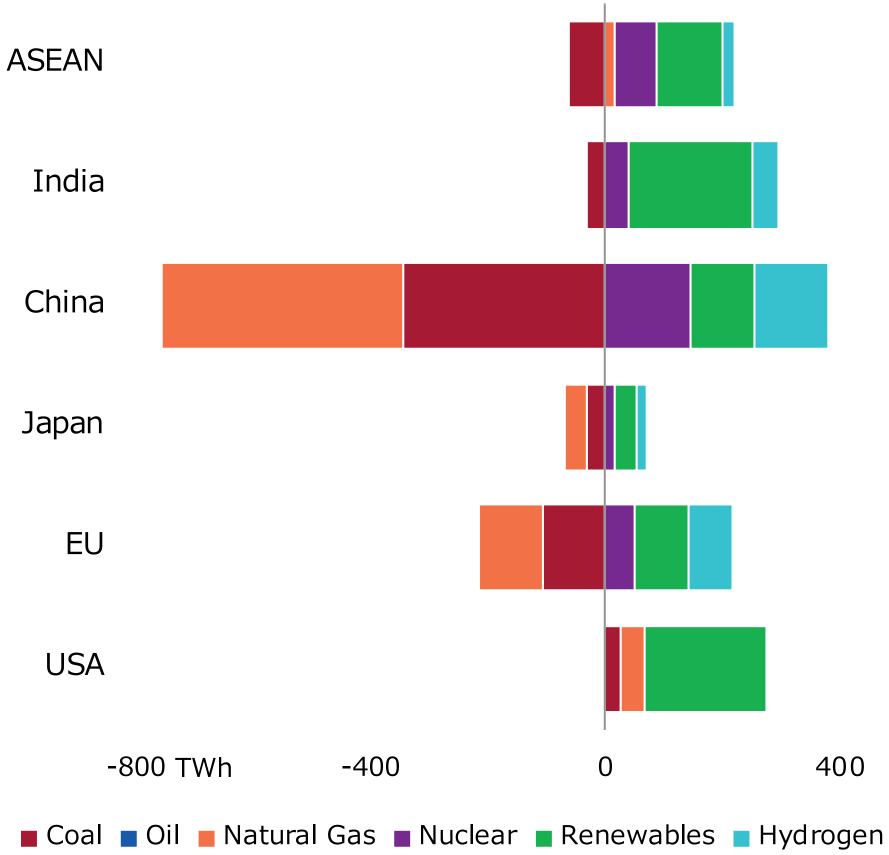
In the PCS, digital transformation (DX) supports remote economic activities and further promotes electrification. The issue is the balance between privacy protection and information management by governments. There are two patterns, “centralized” and “distributed”, and there are various differences.

Power generation shifts to non-fossil power sources, including hydrogen

❖ Power Generation Mix



❖ Generation Change (2050, vs. Reference)

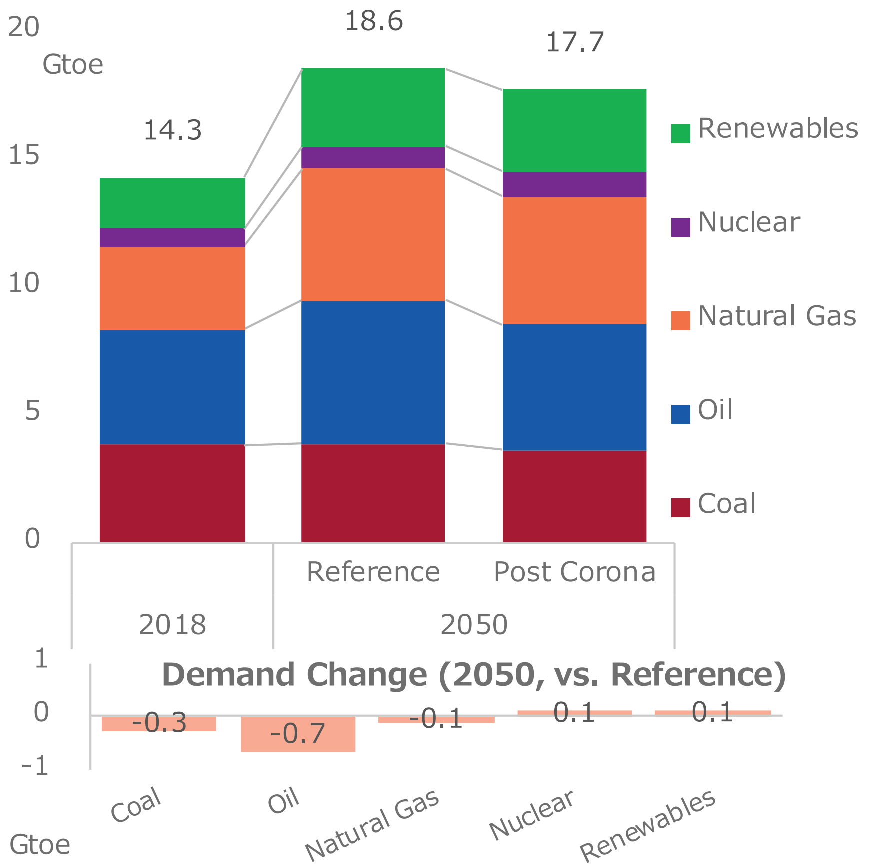


In the RS, gas-fired power and renewable energy support the rapidly increasing electricity demand. Coal-fired power is still needed in developing countries.

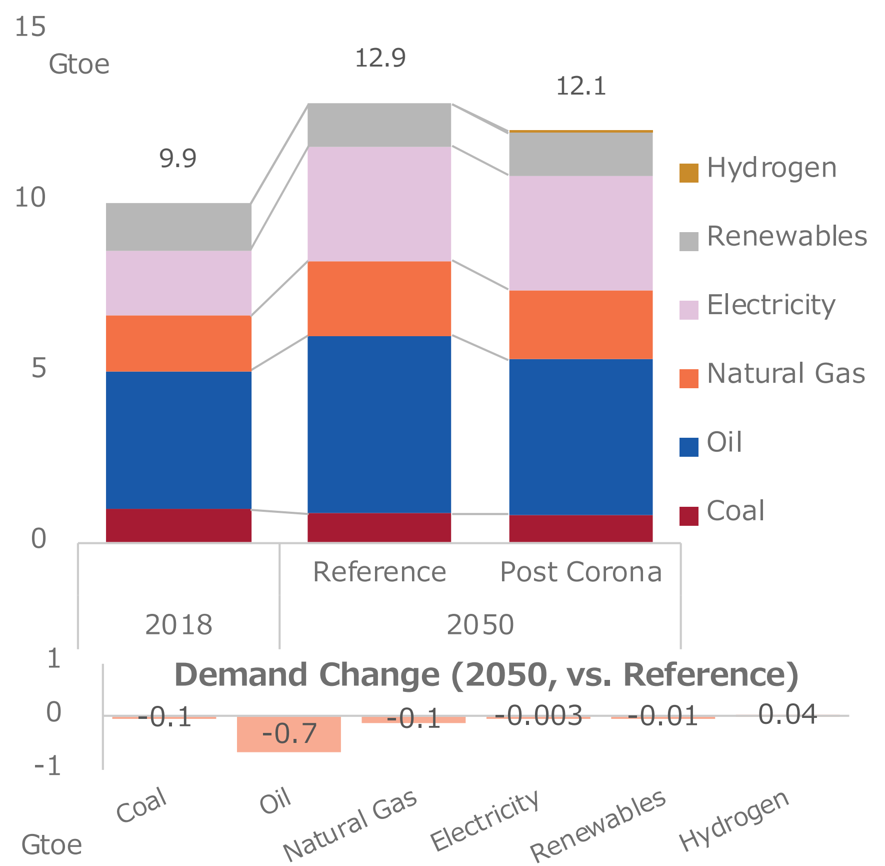
In the PCS, the shift to nuclear and renewable energy sources progresses, while the use of natural gas, which is highly dependent on imports, is curtailed. As competition for the development of innovative technologies progresses, hydrogen begins to be used for power generation. For more on hydrogen introduction, see “Circular Carbon Economy / 4R Scenario”.

Shift to non-fossil fuels but world still depends on fossil fuel

❖ Primary Energy Demand



❖ Final Energy Demand

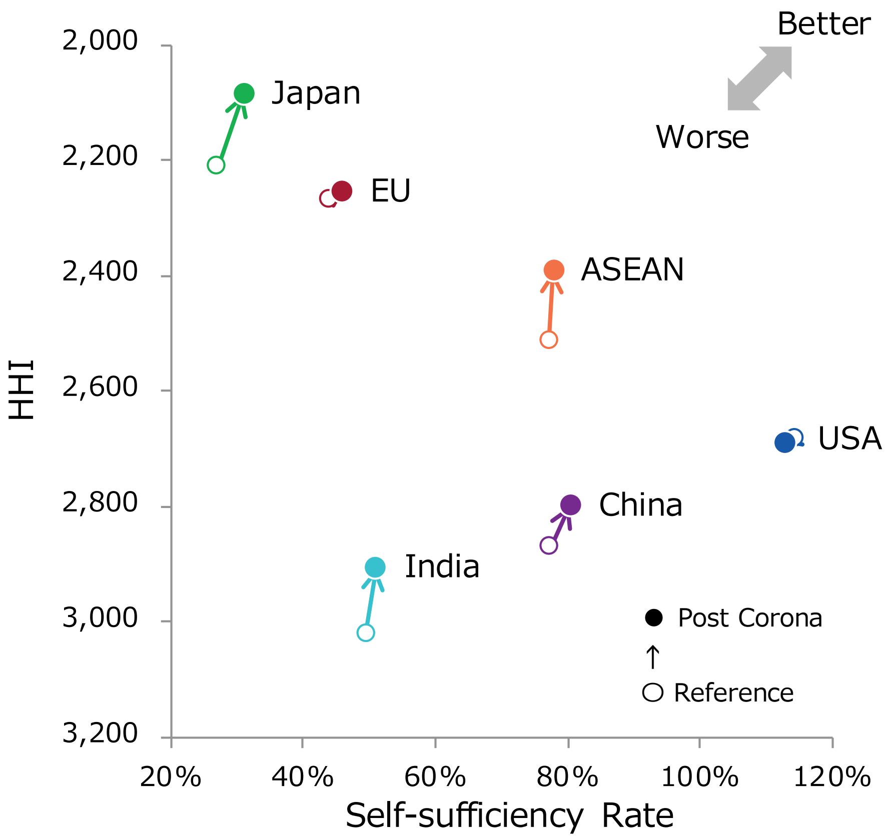


In the RS, primary energy reliance on fossil fuels drops slightly from 81% to 79%.

In the PCS, a shift to (semi-) domestic energy, such as nuclear power and renewable energy, occurs. Due to the stagnation in the transportation sector, oil demand decreases significantly and fossil fuel dependency declines slightly to 77%.

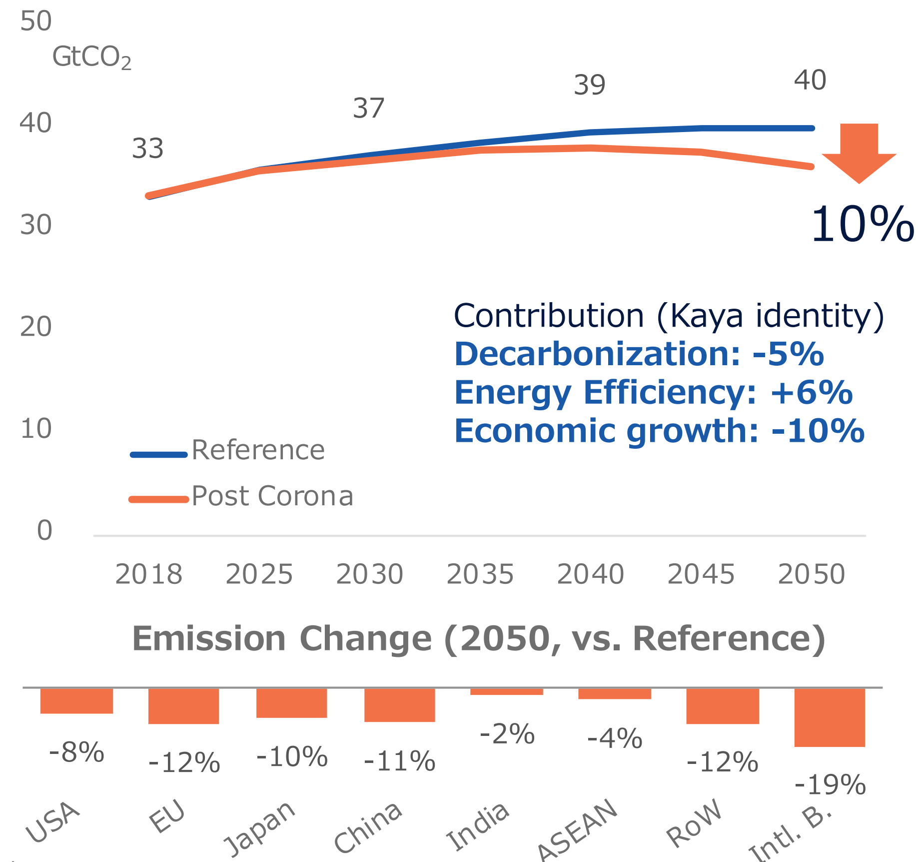
Self-sufficiency / diversity improves and CO_2 peaks earlier

Energy Self-sufficiency/Diversity (2050)



HHI (Herfindahl-Hirschman Index): An indicator of concentration. The higher the number, the higher the concentration, and the lower the number, the more diversified.

Energy-related CO_2 Emissions



In the RS, the energy self-sufficiency rate of ASEAN and India dropped significantly and CO_2 emissions peak in the late 2040s.

In the PCS, the self-sufficiency / diversity improve in importing countries. The peak of CO_2 emissions is accelerated by 10 years due to economic slowdown and decarbonization.

Summary

Reference

- Energy demand increases, especially in Asia, and the fossil fuel dependency remains unchanged even in 2050. Improving living standards in developing countries drives oil and electricity demand.
- CO_2 emissions peak in the late 2040s due to progress in energy saving and low carbonization of power supply.

Post Corona

- The global economy and energy demand are slowing down, due to divergent systems to pursue economic efficiency. The pattern of increase in energy demand by region also changes.
- An earlier peak in oil demand squeezes the oil-producing economies, making economic diversification more important. Meanwhile, appropriate upstream investment is essential because demand is maintained at a certain level.
- Efforts to strengthen energy security and decarbonize induces competition for the development of innovative technologies and promotes non-fossil energy and CO_2-free hydrogen.
- It is important to be aware of the possibility of a world in transformation and to formulate energy policies based on strategic thinking to respond to those changes.

Advanced Technologies Scenario (ATS)

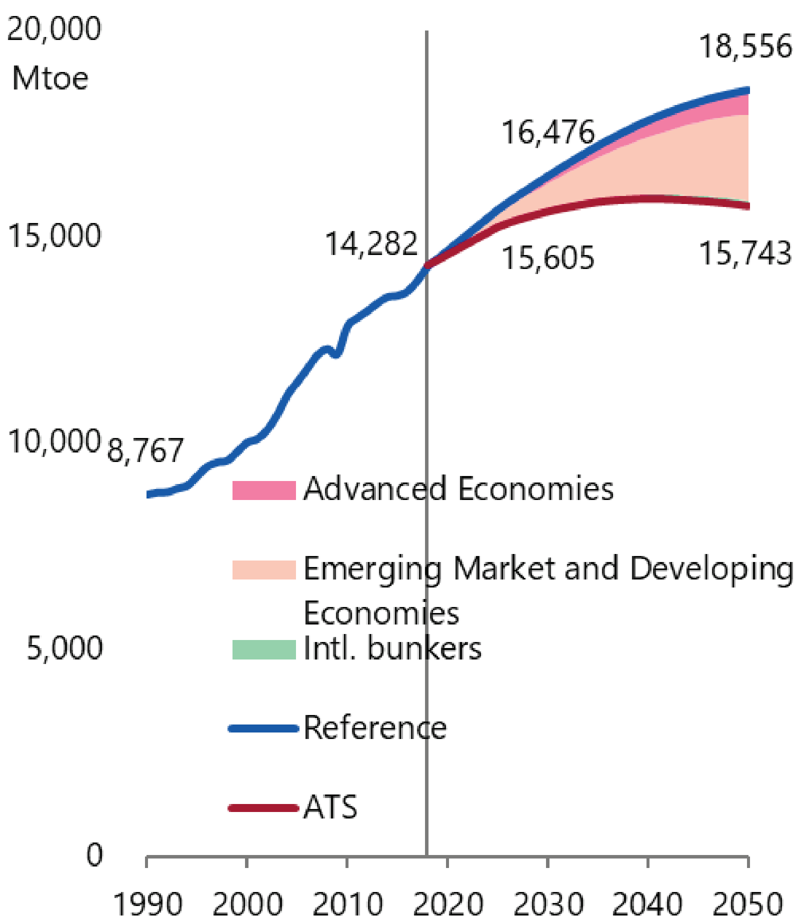
Base scenarios of IEEJ Outlook

	Reference Scenario	Advanced Technologies Scenario
	Reflects past trends with technology progress and current energy policies, without any aggressive policies for low-carbon measures.	**Assumes introduction of powerful policies** to address energy security and climate change issues with the utmost penetration of low-carbon technologies.
Social-economy structure	Stable growth led by developing economies despite slower population growth. Rapid diffusion of energy consuming appliances and vehicles due to higher income.	
International energy price	**Oil** supply cost increases along with demand growth. **Gas** price convergences among Europe, N. America and Asia markets. **Coal** keeps unchanged with today's level.	Slower price increase due to lower demand growth (coal price decreases).
	[LNG in Asia] Higher/lower price cases	
Energy policies	Gradual reinforcement of low-carbon policies with past pace.	Further reinforcement of domestic policies along with international collaboration.
Energy technologies	Improving efficiency and declining cost of existing technology with past pace.	Further declining cost of existing and promising technology.

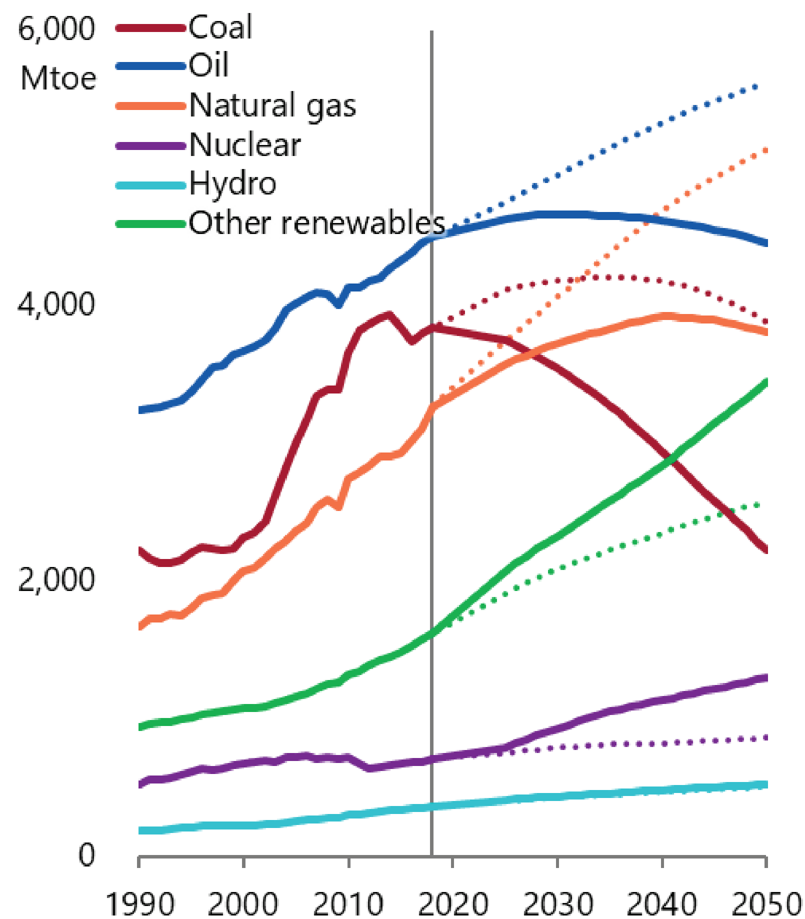
ATS

Total Primary Energy demand (World)

By Region



By Source

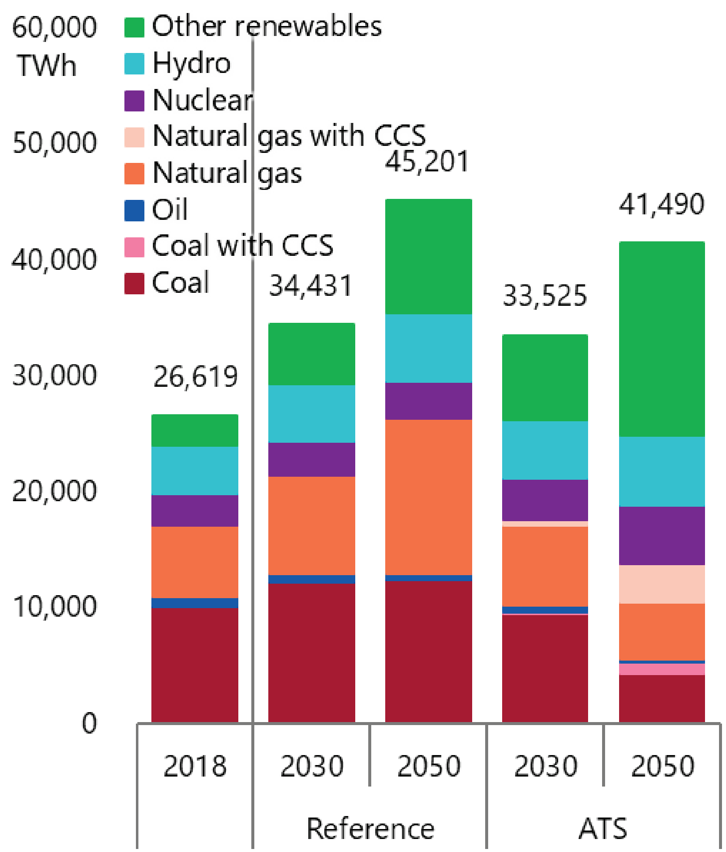


The world's energy demand in ATS is lower by 15% compared to Reference largely because of the energy saving by emerging countries.

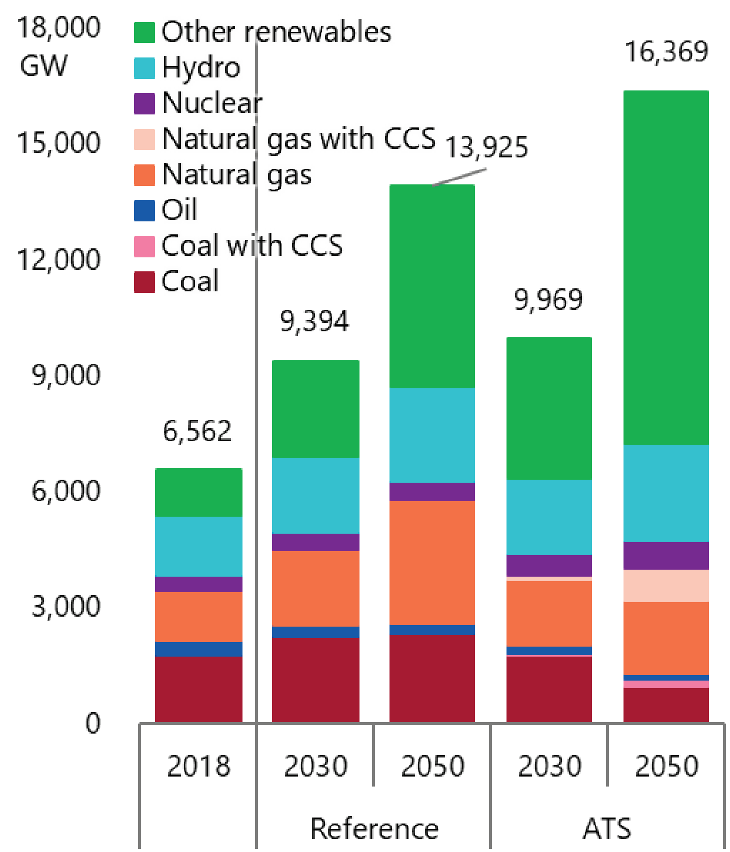
The world will remain dependent on fossil fuels for 67% of the total demand as of 2050.

Electricity generation

Electricity generation



Generation capacity

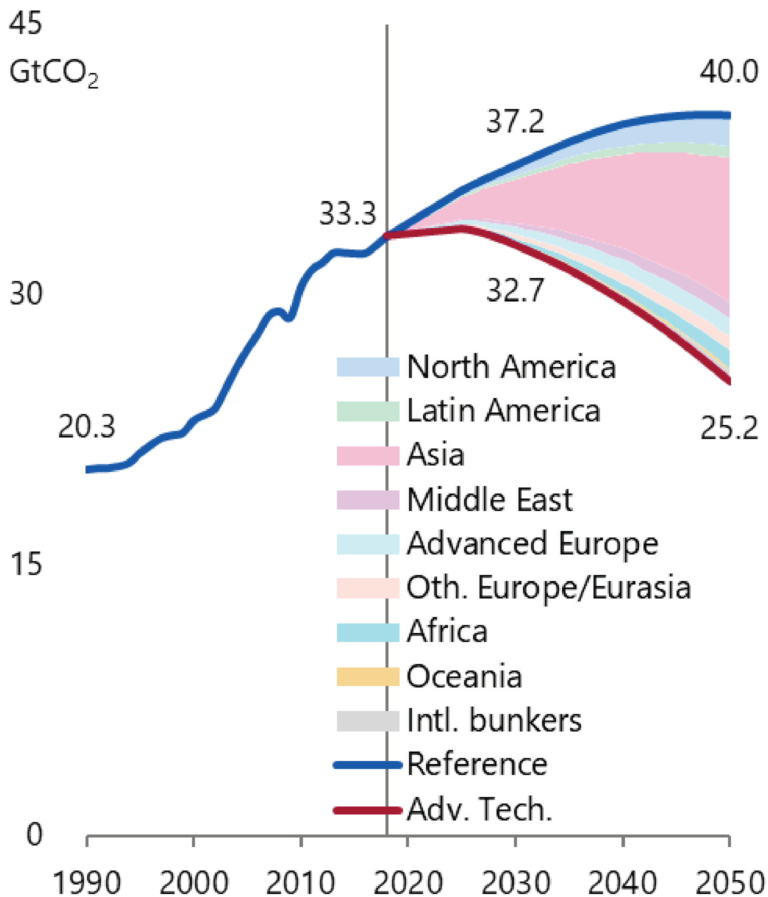


The total electricity generation will decline in ATS. Electricity demand of the transportation sector will grow in ATS, but the decline of the demand of the industrial, residential, and commercial sectors more than offset the growth.

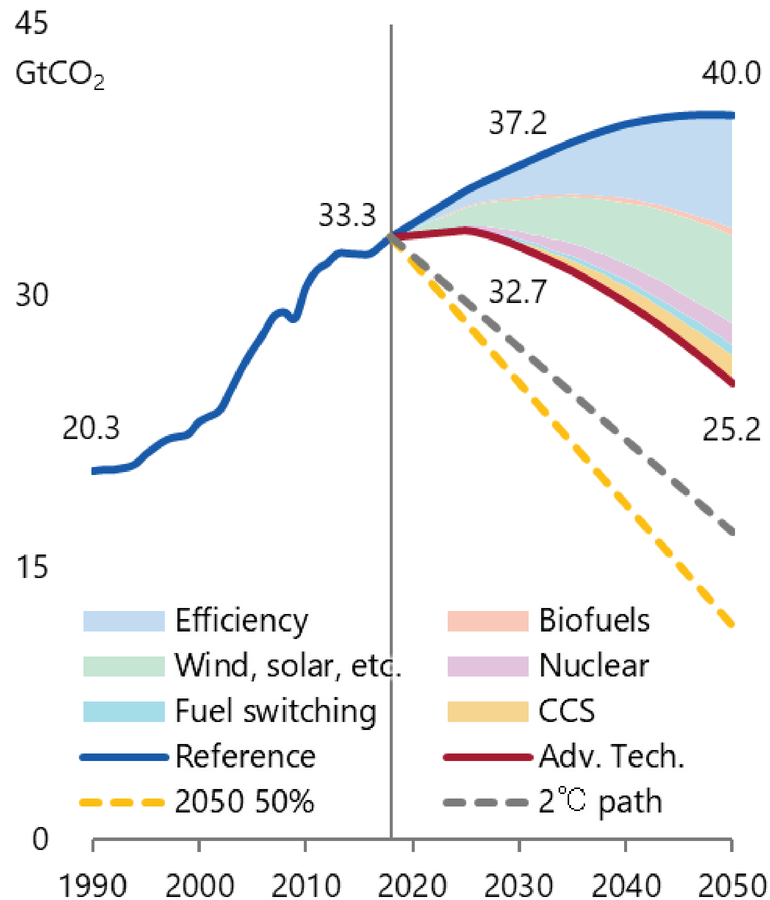
The share of other renewable (solar, wind, etc.) will grow to the largest electricity generation source while the share of coal will decline.

CO_2 Emissions

By country / region



By technology



The world CO_2 emissions in ATS are estimated to peak in around 2025.

The emissions of ATS asof 2050 will be lower by37% compared to Reference. Decarbonization of energy mix is a primary reason of the emissions reduction.

Circular Carbon Economy / 4R Scenario (CCE)

Significance of this scenario

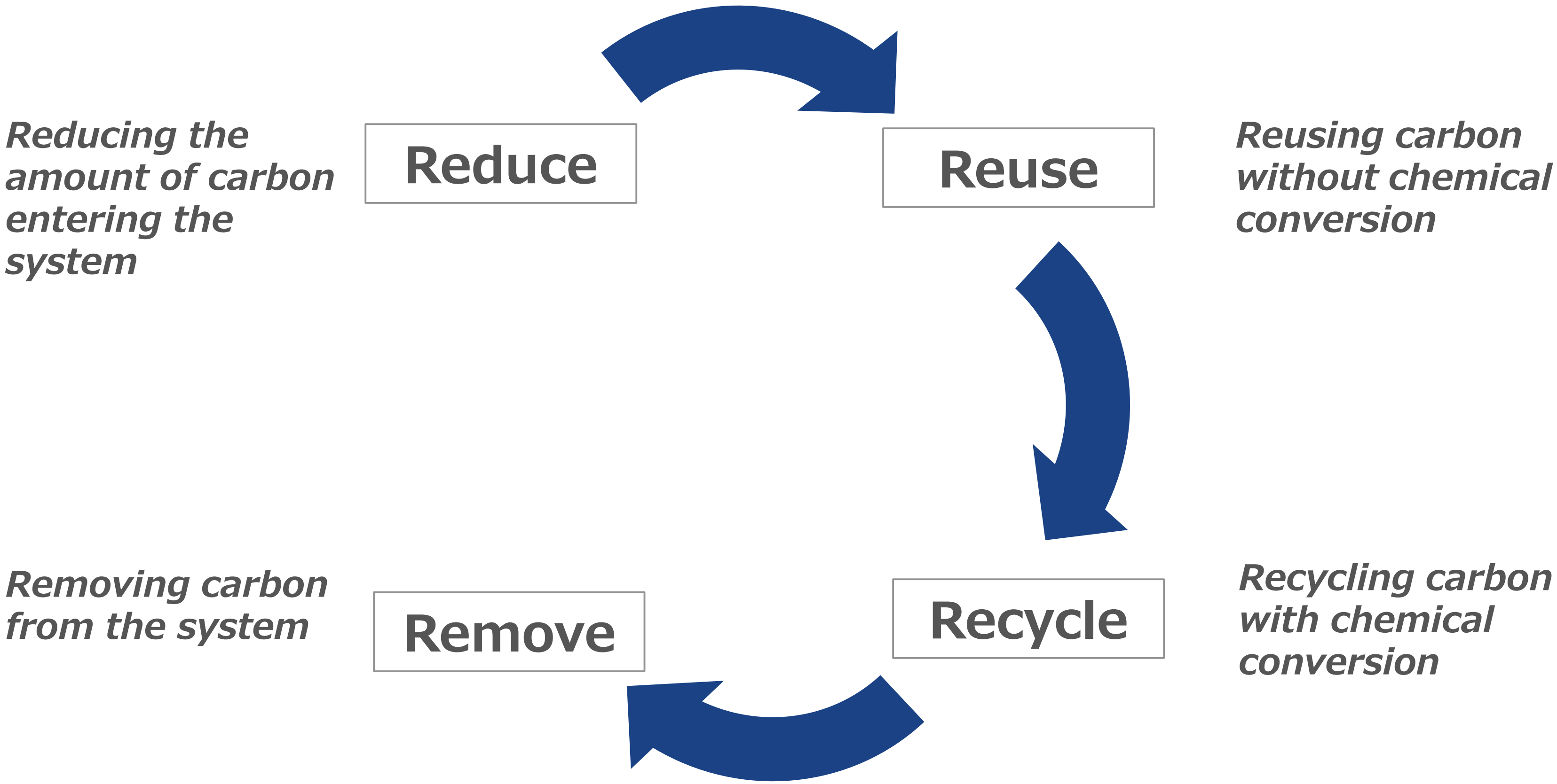
- In order to achieve an ambitious emissions reduction target, a holistic approach to utilize all available emissions reduction technologies at the utmost is necessary.

- In pursuing the emissions reduction, not only technologies of zero-carbon energy sources such as renewable and nuclear but also technologies of carbon-neutral (or decarbonized) use of fossil fuels have to be deployed.

- Global interests on the concept of Circular Carbon Economy (CCE) are growing as the concept will be a major agenda of G20 Summit 2020 hosted by Saudi Arabia.

- Circular Carbon Economy / 4R Scenario (CCE scenario, hereafter) provides a future scenario where technologies of carbon-neutral use of fossil fuels are assumed to be utilized at the utmost to show how the CO_2 emissions, energy mix, and the power generation will evolve.

Circular Carbon Economy: CCE



Circular Carbon Economy (CCE) is a holistic approach to manage carbon emissions as a closed circular system.

CCE aims to utilize all available emissions reduction technologies by the "4R" steps (Reduce, Reuse, Recycle, and Remove).

4R technologies to manage carbon

Major 4R technologies

Reduce	Reuse	Recycle	Remove
Reducing the amount of carbon entering the system	Reusing carbon without chemical conversion	Recycling carbon with chemical conversion	Removing carbon from the system
• Energy and materials efficiency • Renewable energy, including hybrid use with fossil fuel • Nuclear energy, including hybrid use with fossil fuel • Advanced ultra-super-critical technologies for coal power plants • Hydrogen (blue/green) fuel cells for long-distance heavy-duty vehicles • Ammonia produced from zero-carbon hydrogen (blue/green) for power generation and ships • Direct reduction in steel making by using CO_2 free hydrogen (blue/green)	• Carbon capture and utilization (CCU) • Use CO_2 at carbon utilization facilities, such as at greenhouses for enhancing crops • Bio-jet fuels with reed beds • Algal synthesis	• CCU • Artificial photosynthesis • Bioenergy recycle in the pulp and paper industry • Bioenergy with carbon capture and storage • Carbamide (urea production using CO_2 as feedstock) • Coal ash concrete curing with absorbing CO_2 • Electrochemical reduction of CO_2 • Fine chemicals with innovative manufacturing processes and carbon recycling • Fischer-Tropsch exothermic of carbon dioxide with hydrogen syngas • Hydrogenation to formic acid • Oil sludge pyrolysis • Sabatier synthesis (CO_2 methanation: exothermic of carbon dioxide with blue/green hydrogen) • Thermal pyrolysis	• CCS • Direct air capture (DAC) • Carbon dioxide removal • Fossil fuels-based blue hydrogen

Source : Mansouri, N. Y. *et al.*(2020) “A Carbon Management System of Innovation: Towards a Circular Carbon Economy”

The “4R” in CCE covers all available technology options to reduce CO_2 in a systematic manner.

The concept of 4R highlights the importance of Reuse and Recycle technologies that regard carbon as a resource.

Assumptions of CCE Scenario

❖ Assumed adoptions of 4R technologies in CCE scenario

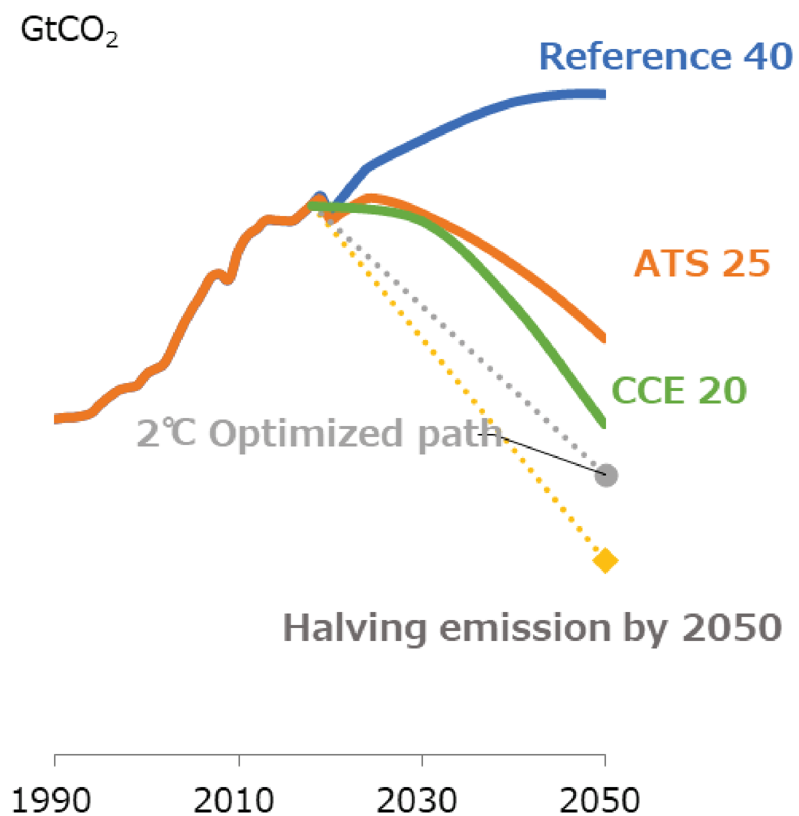
4R	Technology	Assumption
Reduce	Blue hydrogen* for power generation	Adopt blue hydrogen power generation (including ammonia produced from blue hydrogen) for 50% of coal-fired power plants without CCS facility as of 2050 in Advanced Technologies Scenario (ATS)
	Blue hydrogen for transportation	Adopt blue hydrogen (mainly as fuel cell vehicle) to 20% of road transportation demand as of 2050
	Direct reduction in steel making by blue hydrogen	Adopt direct reduction technology utilizing blue hydrogen to 25% of crude steel production in OECD, China, and India as of 2050
	Reduction of cement production	Reduction of cement production by 25% utilizing coal ash and limestone and calcined clay as of 2050
Reuse	Algae synthesis to produce biofuel	Increase algae-based bio-diesel by 50% from ATS
Recycle	Concrete curing capturing CO_2	Adopt concrete curing capturing CO_2 technology to 50% of the world concrete production as of 2050
	Synthetic methane	Replace natural gas with synthetic methane (produced from blue hydrogen and green hydrogen**) for 50% of gas-fired power plants without CCS facility as of 2050 in ATS
Remove	Carbon capture and storage	CCS for blue hydrogen production

*Blue hydrogen : Hydrogen produced from fossil fuels with CCS
**Green hydrogen : Hydrogen produced by electrolysis utilizing electricity from renewable power generation

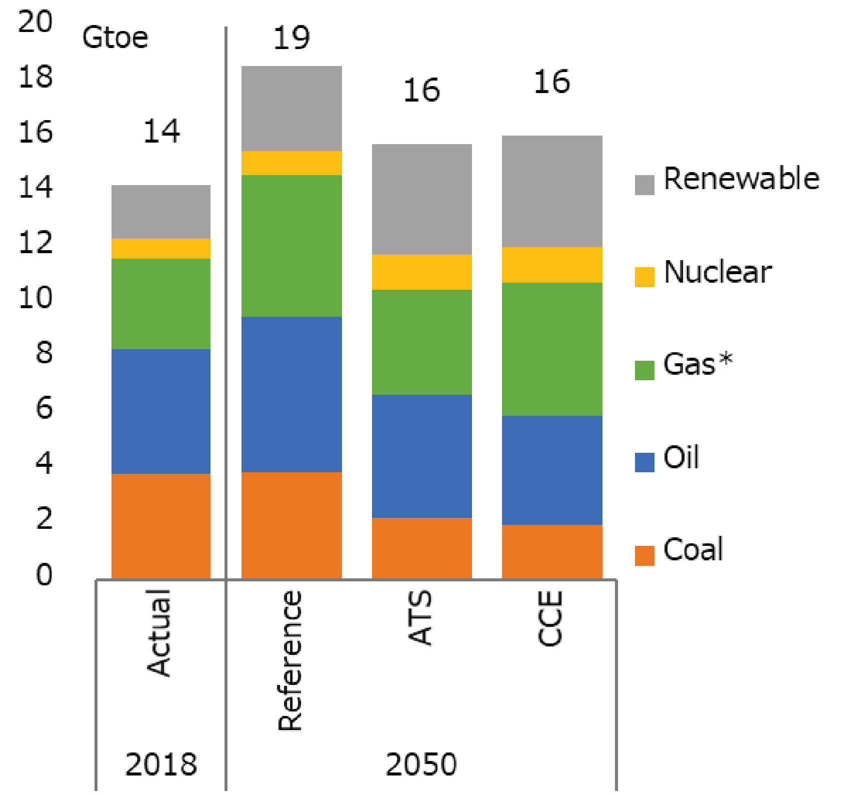
CCE scenario assumes the utmost adoptions of 4R technologies for carbon-neutral use of fossil fuels with all other assumptions based on the Advanced Technologies Scenario.

Emissions reduced while using fossil fuels

World CO_2 Emissions



Total Primary Energy Demand of the World



*Gas in CCE scenario includes synthetic methane

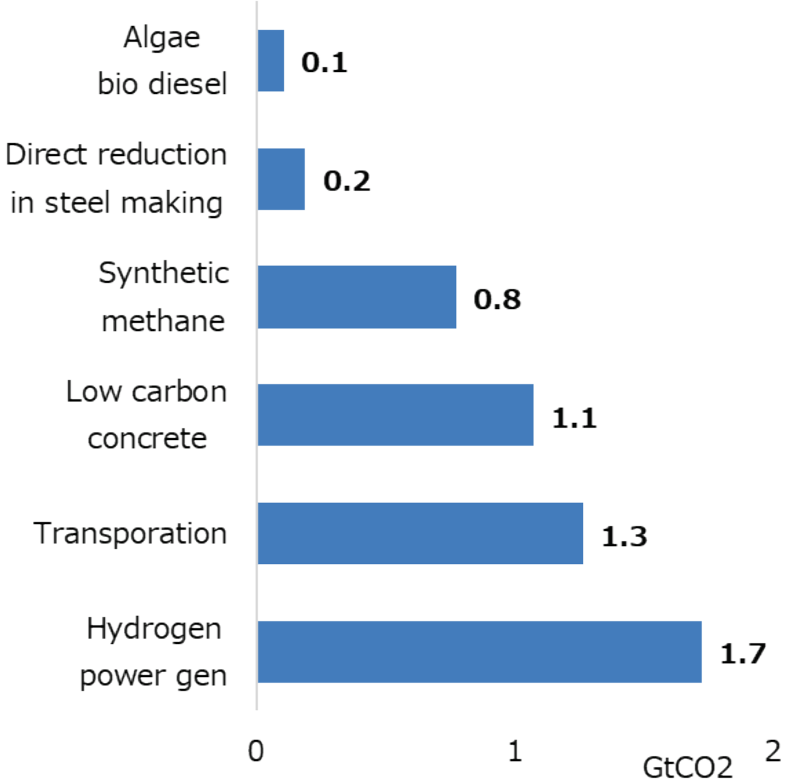
CO_2 emissions are reduced by 5Gt from ATS and approaches 2℃ optimized path.

While the share of fossil fuels of CCE scenario is almost same as ATS', the mix of fossil fuel shifts from coal and oil to natural gas as a primary feedstock of blue hydrogen.

CO_2 emissions significantly reduced while the consumption of fossil fuel unchanged.

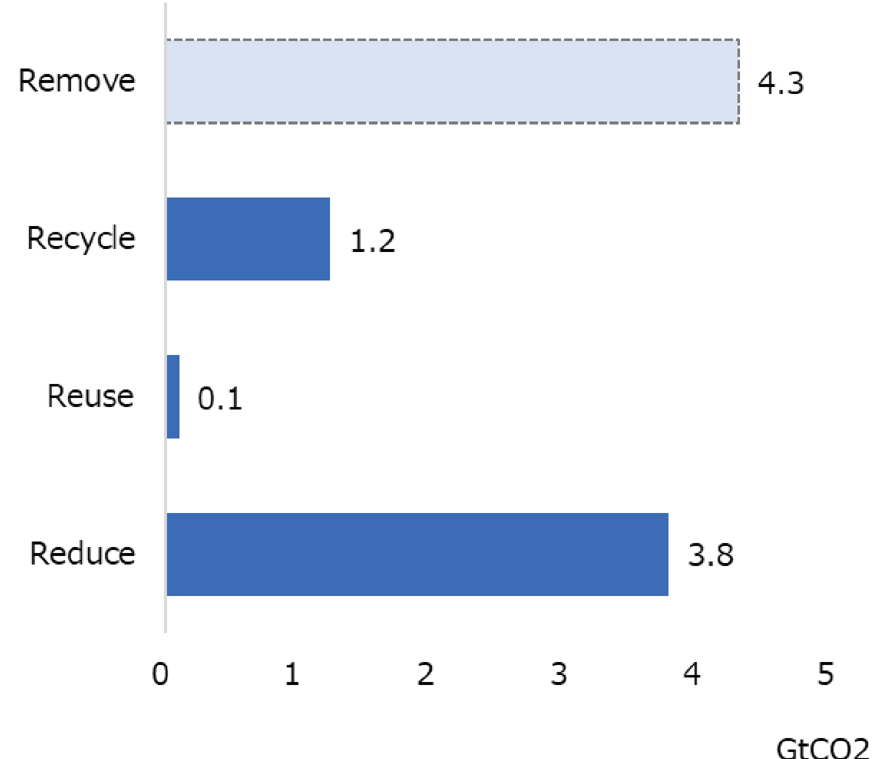
Power and transport have large reduction potential.

❖ CO_2 emissions reduction by technology



* The amount of Low carbon concrete is the sum of reduced volume of cement production reduction and concrete curing absorbing CO_2.

❖ CO_2 emissions reduction by 4R



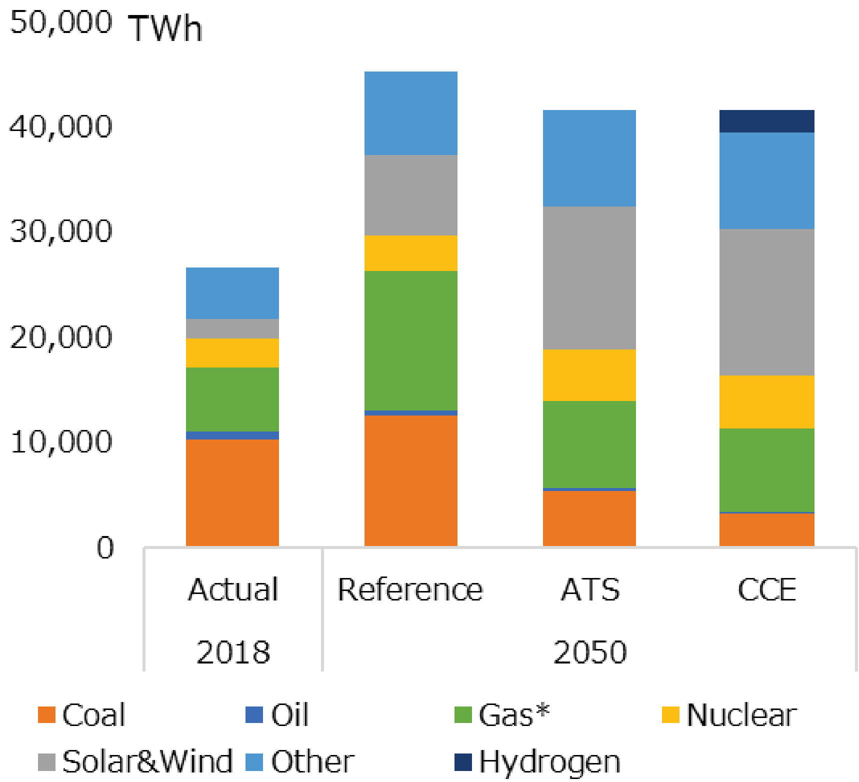
Reduce: Hydrogen power generation, hydrogen for transportation, cement production reduction, direct reduction of steel making
Reuse : Algae biodiesel
Recycle : CO_2 absorbing concrete, synthetic methane
Remove: CCS（also counted in Reduce and Recycle technologies)

Power and Transportation sectors have high potential of emissions reduction in CCE scenario. Blue hydrogen plays a significant role in both sectors.

Reduce technologies contributes the reduction most while the Reuse and Recycle's contributions are relatively small.

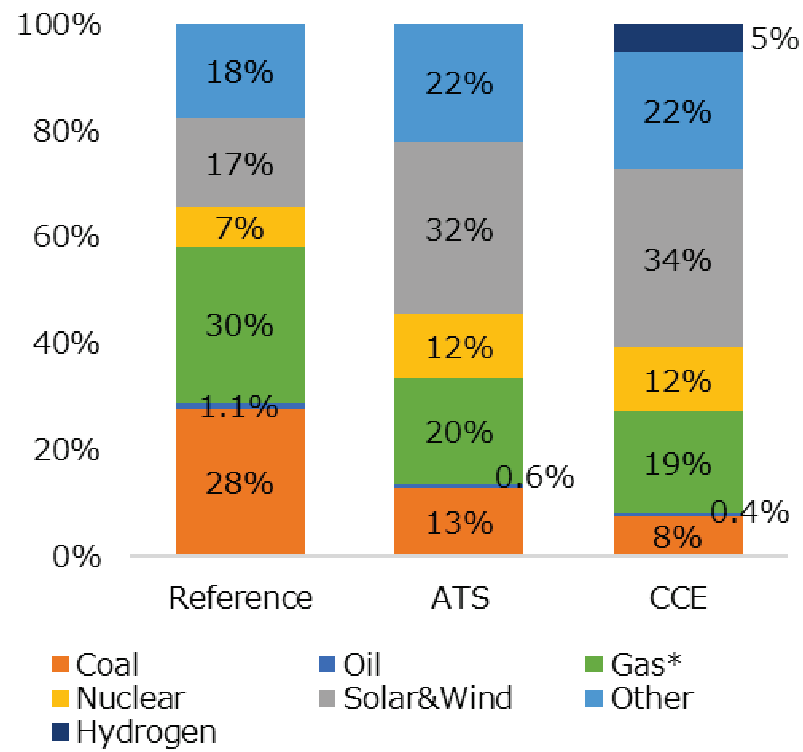
Coal power will be partially replaced with H_2.

❖ Electricity generation (World)



*CCE scenario includes synthetic methane.

❖ Power generation mix (World as of 2050)



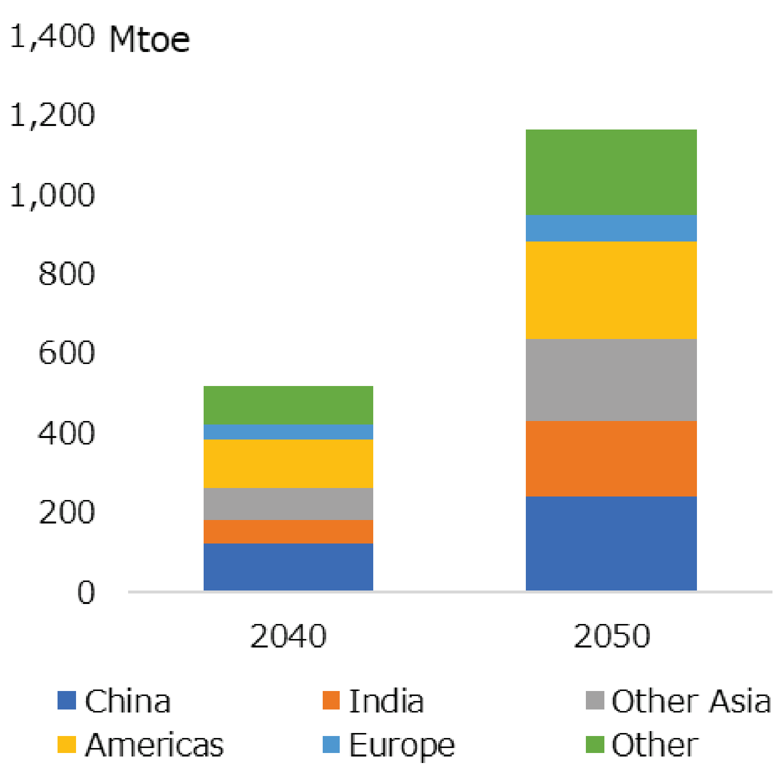
*CCE scenario includes synthetic methane.

Share of fossil fuels will decline from 34% to 27% in CCE scenario.
Share of hydrogen power will be 5% as of 2050.

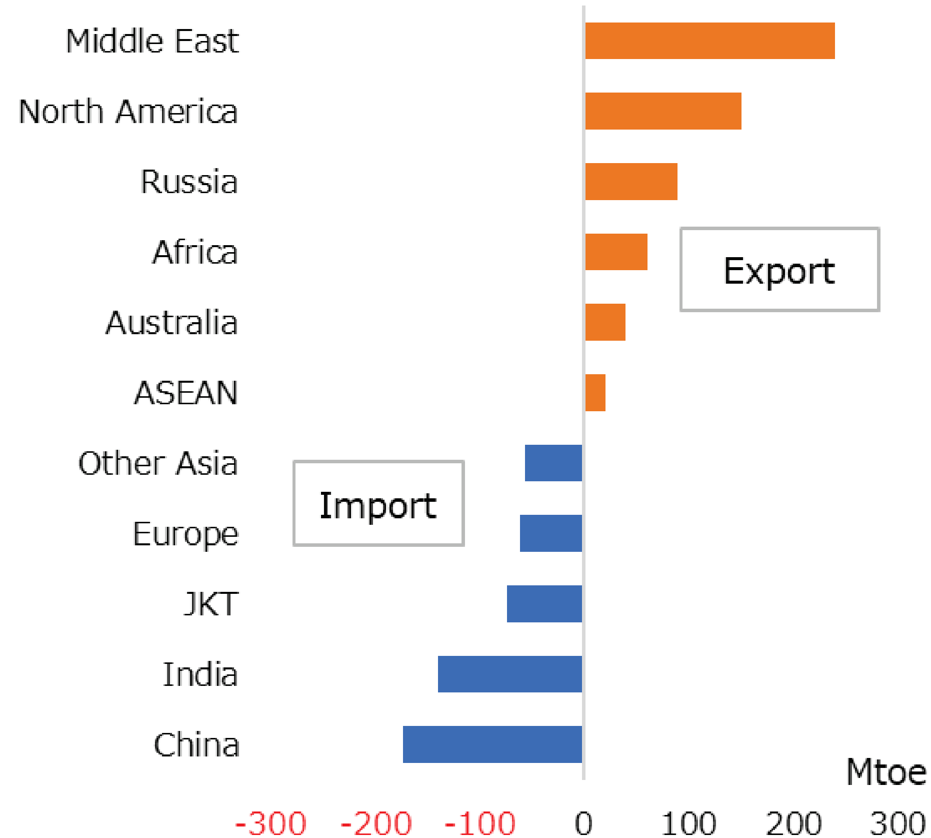
CCE

Hydrogen demand will grow in Asia.

World hydrogen demand



Hydrogen balance (2050)

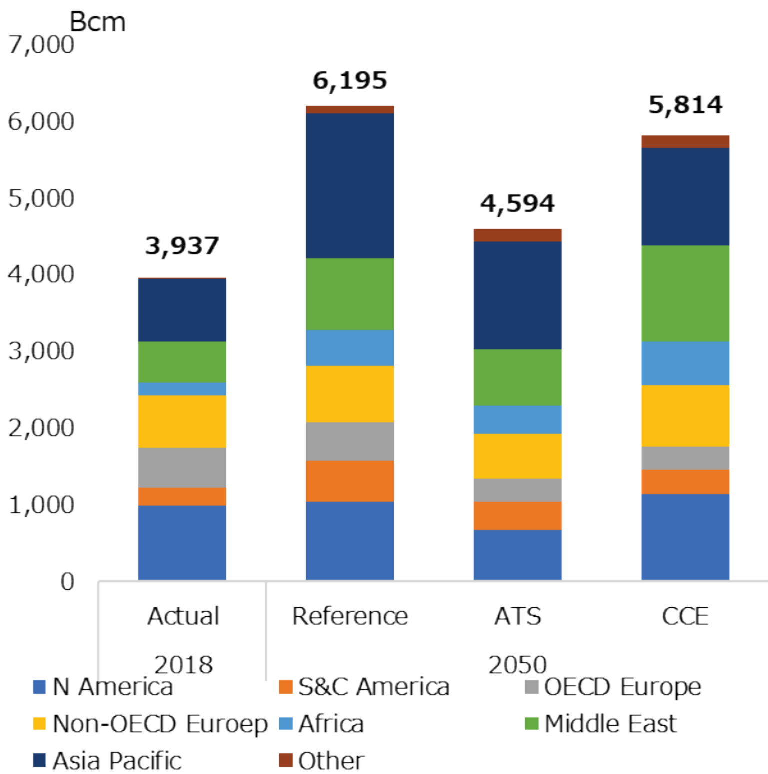


World hydrogen demand is expected to grow mainly in Asia in CCE scenario.

Countries without blue hydrogen production capability will need to import blue hydrogen from countries with low cost and abundant fossil fuel resources with CCS capability.

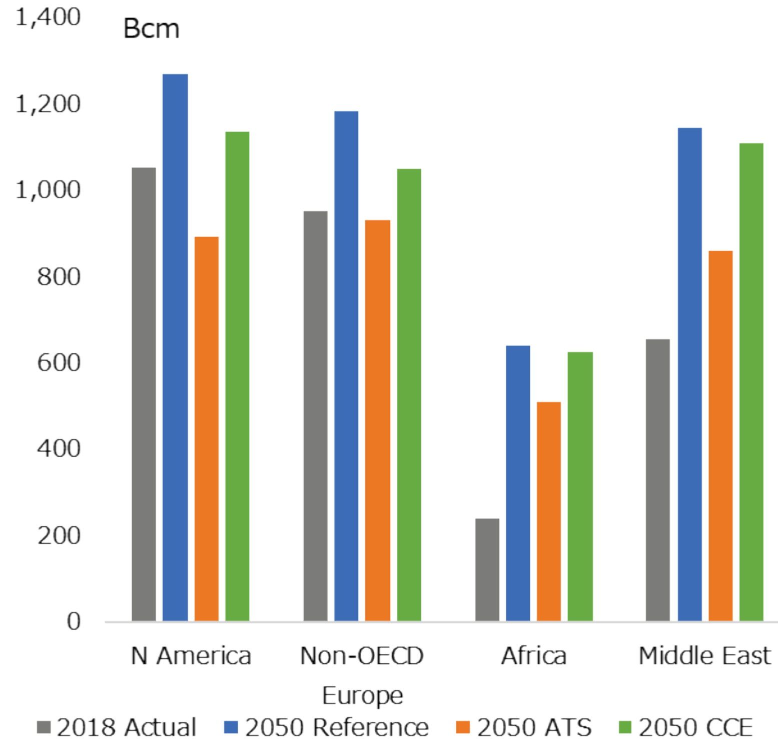
New natural gas demand will emerge.

❖ Natural gad demand* (World)



*Includes synthetic methane

❖ Natural gas production (as of 2050)



Natural gas demand will grow by 27% in CCE scenario as of 2050 because of the additional feedstock demand for blue hydrogen.*

Major gas producing countries are required to increase their production although the volume of production will not exceed the reference scenario.

***This scenario assumes a major feedstock of blue hydrogen will be natural gas.**

Implications

- Significant emissions reduction of CO_2 and the use of fossil fuels can be pursued simultaneously by utilizing 4R technologies for carbon-neutral use of fossil fuels.

- Blue hydrogen will play a key role. Reduction of its production cost and infrastructure developments will be necessary.

- Among 4R technologies, technologies of Reuse and Recycle need to be further developed. Policy and financial support for R&D as well as international collaboration are important.

- Significance and implications of the concept of Circular Carbon Economy need to be more publicized.

Climate change scenario analysis

— Towards a more robust estimation of costs and benefits —

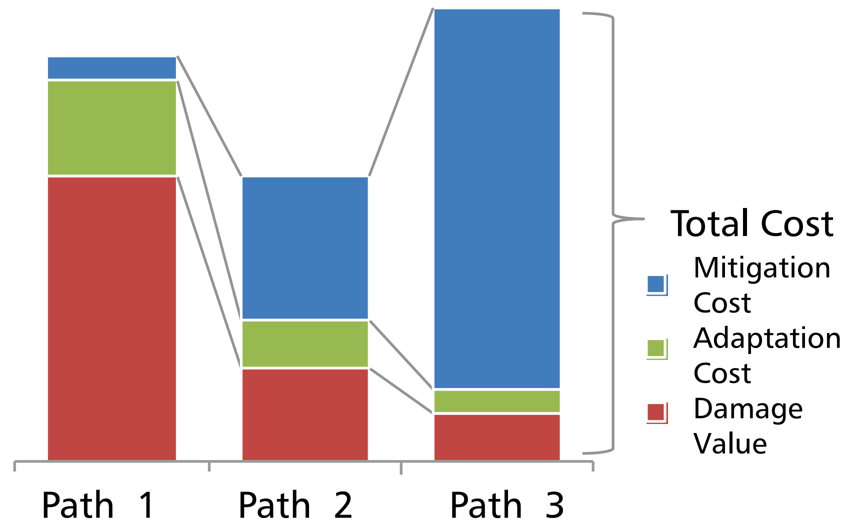
Cost-benefit analysis of climate change

Note: Exactly, the optimal path is calculated not by minimizing the cost, but by maximizing the utility.

❖ Mitigation+Adaptation+Damage=Total Cost

Mitigation	•Typical measures are GHG emissions reduction via energy efficiency and non-fossil energy use. • Includes reduction of GHG release to the atmosphere via CCS • These measures **mitigate** climate change.
Adaptation	•Temperature rise may cause sea-level rise, agricultural crop drought, disease pandemic, etc. • **Adaptation** includes counter measures such as building banks/reservoir, agricultural research and disease preventive actions.
Damage	If mitigation and adaptation cannot reduce the climate change effects enough to stop sea-level rise, draught and pandemics, **damage** will take place.

❖ Illustration of the Total Cost



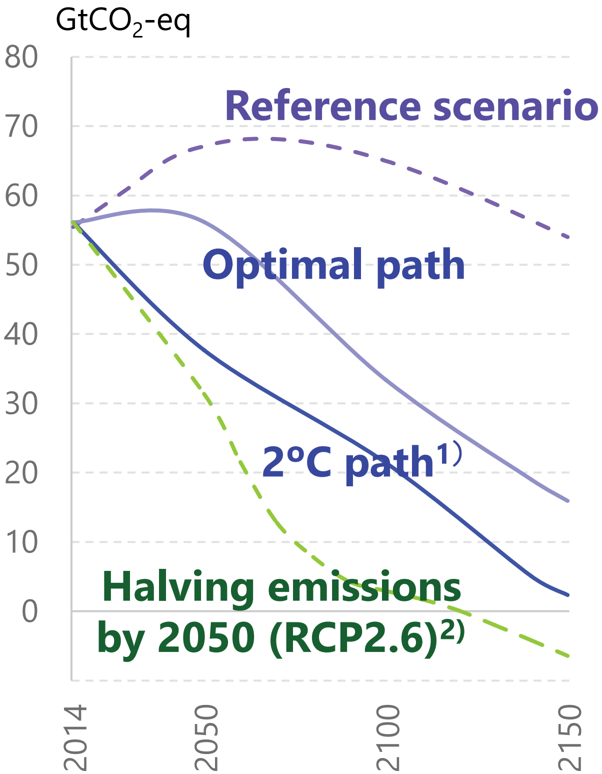
	Path 1	Path 2	Path 3
Mitigation	Too Small	Reasonable	Too Big
Adaptation	Big	Medium	Small
Damage	Big	Medium	Small

Without measures against climate change, the mitigation cost is small, while the adaptation and damage costs become substantial. Aggressive mitigation measures on the other hand, would reduce the adaptation and damage costs but the mitigation costs would be notably colossal.

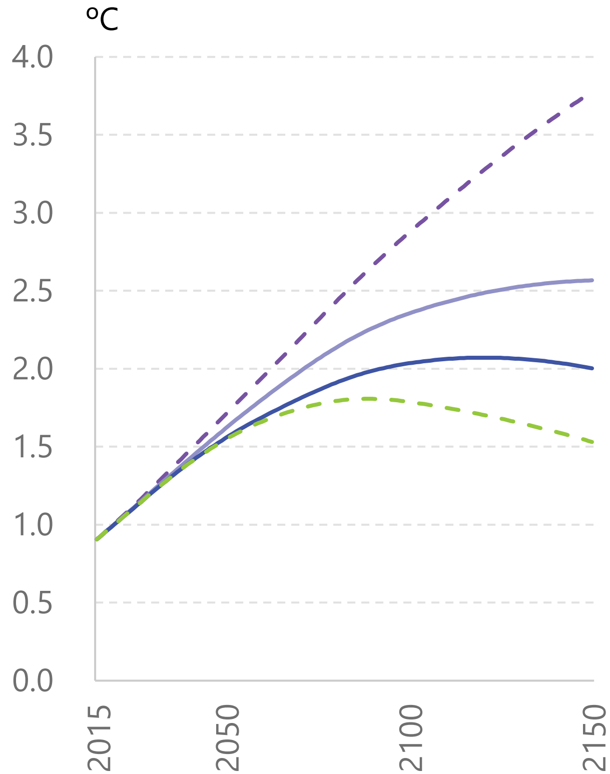
The climate change issue is a long-term challenge influencing vast areas over many generations. As such, and from a sustainability point of view, the combination (or the mix) of different approaches to reduce the total cost of mitigation, adaptation and damage is important.

Optimal and 2°C paths

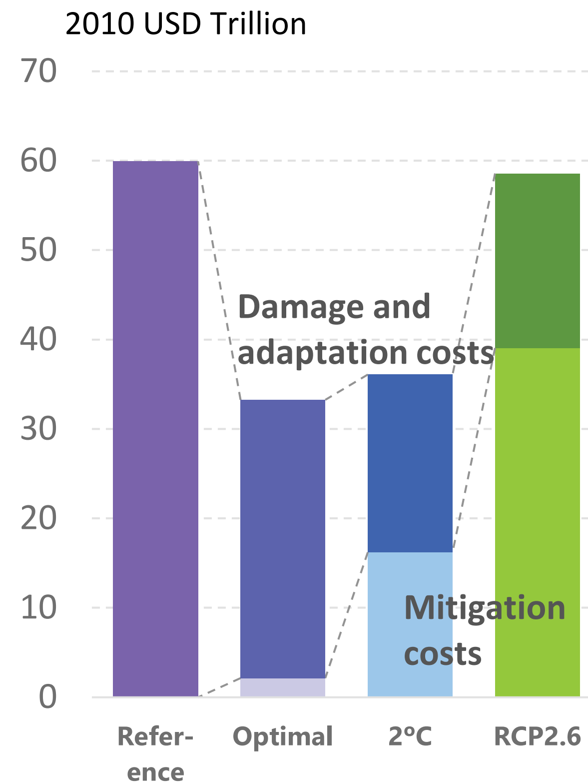
GHG emissions



Temperature rise from preindustrial levels



Total cost (Cumulative up to 2500)



1) A path in which the global mean temperature exceeds 2°C and the returns to 2°C by 21

2) A path roughly equivalent to IPCC's RCP2.6.

- The temperature rise in the optimal path exceeds 2.5°C by 2150, although the results vary strongly depending on the assumptions.
- At the same time, an overshooting path, in which the temperature rise returns to 2.0°C by 2150, may also be achievable without large cost increases.

Challenges for cost-benefit analysis

Accuracy of the damage function

- Estimation of the damages caused by climate change involves great uncertainties. Although research is progressing around the world, sufficient knowledge has not been accumulated.
- It is important to refine the damage function (relationship between temperature rise and damage value) based on the latest scientific knowledge.

Effects of "tipping elements"

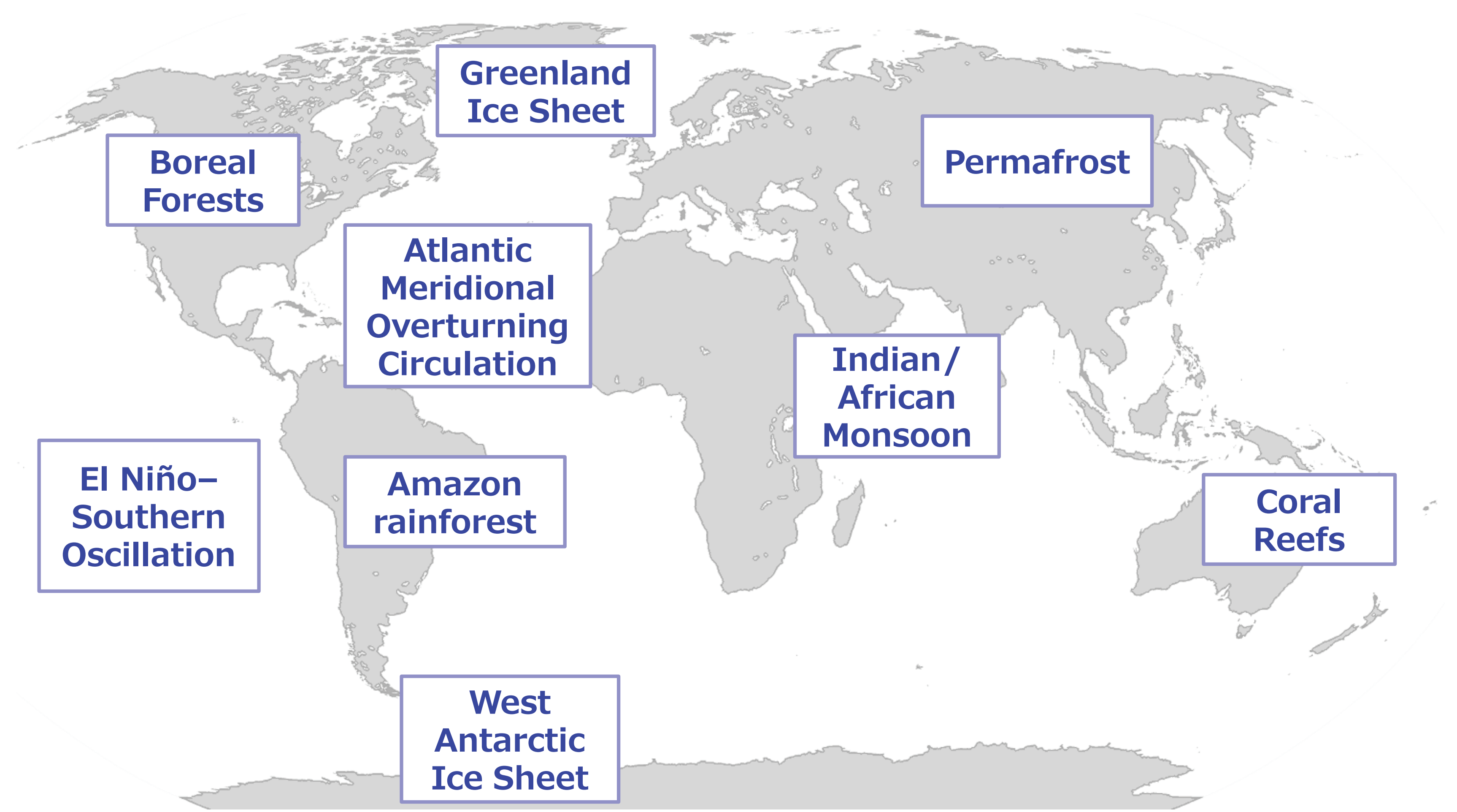
- If the progress of an event exceeds the critical point, negative feedbacks of the Earth system may stop functioning, and the change may be accelerated.
- For example, as Siberian permafrost melting progresses due to global warming, underground methane and CO_2 are released into the atmosphere. The release itself contributes to global warming, further thawing the frozen soil.
- They point out that there is a risk of shifting to a different equilibrium state, for example, "Hothouse Earth" where the temperature is higher by several degrees or more than before as a result.

Other theoretical issues

- Issues related long-term discount rates, "fat tails,"[1)] etc.
- Discussions continue, and no consensus has been found among researchers at present.

1):It has been pointed out that the tail of the probability distribution of the damage by climate change may be thick (i.e. higher probability of occurrence than the normal distribution).

Tipping points of the earth system



- The earth system is supposed to have been in a quasi equilibrium state; when the CO_2 concentration in the atmosphere increases to a certain extent, it is offset by negative feedbacks.
- In recent years, however, scientists have expressed concern that once the change in the Earth System surpasses a certain point, it may become irreversible, and the System may shift to another stable state with higher temperatures. Such critical points are known as "tipping points," and the events that cause the transition over a tipping point are called "tipping elements.

Example of tipping elements

Disintegration of the Greenland ice sheet (GIS)

The Greenland ice sheet has already been melting rapidly because of global warming. Its complete disintegration would raise the Global Mean Sea Level (GMSL) by approximately 7 m. The melting of the ice sheet may exhibit a hysteretic response, which may cause an irreversible transition to a catastrophic state.

Collapse of the West Antarctic ice sheet (WAIS)

Antarctica holds a huge ice sheet that can raise the GMSL by around 60 m. It is divided by the Transantarctic Mountains into two parts: East AIS (EAIS) and West AIS (WAIS). Although the WAIS contains less ice than the EAIS, it is considered to be more vulnerable to global warming, because it is grounded below sea level.

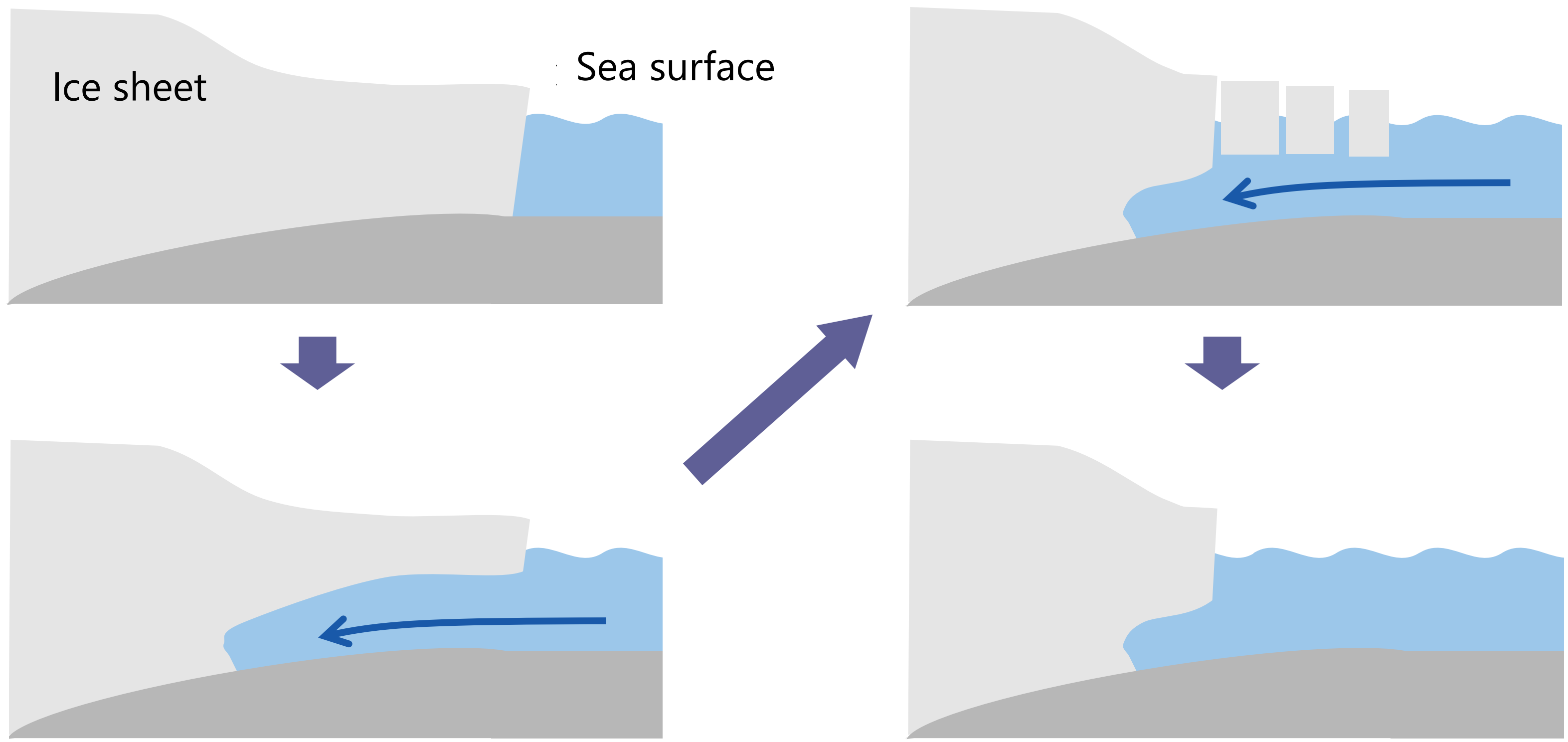
Permafrost carbon feedback (PCF)

Even a small part of the estimated 1.7 trillion tons of carbon contained in arctic permafrost could cause significant global warming, if it is released into the atmosphere. This is a typical example of the possible positive feedbacks of the Earth System, with rising surface temperatures promoting additional release of carbon.

Disappearance of coral reefs (CR)

Coral reefs are home to nearly one-quarter of all marine species, providing fishery and tourism resources to humankind. The economic damage caused by the disappearance of coral reefs was estimated at 0.5% of the global GDP. According to the IPCC, coral reefs will experience severe bleaching at 1.5°C, resulting in extensive damages, with the number reaching almost 100% at 2°C.

Marine Ice-Cliff Instability (MICI)



- In West Antarctica, a large part of ice sheet is grounded below sea level. DeConto and Pollard (2016) pointed out the risk of Marine Ice Cliff Instability (MICI) associated with the WAIS, in which coastal ice cliffs collapse rapidly after the disintegration of ice shelves caused by surface and sub-shelf melting.
- According to Edwards et al. (2019), however, the MICI is not required to reproduce historical GMSL changes due to the Antarctic ice loss. The IPCC's sea level rise projection in the Special Report on the Ocean and Cryosphere in a Changing Climate does not assume MICI, because the validity of MICI currently remains unproven.

Simple representation of tipping elements

Definition of the equilibrium state

$$X^*(t) = X_0 \frac{max(T(t) - T_C)}{T_0} = \alpha\, max(T(t) - T_C)$$

Equation of motion

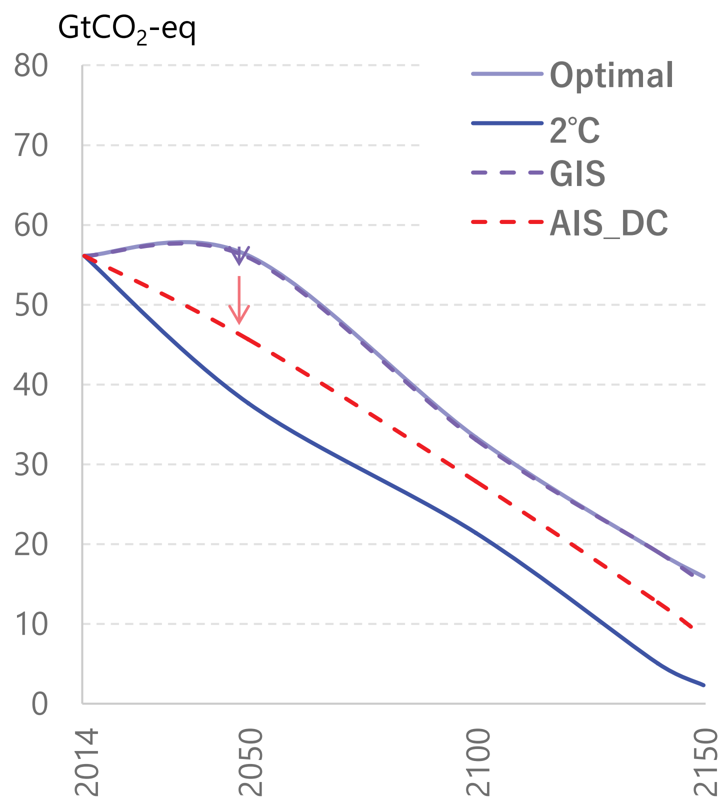
$$\frac{\Delta X(t)}{\Delta t} = \beta\, X_0 sign\big(X^*(t) - X(t)\big) \left|\frac{X^*(t) - X(t)}{X_0}\right|^{\gamma}$$

X : Variable that describes the event (e.g. relative volume of melted ice)
X^* : Equilibrium state of X
T : Global mean surface temperature
T_C : Critical temperature
X_0 : Characteristic scale of the event
T_0 : Characteristic temperature
$\alpha \cdot \beta \cdot \gamma$: Parameters

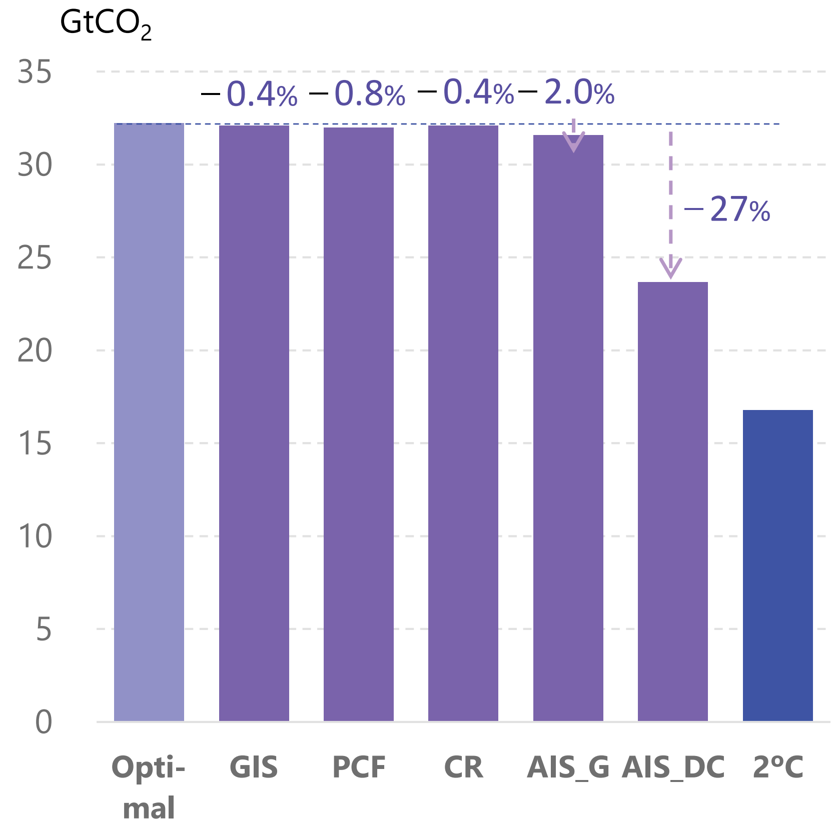
- The motion of tipping elements was modeled according to the simple equations described above. Here, for example, the "equilibrium state" (X^*) of the AIS, or the potential volume of melted ice is supposed to be determined by the temperature rise T, and the actual state X is supposed to move towards the equilibrium state with time delays.
- The parameters for the GIS are determined according to Nordhaus (2019), while those for the AIS are set according to DeConto and Pollard (2016), for a case with MICI, and according to Golledge et al. (2019) for the case without MICI. PCF is modeled according to Yumashev et al. (2019), and coral reefs are assumed to disappear according to the literature (50% at 1.2°C and almost 100% at 2°C), with a time delay of 20 years.

Changes in the optimal path by considering tipping elements

Changes in the optimal path



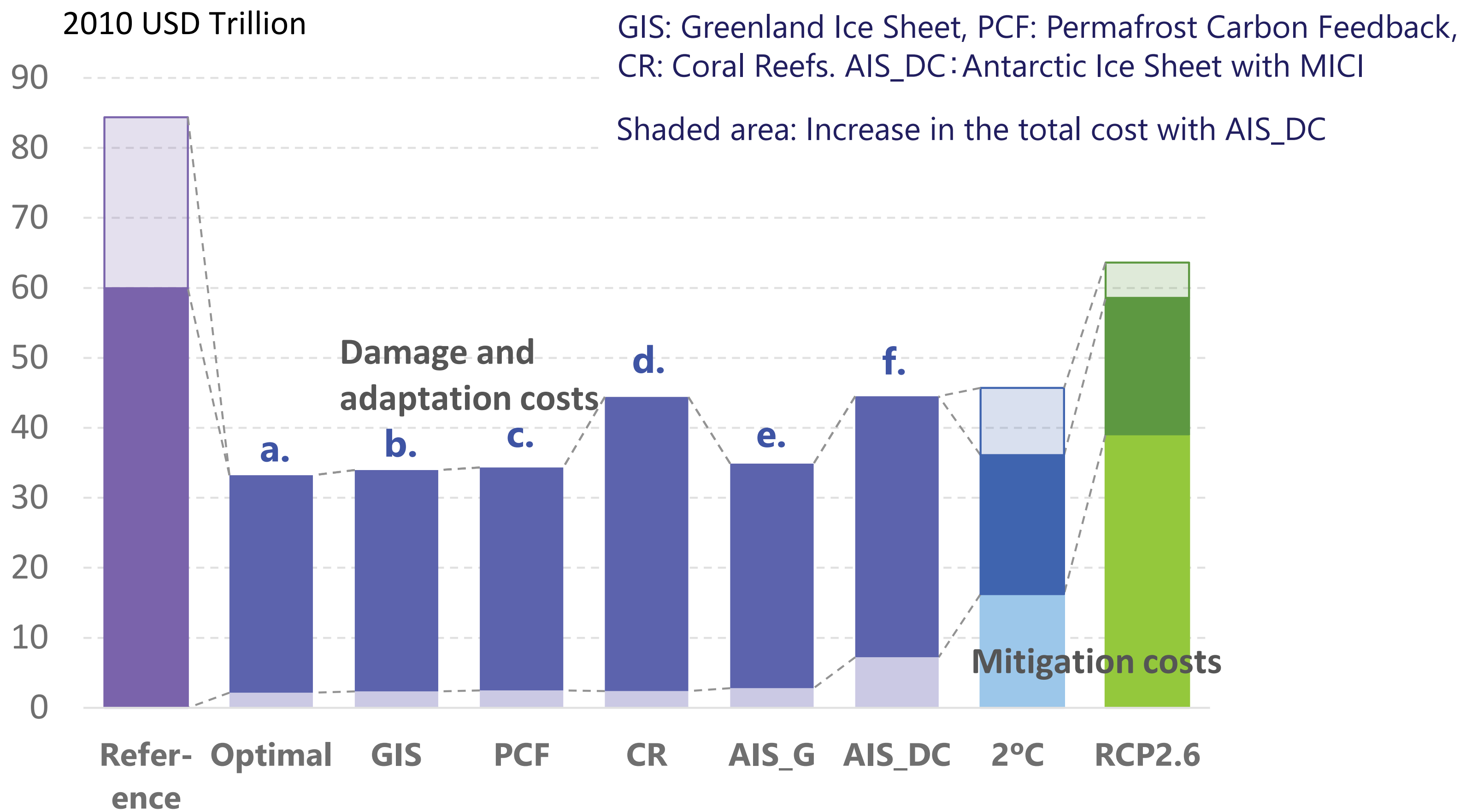
Optimal CO_2 emissions in 2050



GIS：Greenland Ice Sheet, PCF: Permafrost Carbon Feedback, CR: Coral Reefs, AIS_G: Antarctic Ice Sheet without MICI, AIS_DC: Antarctic Ice Sheet with MICI.

- The optimal path does not change greatly with consideration of GIS, PCF, CR, and AIS without MICI (AIS_G).
- On the other hand, if we assume the rapid collapse of AIS by MICI (AIS_DC), the optimal path changes largely to the red dotted path, and the optimal global CO_2 emission in 2050 declines by 27%, although still larger than that in the 2°C path.

Changes in the total cost by considering tipping elements



- Considering Greenland ice sheet, permafrost, or Antarctic ice sheet without MICI boosts the total cost only slightly (a. versus b., c., and e.)
- With explicit consideration of Antarctic ice sheet with MICI, or coral reefs, the total cost rises considerably (d. and f.) Although the economic damages related to the loss of coral reefs may be huge, it hardly affects the optimal path, because most part of coral reefs will be lost even with a temperature rise of 1.5°C.

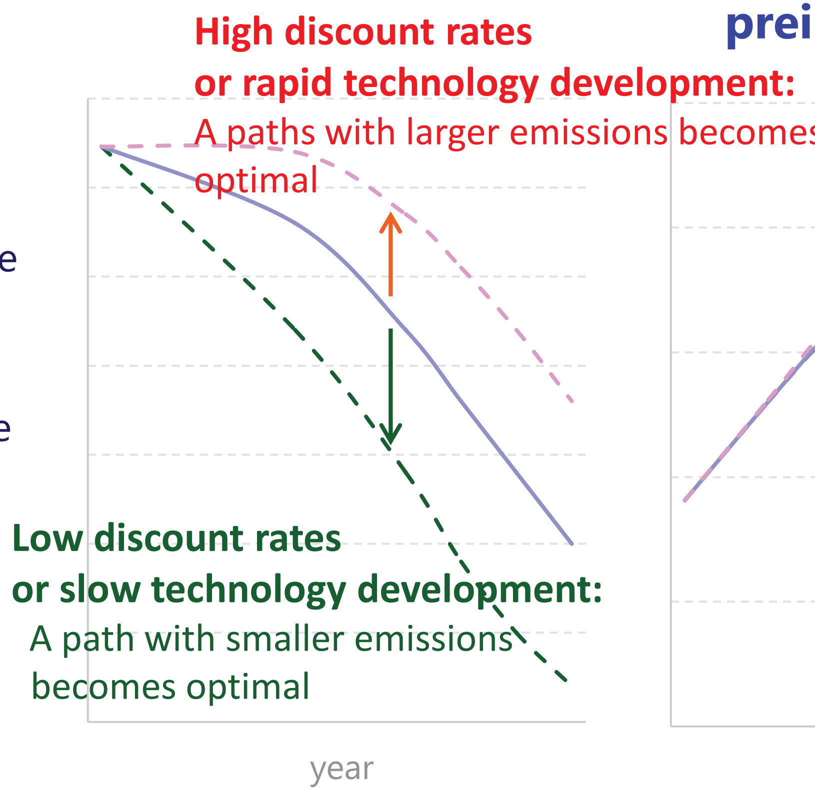
Assumptions on discount rates and technology development

Assumptions on discount rates

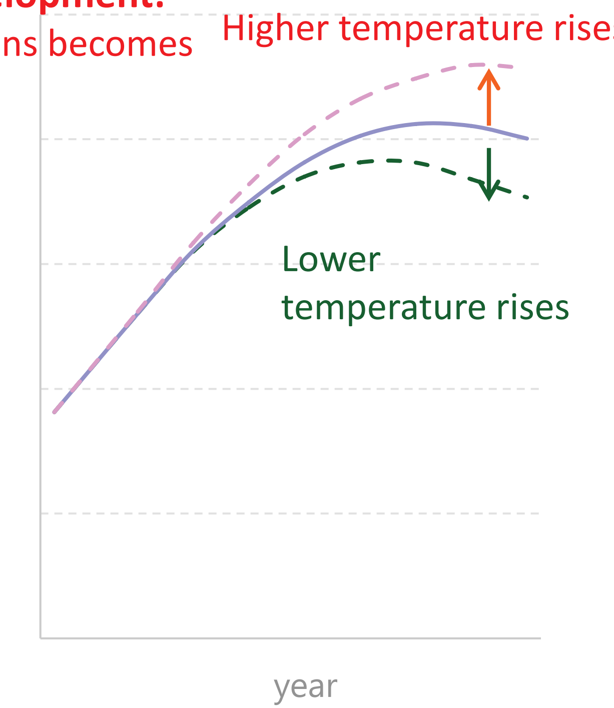
- The discount rate is an annual ratio used to convert a future value to the present value.
- When a certain rate of interest is expected for sure, the interest rate can be regarded as the discount rate.

- With higher discount rates, future climate damages are valued less, resulting in smaller mitigation being optimal.
- Lower assumptions on discount rates can be seen to represent views that put more emphasis on intergenerational equity.

Optimal path



Temperature rise from preindustrial levels

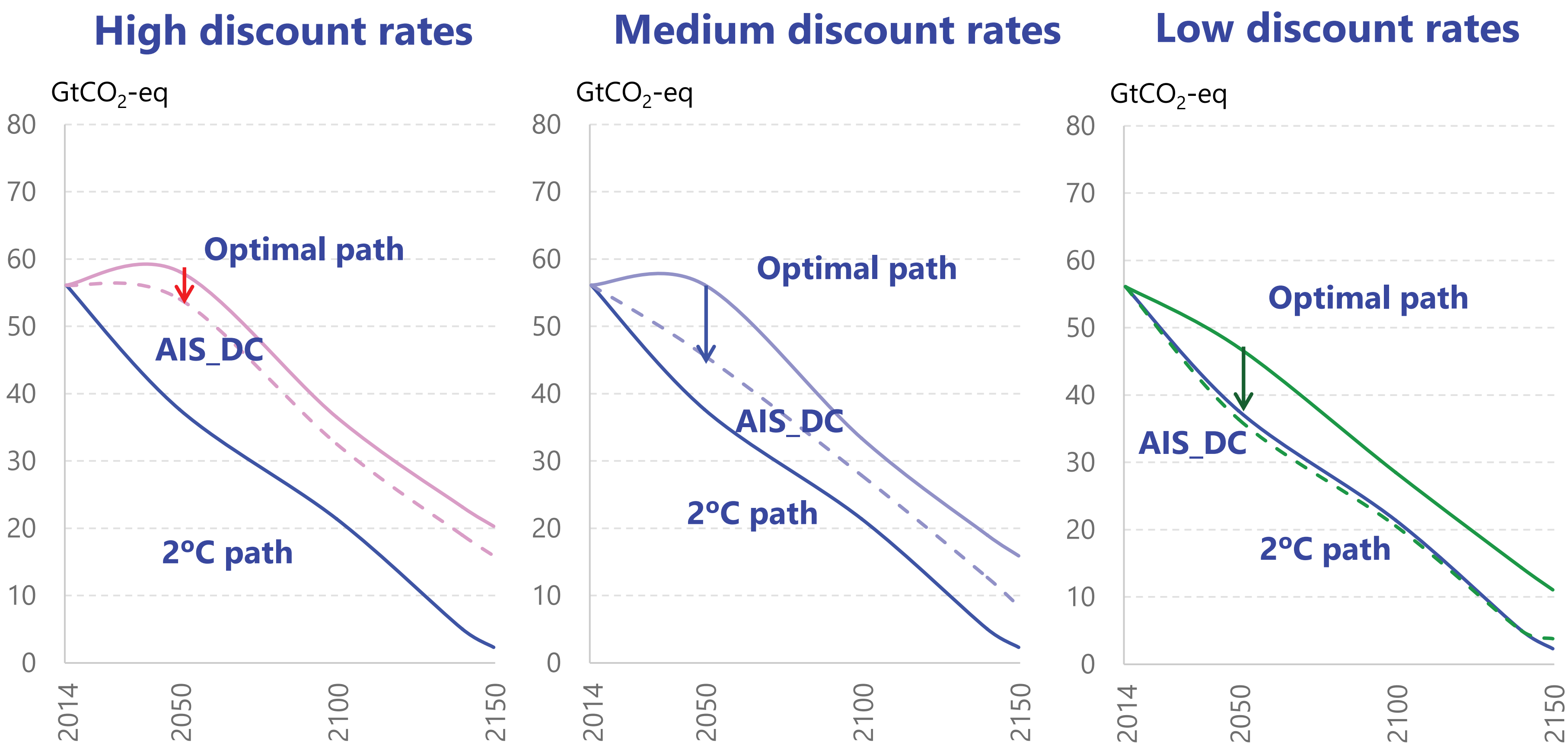


Assumptions on the speed of technology development

- Assumes more rapid declines in mitigation costs, as well as the future potentials of negative emission technologies.
- With slower technology development, the optimal path requires larger near-term mitigations.

Simulation cases: "High", "Medium", and "Low" discounting assumptions
"Normal" and "Rapid" technology

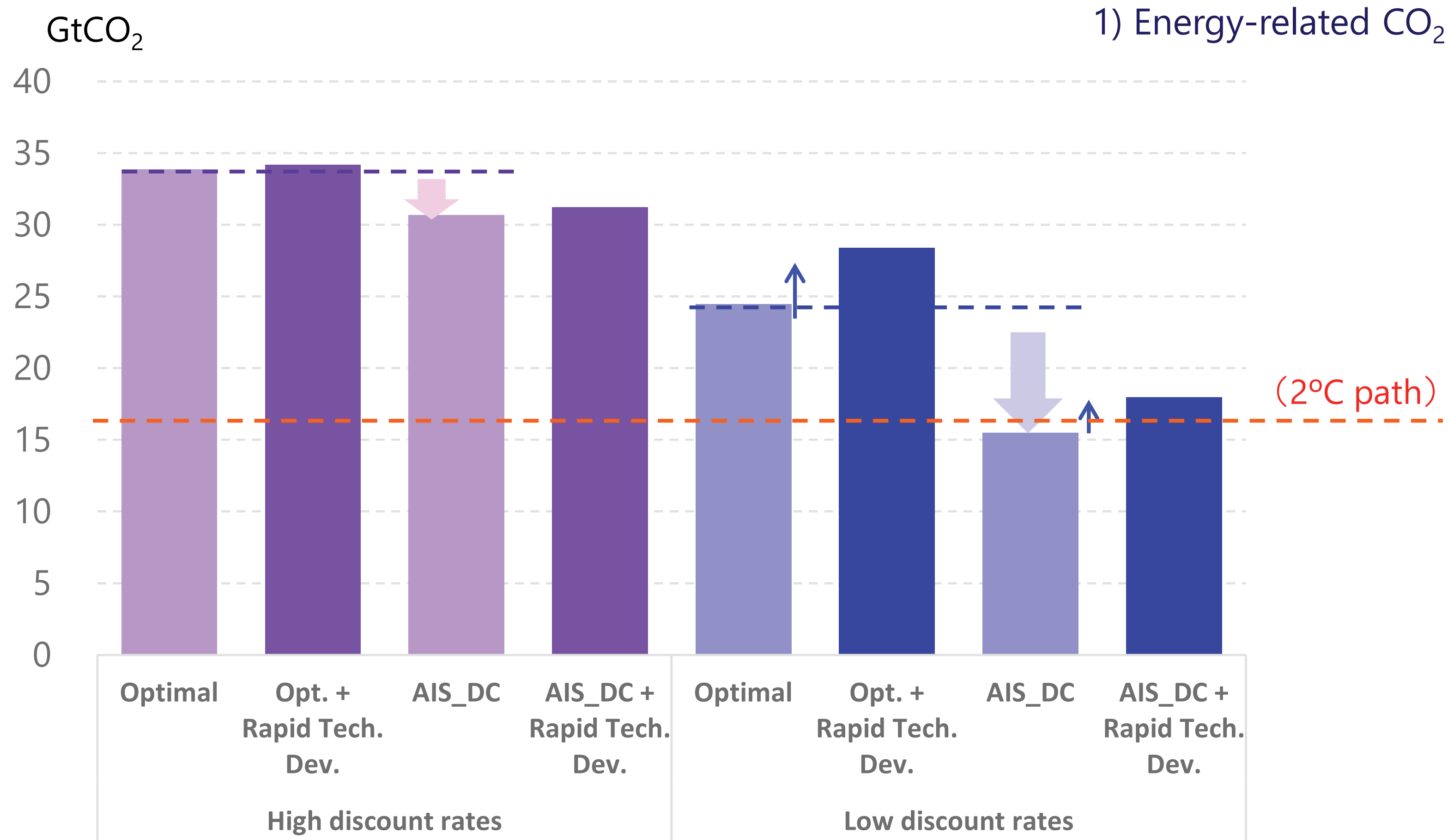
Effect of tipping element with different discounting rates



- Assuming lower discount rates, the optimal path moves downwards, and becomes closer to the 2°C path.
- In addition, if the Antarctic Ice Sheet collapses rapidly with MICI (AIS_DC), the optimal path moves downwards further; we can observe larger change in the optimal path for the cases with lower discount rates.

Effect of technology development: CO_2 emission[1)] in 2050

1) Energy-related CO_2



- With high discount rate assumptions, rapid technology development does not affect the optimal emissions in 2050 greatly, as high discount rates put more focus on the costs and damages in the near future.
- On the other hand, with low discount rate assumptions, rapid technology development boosts up the optimal emission in 2050, which implies that the low discount rates represent views that emphasizes the importance of long-term technology development.

Conclusions

- If we neglect to take strong actions to address climate change, future climate damages, and/or adaptation costs would be enormous. On the other hand, if we take very strong mitigation measures, the adaptation and damage costs are alleviated, but larger mitigation costs will be required.
- In this regard, many researchers have attempted to assess the “optimal” path considering the total cost including mitigation, adaptation, and damage costs, although with considerable discussion.
- In recent years, scientists have expressed concerns about so-called tipping elements, or the subsystem of the earth that may cause an irreversible transition of the earth system. In many cases, explicit consideration of these elements does not affect the optimal path greatly, partly because of the very long characteristic times of the events.
- However, if self-sustaining mechanisms, such as MICI for the collapse of Antarctic ice sheet, accelerate the occurrence of the events, the optimal path may be pushed downwards. Obtaining deeper scientific insights into these events are crucial for decent climate policies.
- The impacts of tipping elements are dependent on the assumptions on the discount rates: With lower discount rates, tipping elements exert larger influences on the optimal mitigation path, which can partly be mitigated by long-term technology development.
- At the same time, the explicit consideration of tipping elements, as well as lower discount rate assumptions, put more focus on the importance of long-term technology development. Thus, policy measures to promote technology development in long-term perspectives would be regarded as more and more important to address climate change issues.

Appendix: Specification of the assumptions

Assumptions on discount rates

- The social discount rate ρ is calculated by the following Ramsey formula:

$$\rho = \delta + \eta g$$

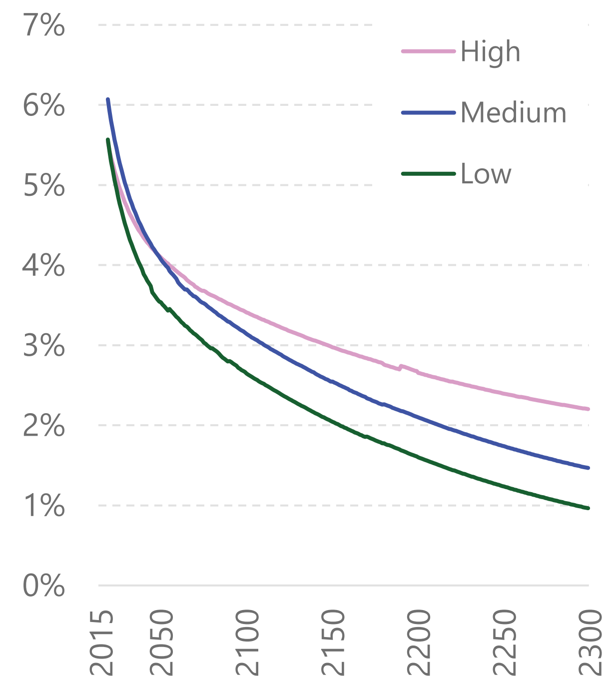
δ: Pure rate of time preference
g: Growth rate of per capita consumption
η: Elasticity of marginal utility with respect to consumption

- Three sets of parameters have been used:

High: $\delta = 1.5\%$、$\eta = 1.45$

Medium: $\delta = 0.5\%$、$\eta = 2.0$

Low: $\delta = 0.05\%$、$\eta = 2.0$



Assumptions on the speed of technology development

- Accelerating future technology development is supposed to contribute to declines in mitigation costs, as well as to larger reductions in GHG emissions.

- In the "rapid technology development" case, the annual reduction rate of mitigation costs are assumed to be 50% larger (0.75%/year compared to the default value of 0.5%/year), and negative emission technologies are assumed to be available after 2100, absorbing CO_2 equivalent to 20% of the baseline emissions.

Reference materials

Geographical coverage

Countries / regions in the world are geographically aggregated into 42 regions.

Especially the Asian energy supply / demand structure is considered in detail, aggregating the area into 15 regions.

Source: [Map] www.craftmap.box-i.net

Modelling framework

Major assumptions

GDP, population, energy prices, exchange rates, international trade, etc.

Macroeconomic model

Calculate GDP-related indices, price indices, activity indices including material production, etc. consistently.

Technology assessment model

Use a bottom-up approach to calculate future efficiencies of appliances, vehicles, etc.

Optimal power generation planning model

Calculate the cost-optimal power generation mix to meet the projected future electricity demand.

Energy supply-demand model

Econometric model to project future energy supply and demand by regression analysis of historical trends based on the energy balance tables data of the International Energy Agency.

This model calculates energy demand, supply and transformation as well as related indices including CO_2 emissions, CO_2 intensities and energy self-sufficiency ratios.

Experts' opinions

World trade model

Use the linear programming (LP) method to calculate the future international trade flows of crude oil, petroleum products, etc.

Computable general equilibrium model

Estimate economic impacts induced by changes in energy supply and demand, based on input-output table data.

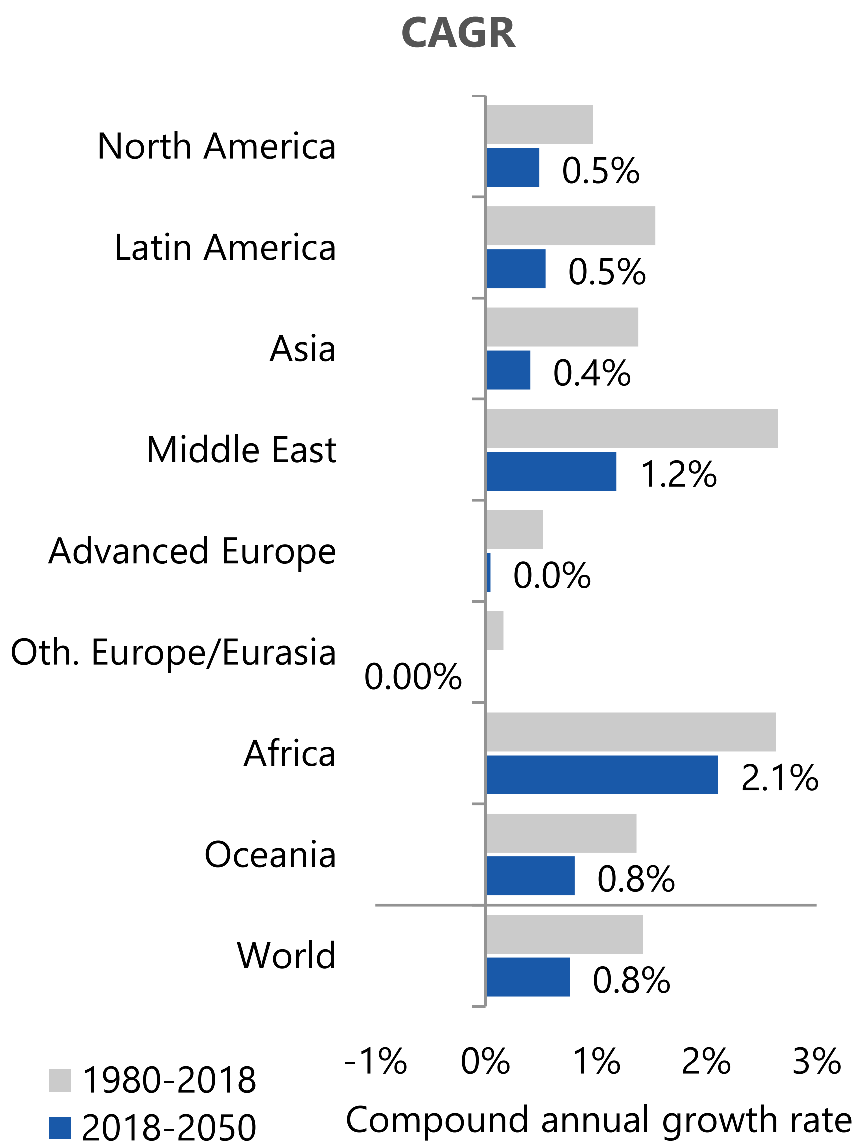
Climate change model

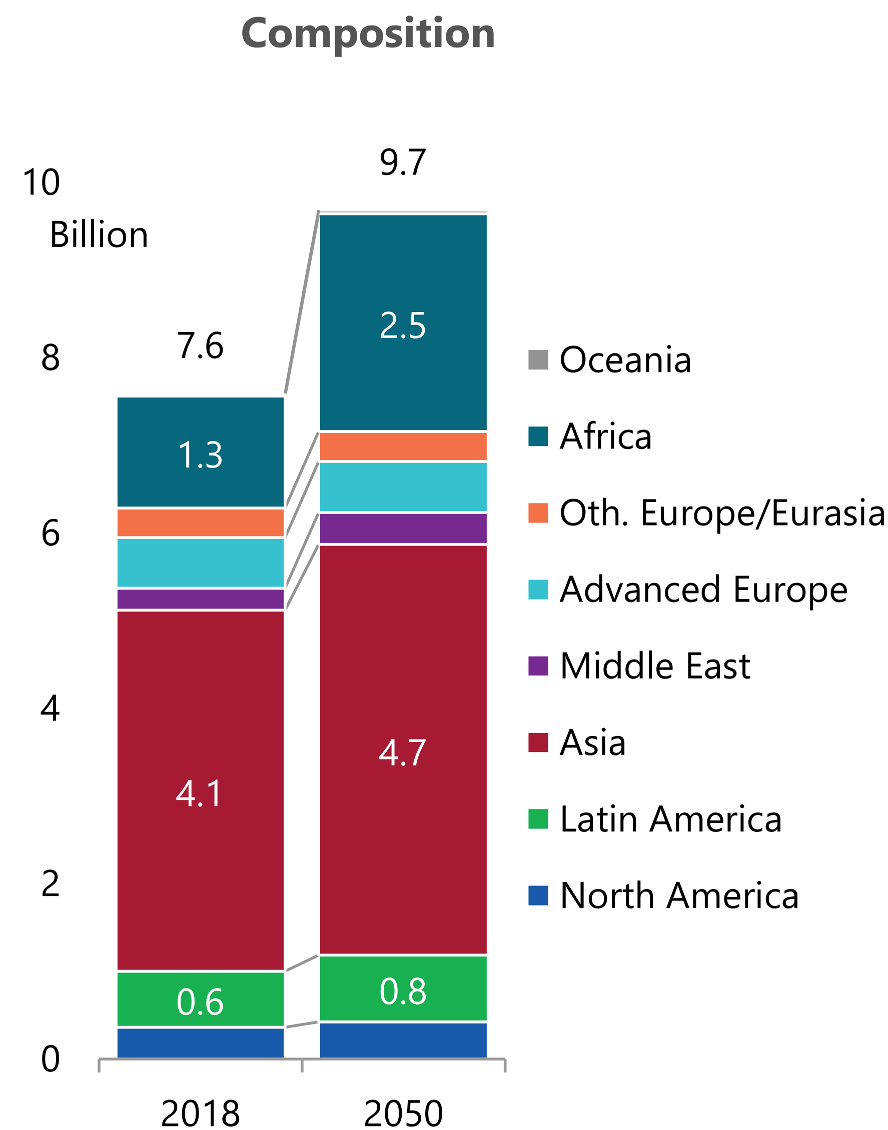
Calculate future GHG concentration in the atmosphere, temperature rise, damage caused by climate change, etc.

Basic scenarios in IEEJ Outlook

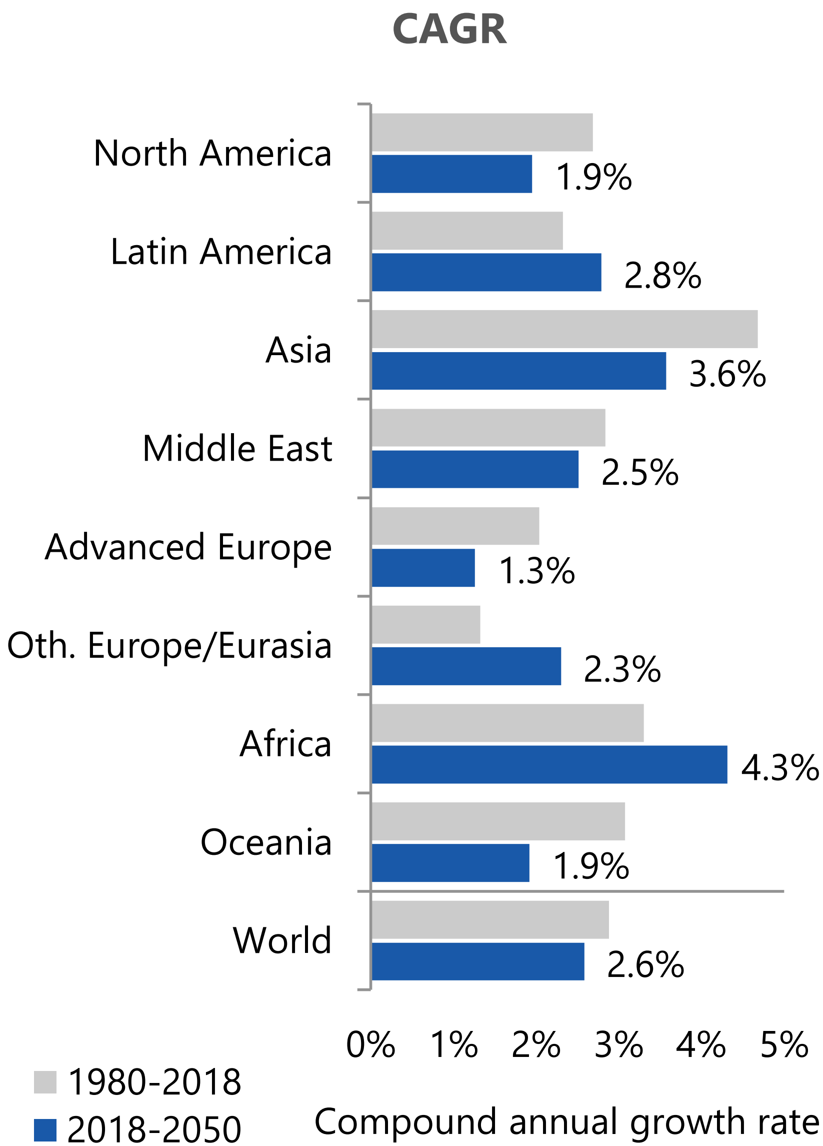
	Reference Scenario	Advanced Technologies Scenario
	Reflects past trends with technology progress and current energy policies, without any aggressive policies for low-carbon measures	Assumes introduction of powerful policies to address energy security and climate change issues with the utmost penetration of low-carbon technologies
Socio-economic structure	Stable growth led by developing economies despite slower population growth. Rapid penetration of energy consuming appliances and vehicles due to higher income.	
International energy prices	**Oil** supply cost increases along with demand growth. **Natural gas** prices converge among Europe, North America and Asia markets. **Coal** keeps unchanged with today's level.	Slower price increase due to lower demand growth (coal price decreases)
Energy and environmental policies	Gradual reinforcement of low-carbon policies with past pace	Further reinforcement of domestic policies along with international collaboration
Energy and environmental technologies	Improving efficiency and declining cost of existing technology with past pace	Further declining cost of existing and promising technology

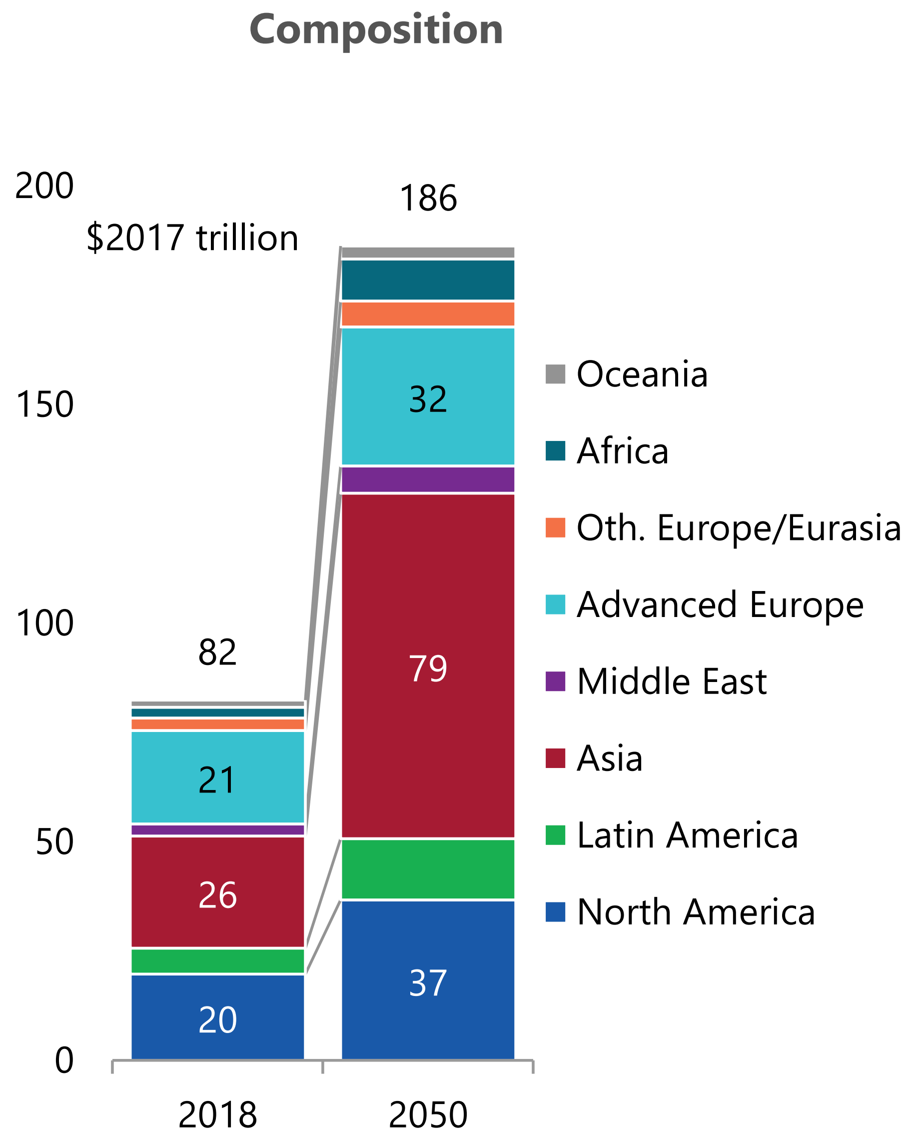
Population


CAGR
North America
Latin America
Asia
Middle East
Advanced Europe
Oth. Europe/Eurasia
Africa
Oceania
World
0.5%
0.5%
0.4%
1.2%
0.0%
0.00%
2.1%
0.8%
0.8%
-1%
0%
1%
2%
3%
Compound annual growth rate
1980-2018
2018-2050


Composition
Billion
10
8
6
4
2
0
7.6
9.7
1.3
2.5
4.1
4.7
0.6
0.8
2018
2050
Oceania
Africa
Oth. Europe/Eurasia
Advanced Europe
Middle East
Asia
Latin America
North America

Real GDP

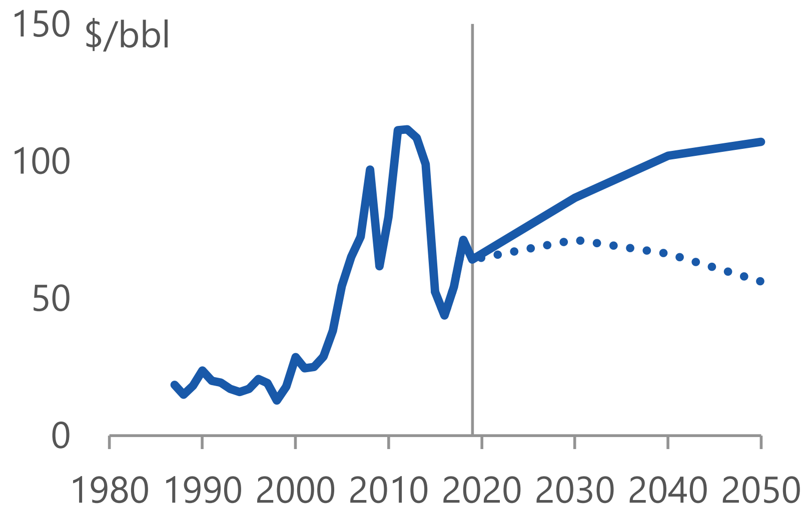

CAGR
North America
1.9%
Latin America
2.8%
Asia
3.6%
Middle East
2.5%
Advanced Europe
1.3%
Oth. Europe/Eurasia
2.3%
Africa
4.3%
Oceania
1.9%
World
2.6%
0%
1%
2%
3%
4%
5%
Compound annual growth rate
1980-2018
2018-2050


Composition
$2017 trillion
200
150
100
50
0
82
186
21
26
20
32
79
37
2018
2050
Oceania
Africa
Oth. Europe/Eurasia
Advanced Europe
Middle East
Asia
Latin America
North America

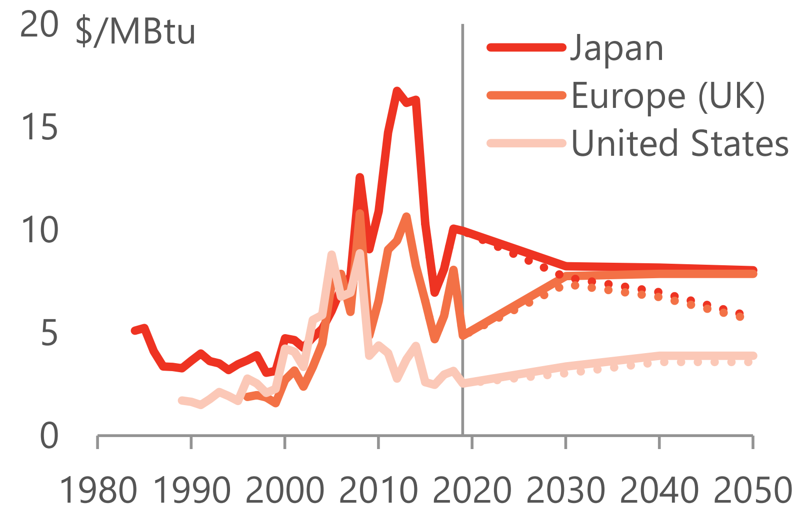
International energy prices

Reference : ———
Advanced Technologies : ··········

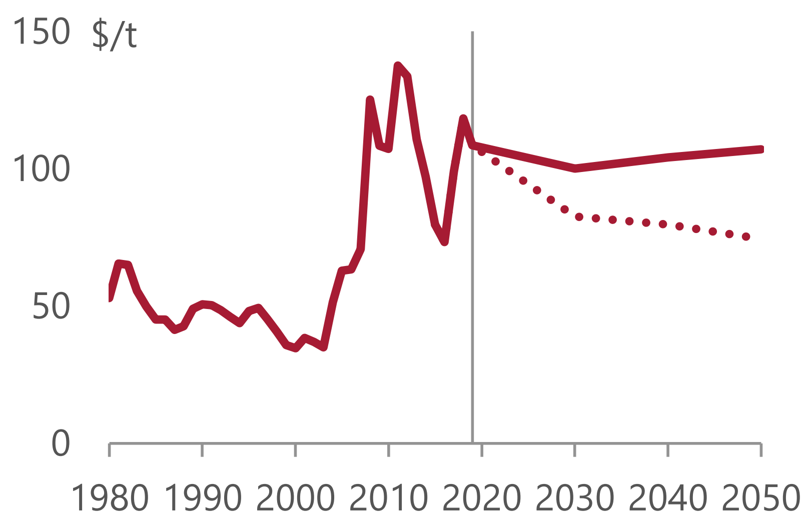
Crude oil



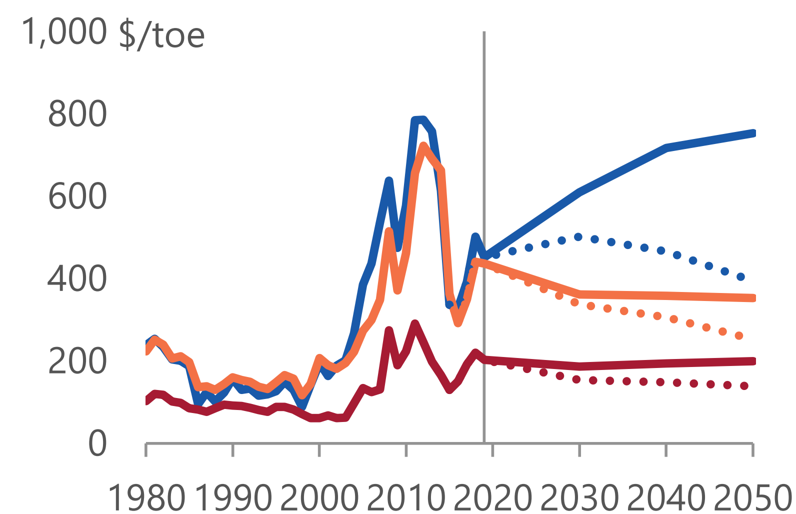
Natural gas



Coal



CIF import prices for Japan



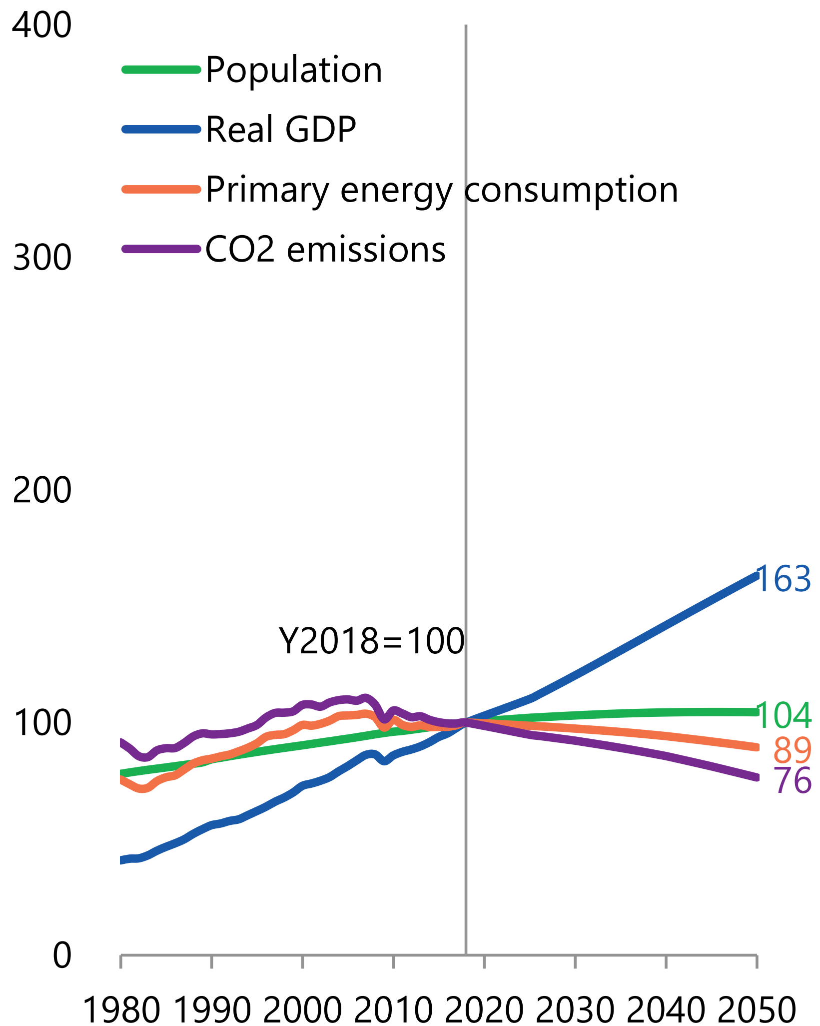
Note: Historical prices are nominal. Assumed future prices as real in $2019.

Energy and environmental technology

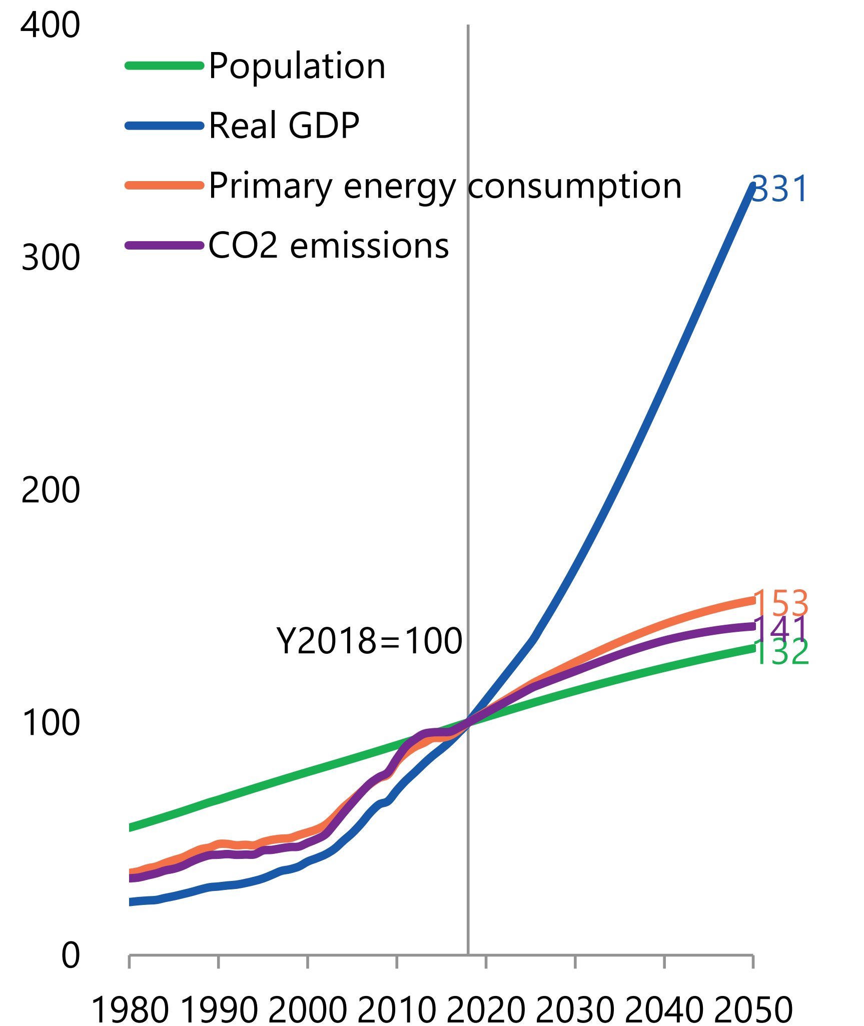
		2018	2050 Reference	2050 Advanced Technologies	Assumptions for Advanced Technologies Scenario
Improving energy efficiency					
Industry	Intensity in steel industry (ktoe/kt)	0.274	0.245	0.217	100% penetration of Best Available Technology by 2050.
	Intensity in non-metallic minerals industry	0.093	0.072	0.064	
Transport	Electrified vehicle share in passenger car sales	6%	55%	87%	Cost reduction of electrified vehicles. Promotion measures including fuel supply infrastructure. *electrified vehicle includes hybrid vehicle, plug-in hybrid vehicle, electric vehicle and fuel-cell vehicle
	Average fuel efficiency in new passenger car (km/L)	14.4	23.7	34.0	
Buildings	Residential total efficiency (Y2018=100)	100	150	181	Efficiency improvement at twice the speed for newly installed appliance, equipment and insulation.
	Commercial total efficiency	100	180	211	Electrification in space heating, water heater and cooking (clean cooking in developing regions).
Power	Thermal generation efficiency (Power transmission end)	38%	45%	46%	Financial scheme for initial investment in high-efficient thermal power plant.
Penetrating low-carbon technology					
Biofuels for transport (Mtoe)		90	134	254	Development of next generation biofuel with cost reduction. Relating to agricultural policy in developing regions.
Nuclear power generation capacity (GW)		416	480	725	Appropriate price in wholesale electricity market. Framework for financing initial investment in developing regions.
Wind power generation capacity (GW)		564	1,850	3,625	Further reduction of generation cost. Cost reduction of grid stabilization technology. Efficient operation of power system.
Solar PV power generation capacity		480	2,909	4,737	
Thermal power generation capacity with CCS (GW)		0	0	1,023	Installing CCS after 2030 (regions which have storage potential except for aquifer).
Zero-emission generation ratio (incl. CCS)		36%	42%	77%	Efficient operation of power system including international power grid.

Population, GDP, energy and CO_2

Advanced Economies

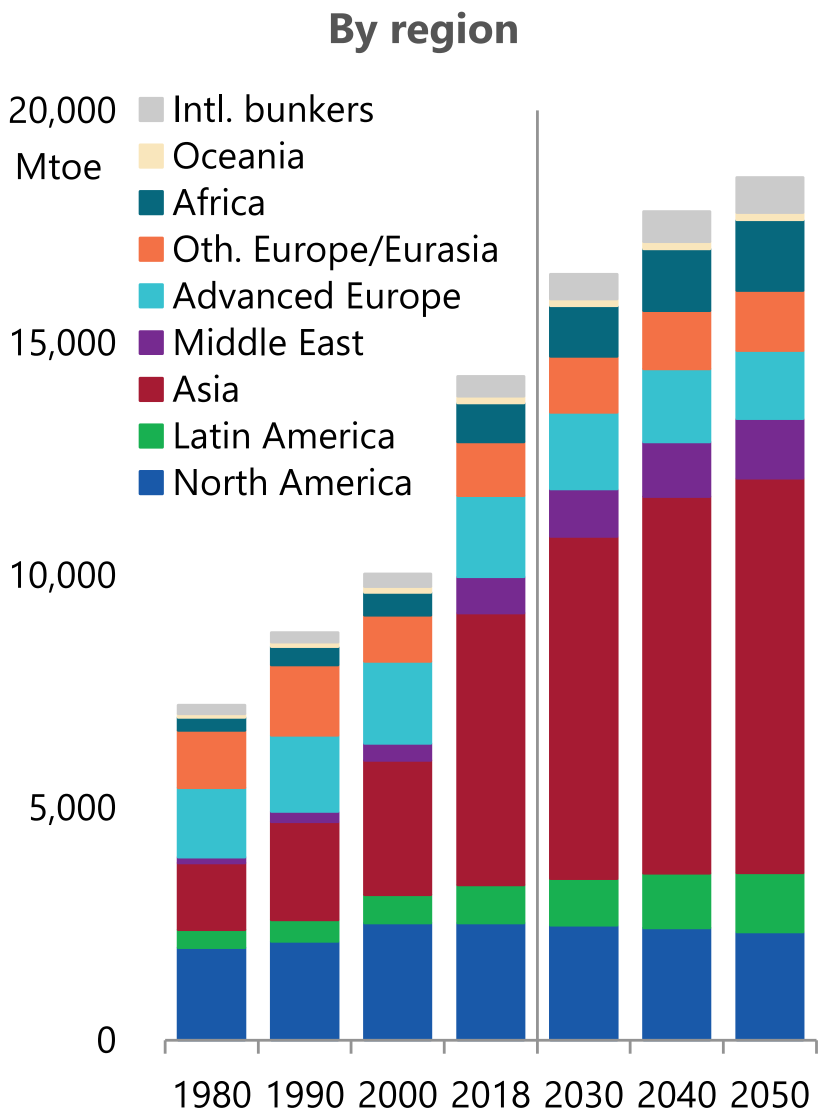


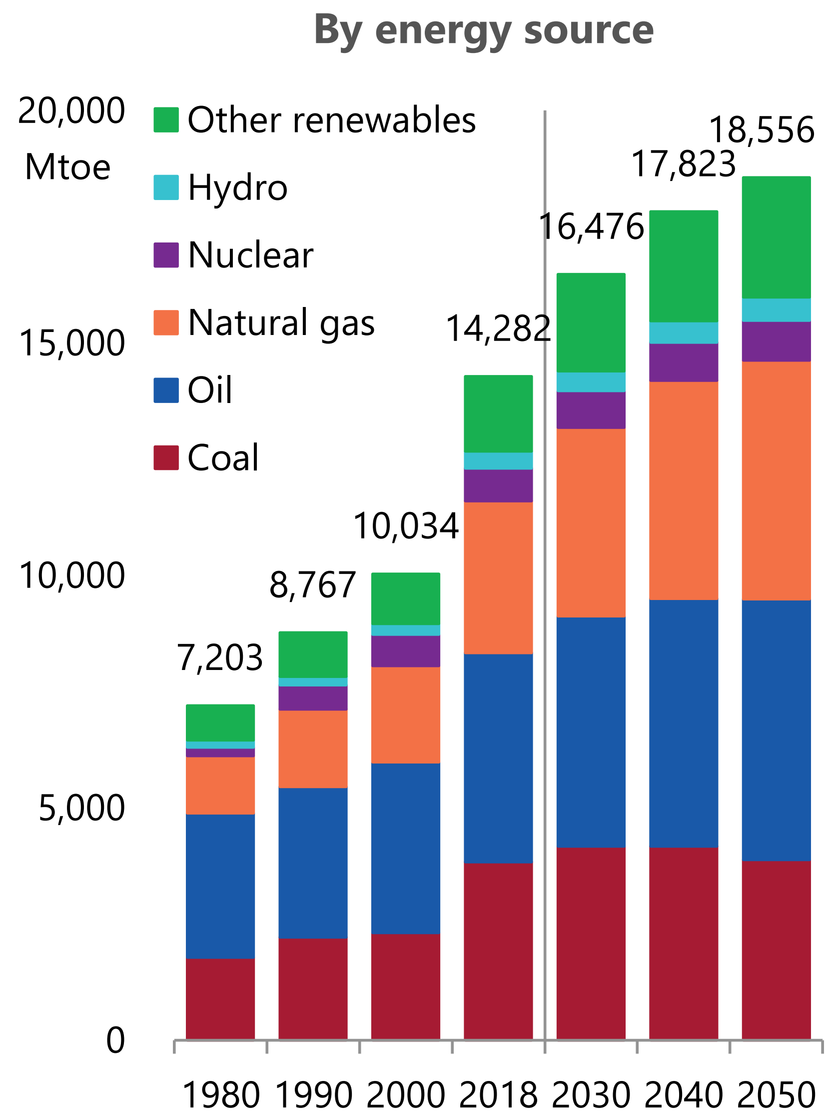
Emerging Market and Developing Economies



Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.

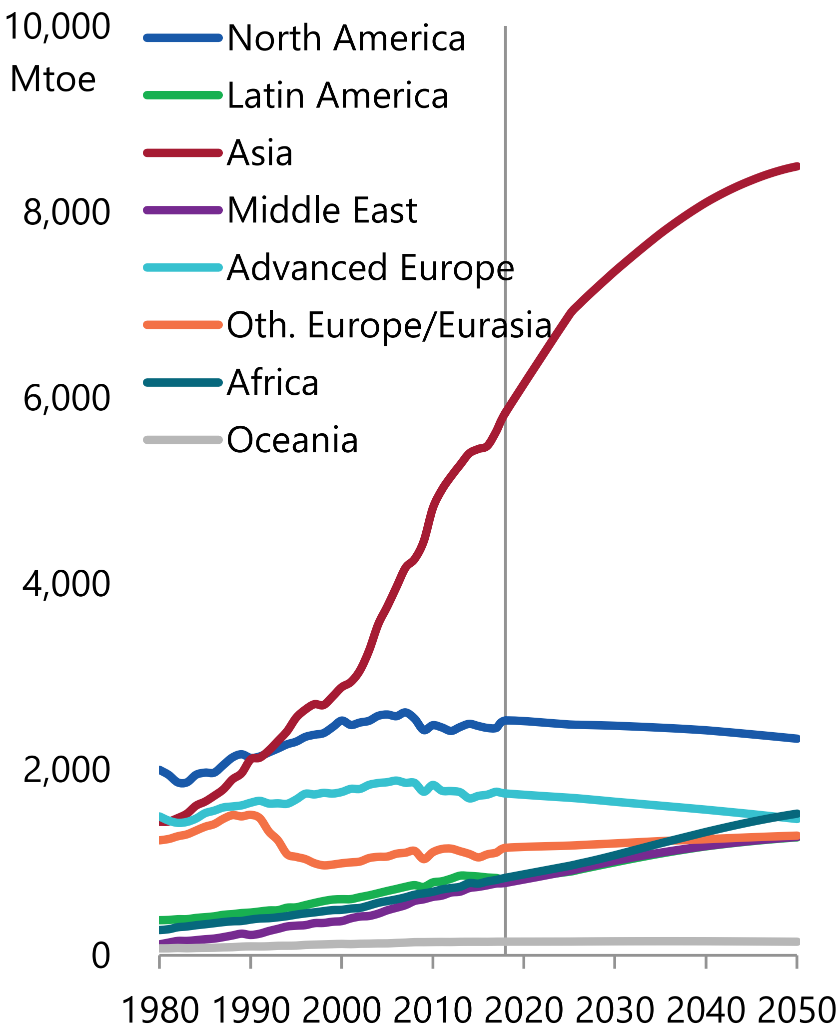
Primary energy consumption



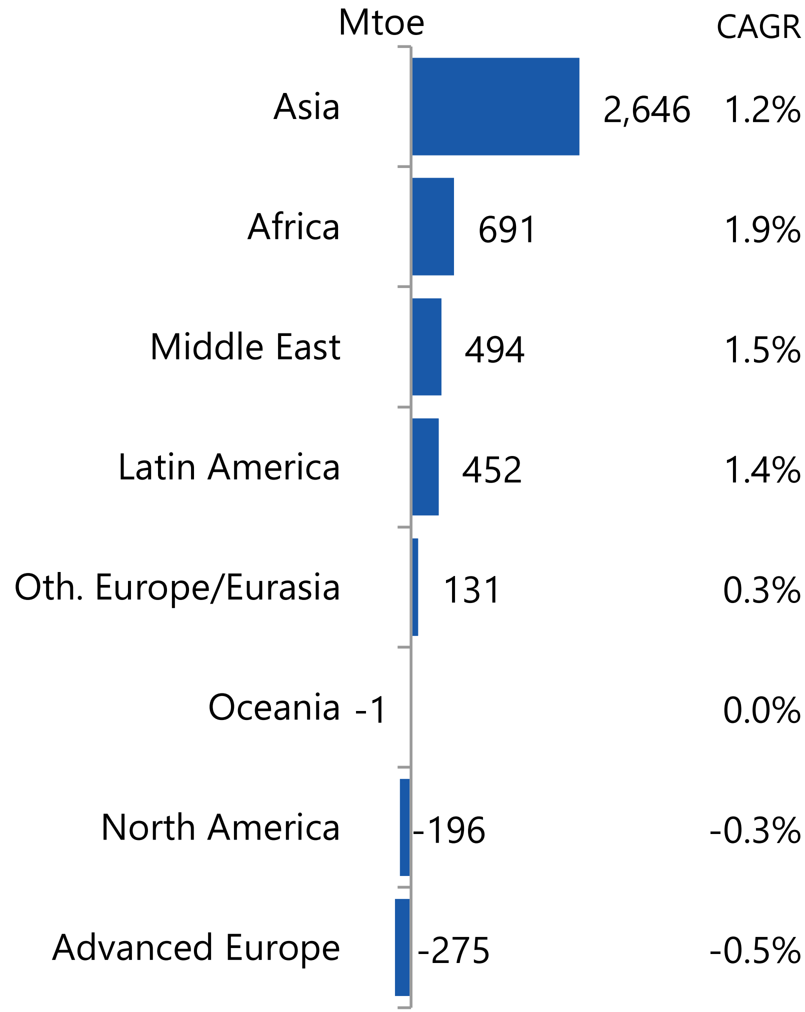


Primary energy consumption (by region)

Energy consumption



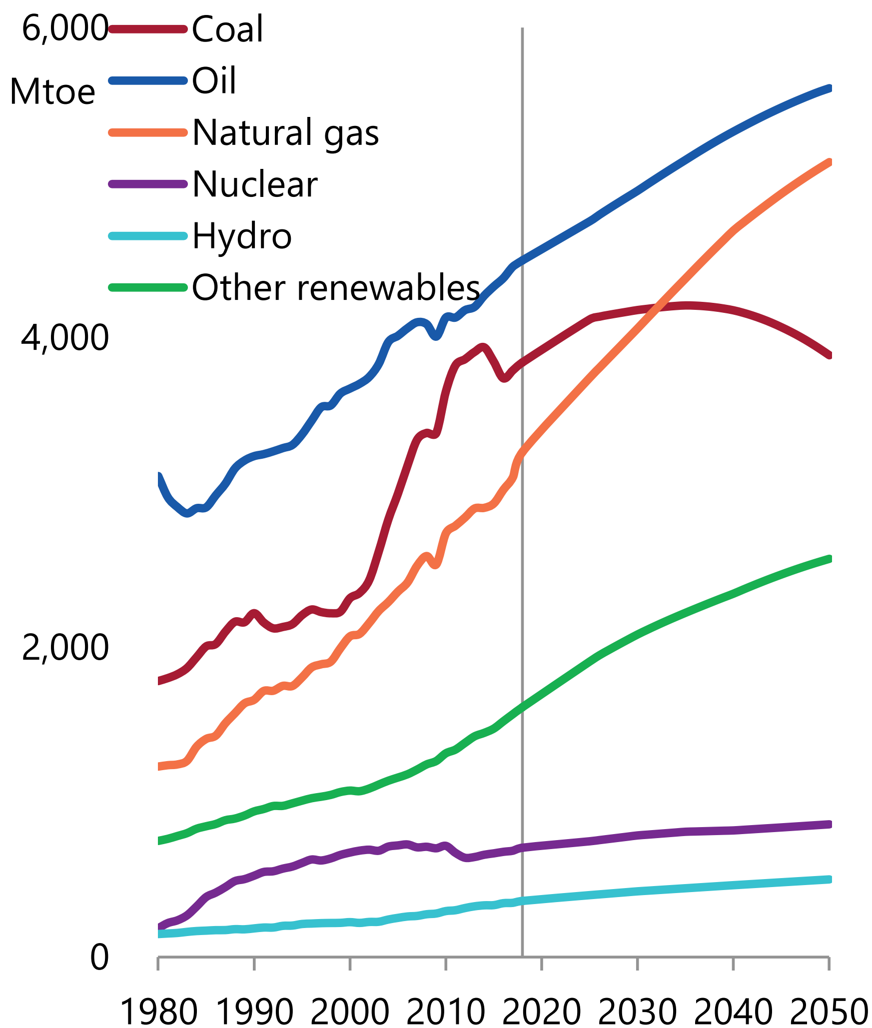
Changes (2018-2050)



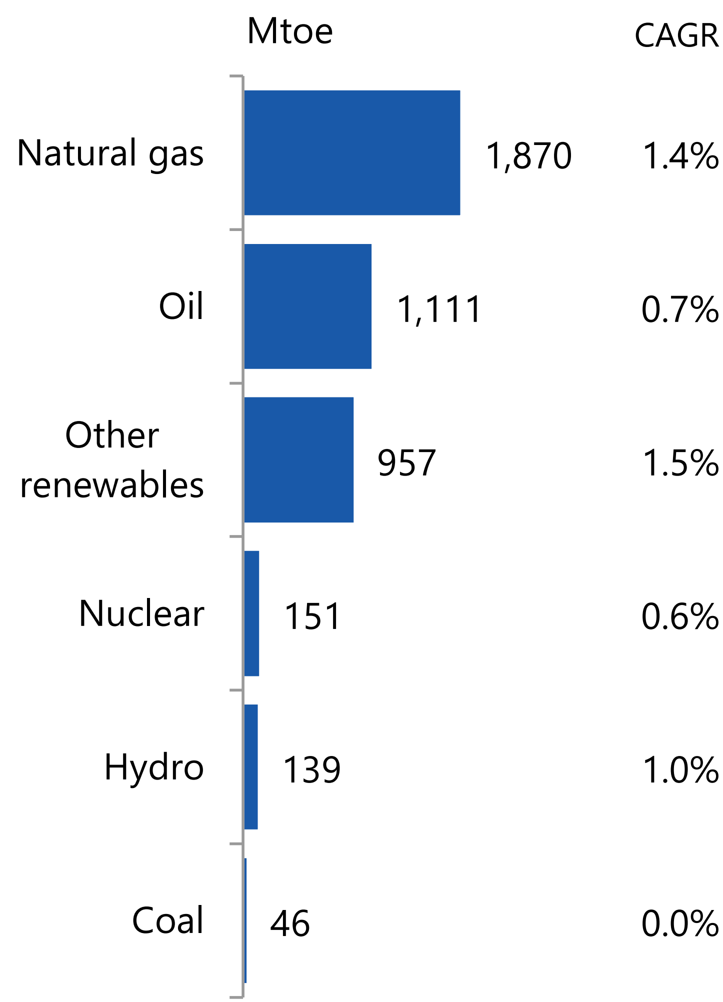
Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.

Primary energy consumption (by energy source)

Energy consumption



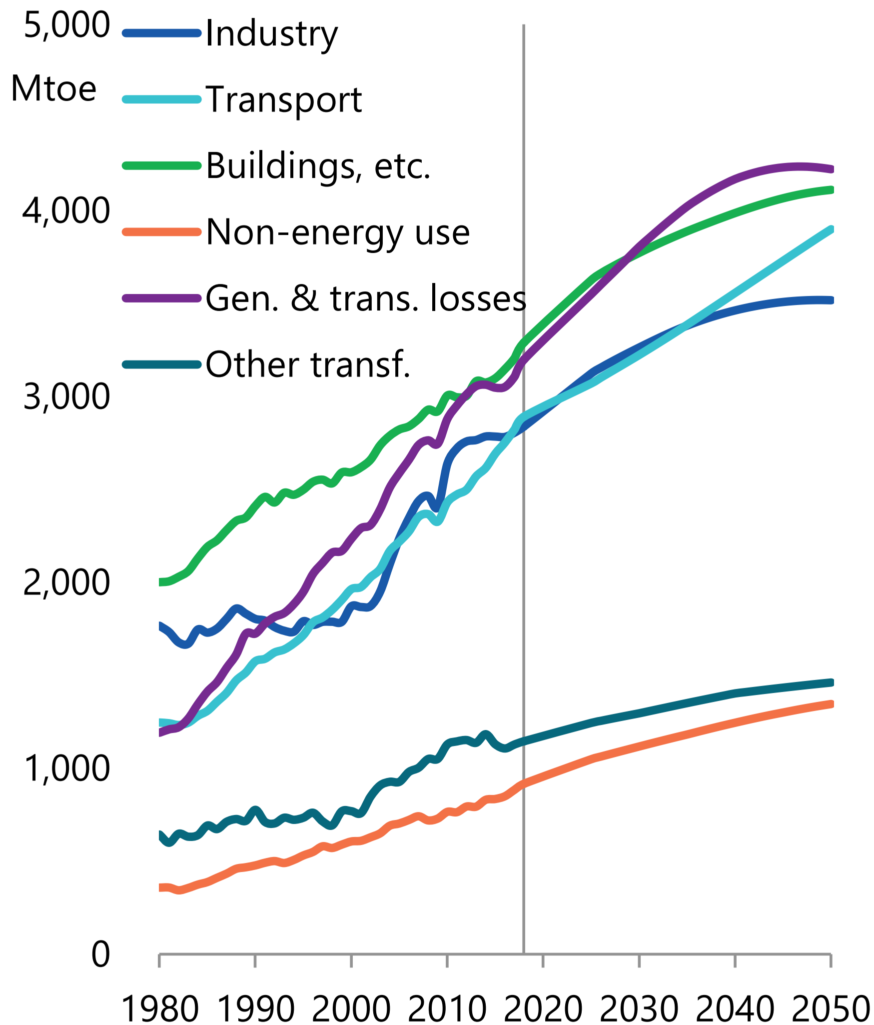
Changes (2018-2050)



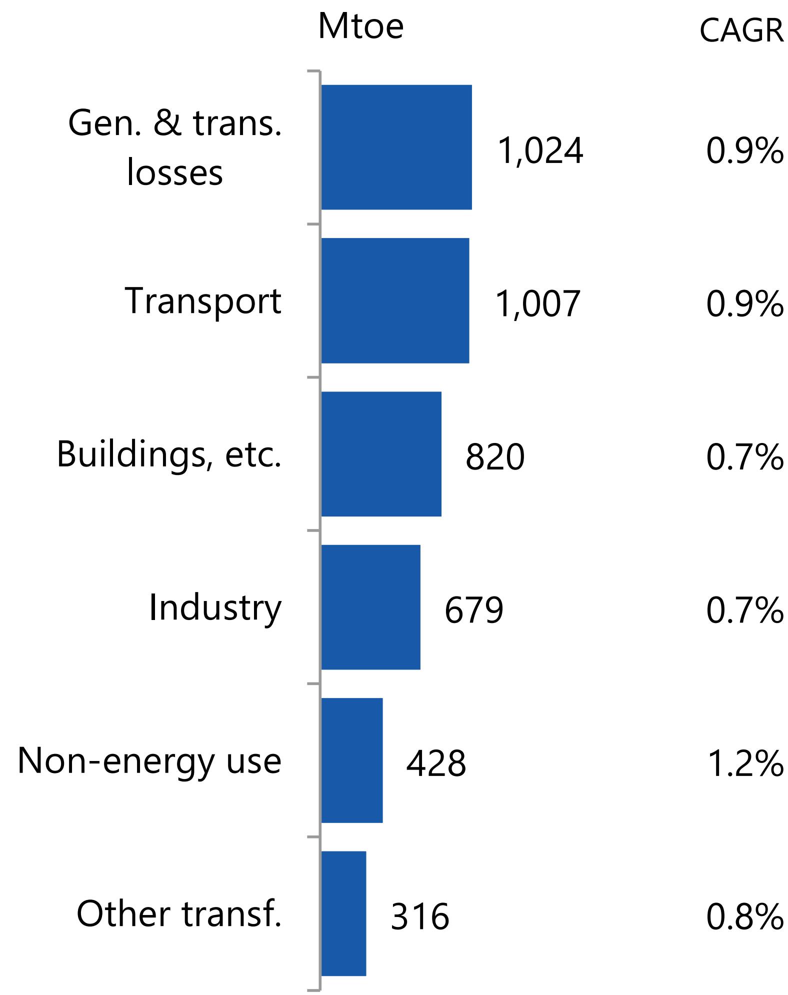
Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.

Primary energy consumption (by sector)

Energy consumption

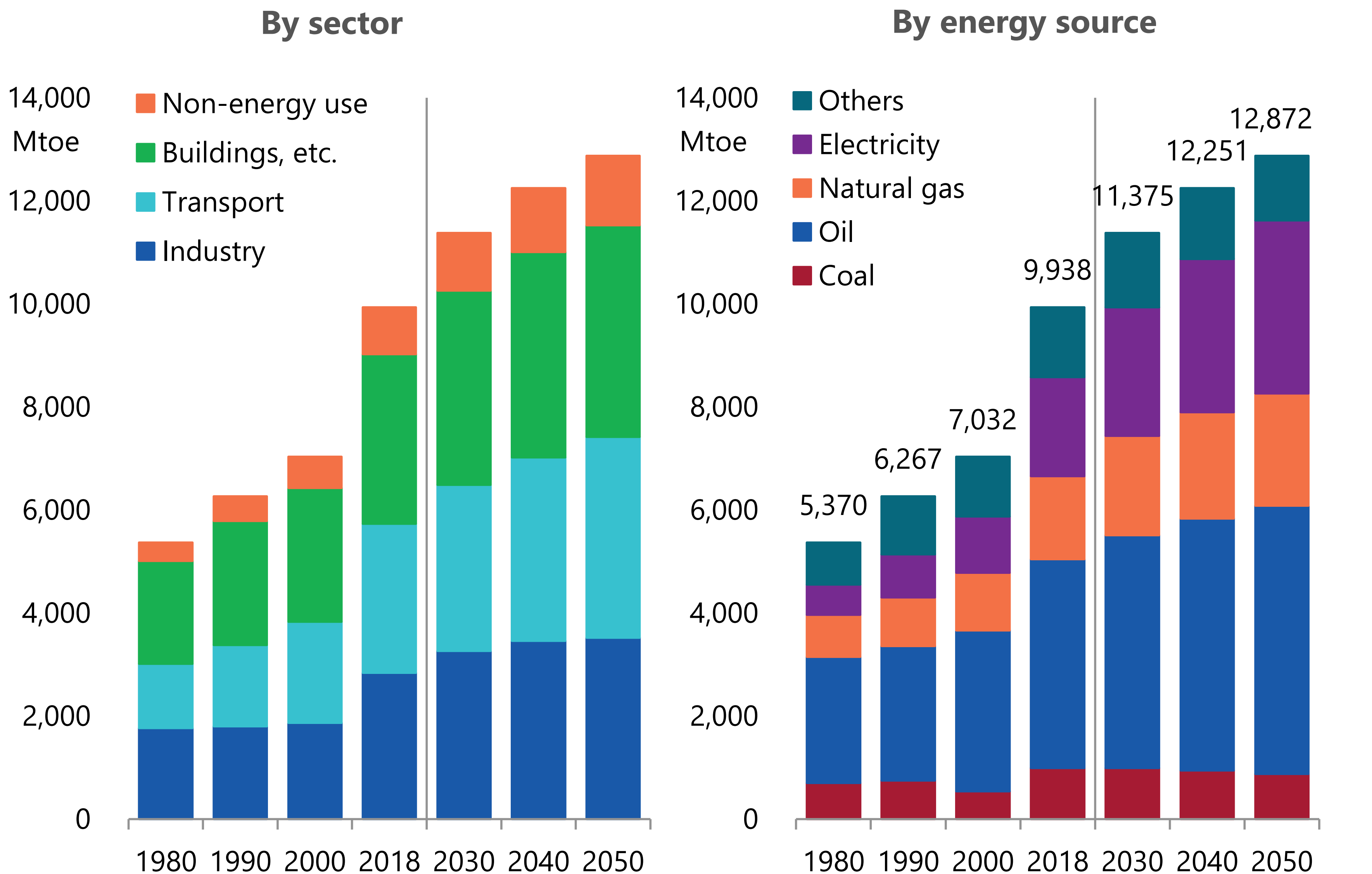


Changes (2018-2050)

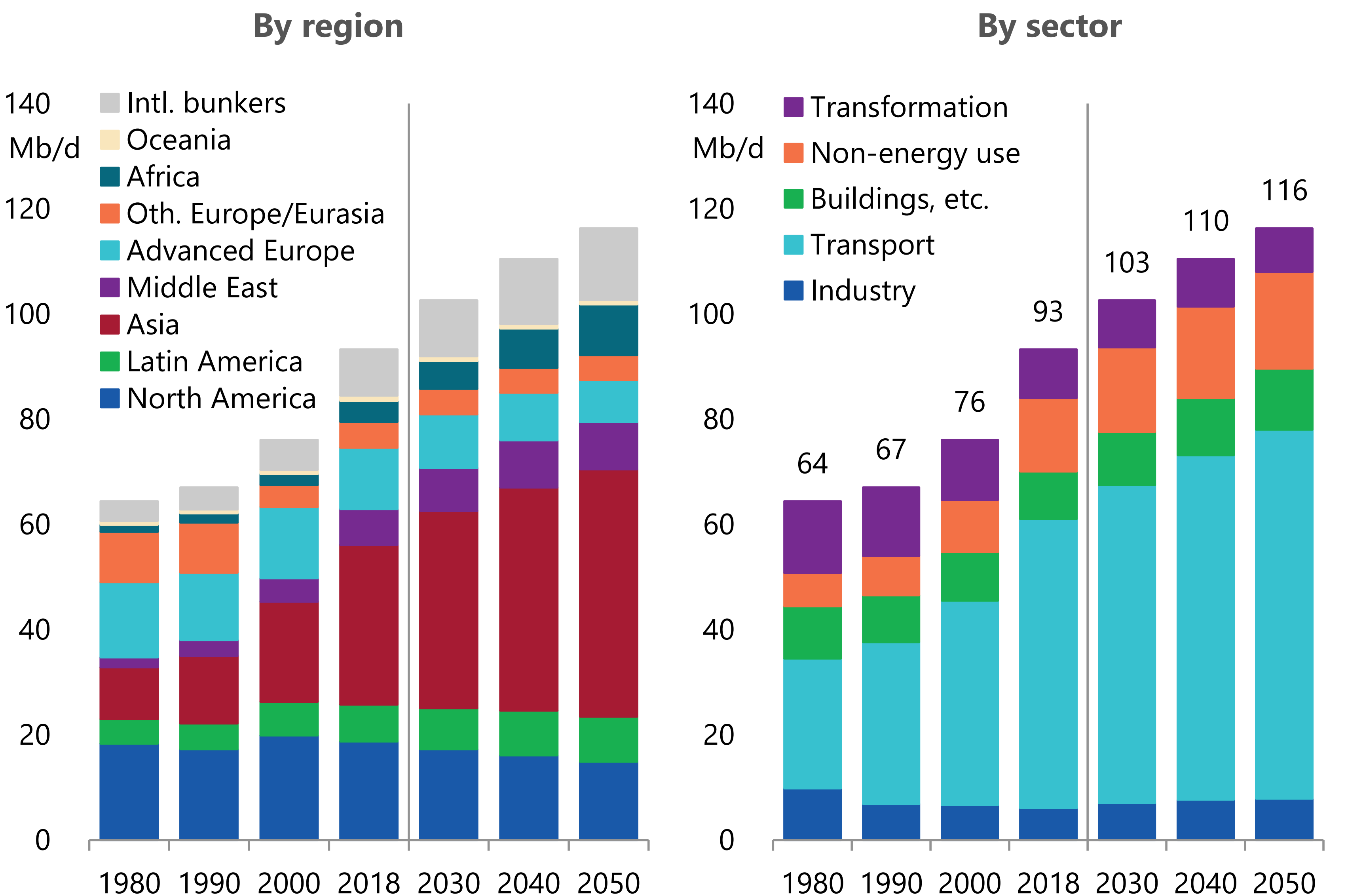


Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.

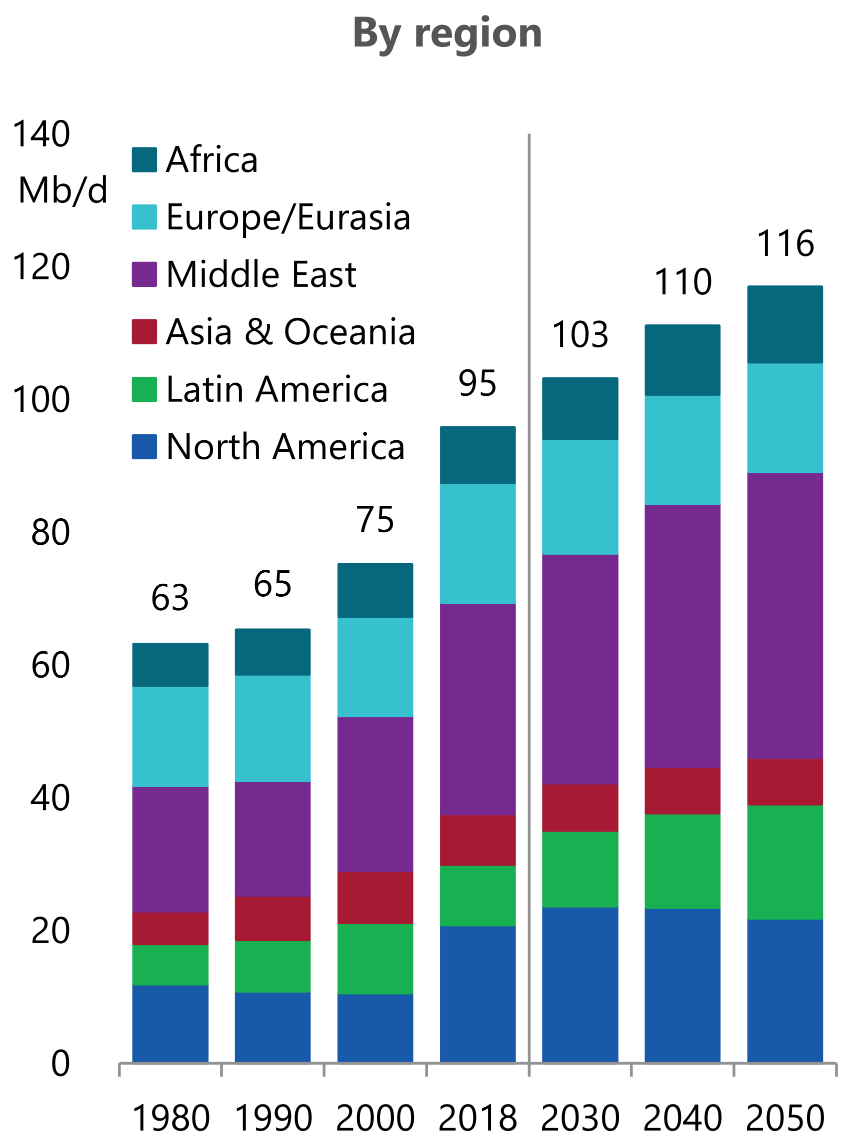
Final energy consumption

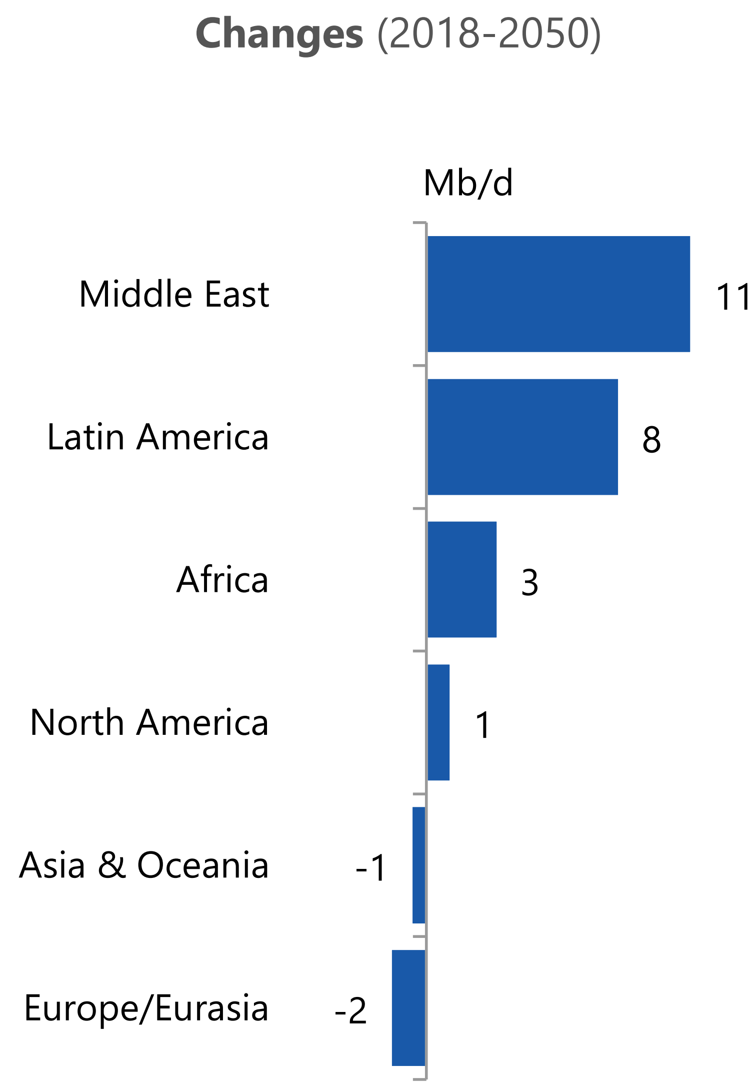


Oil consumption

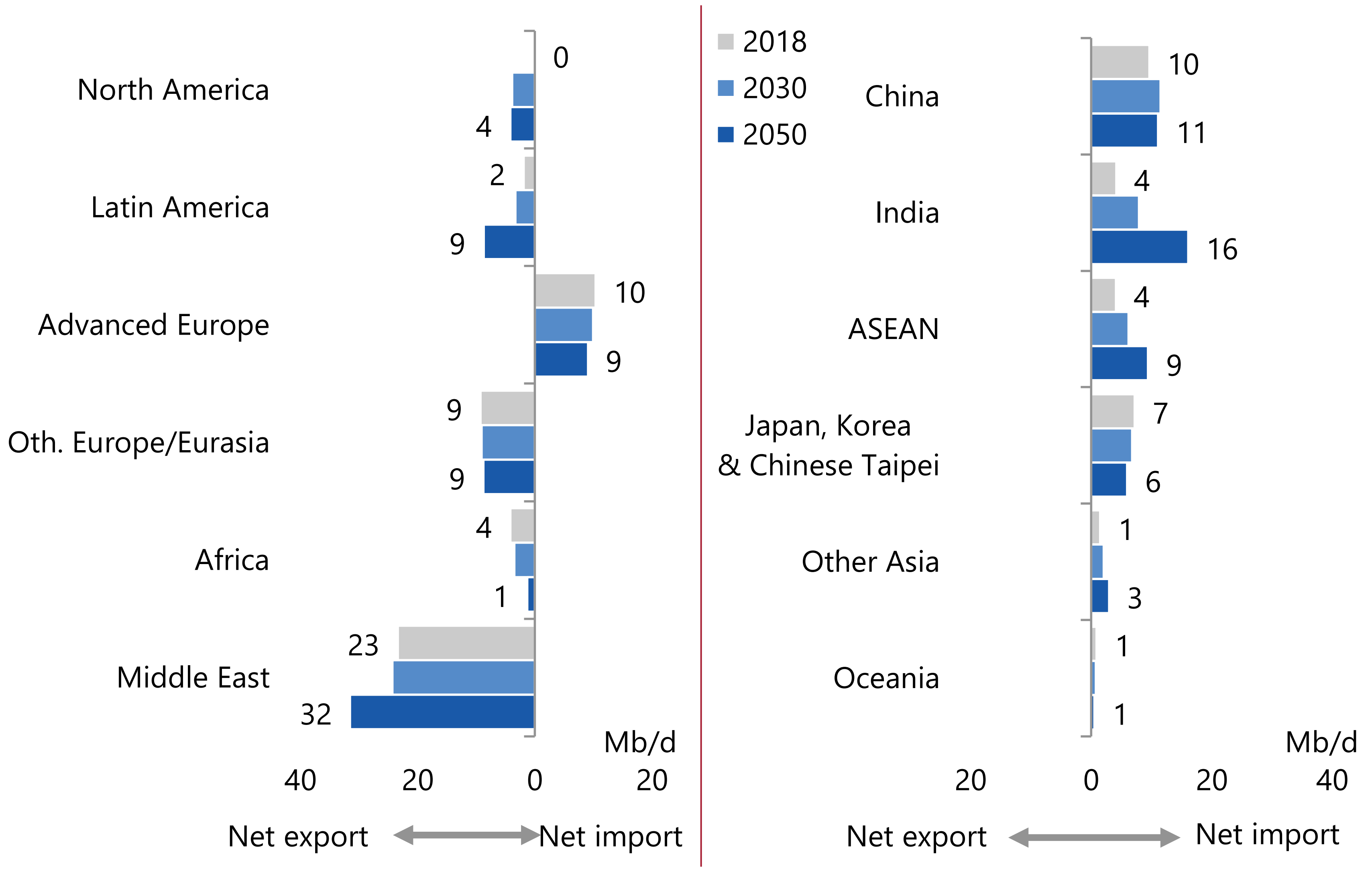


Crude oil production

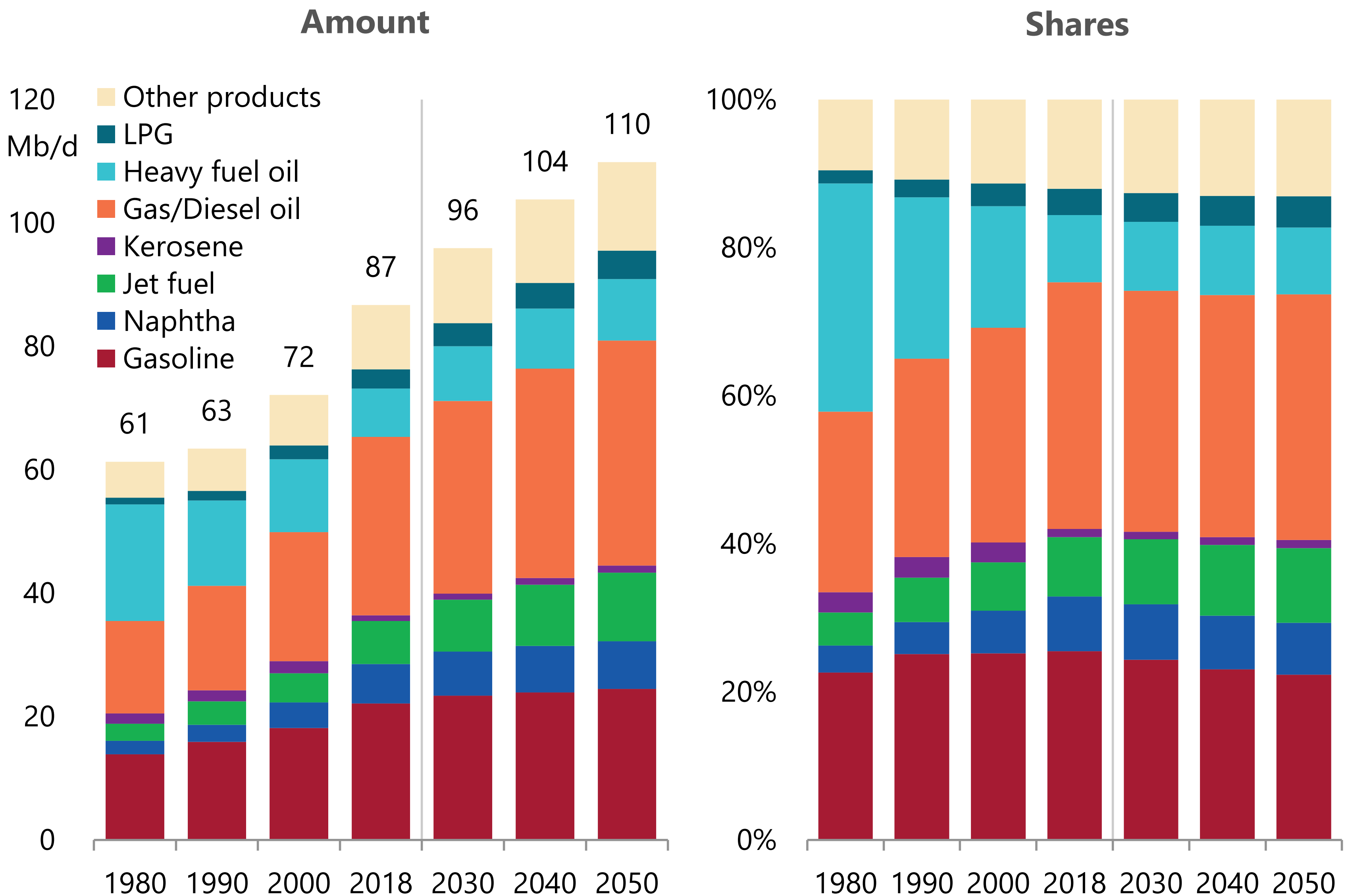




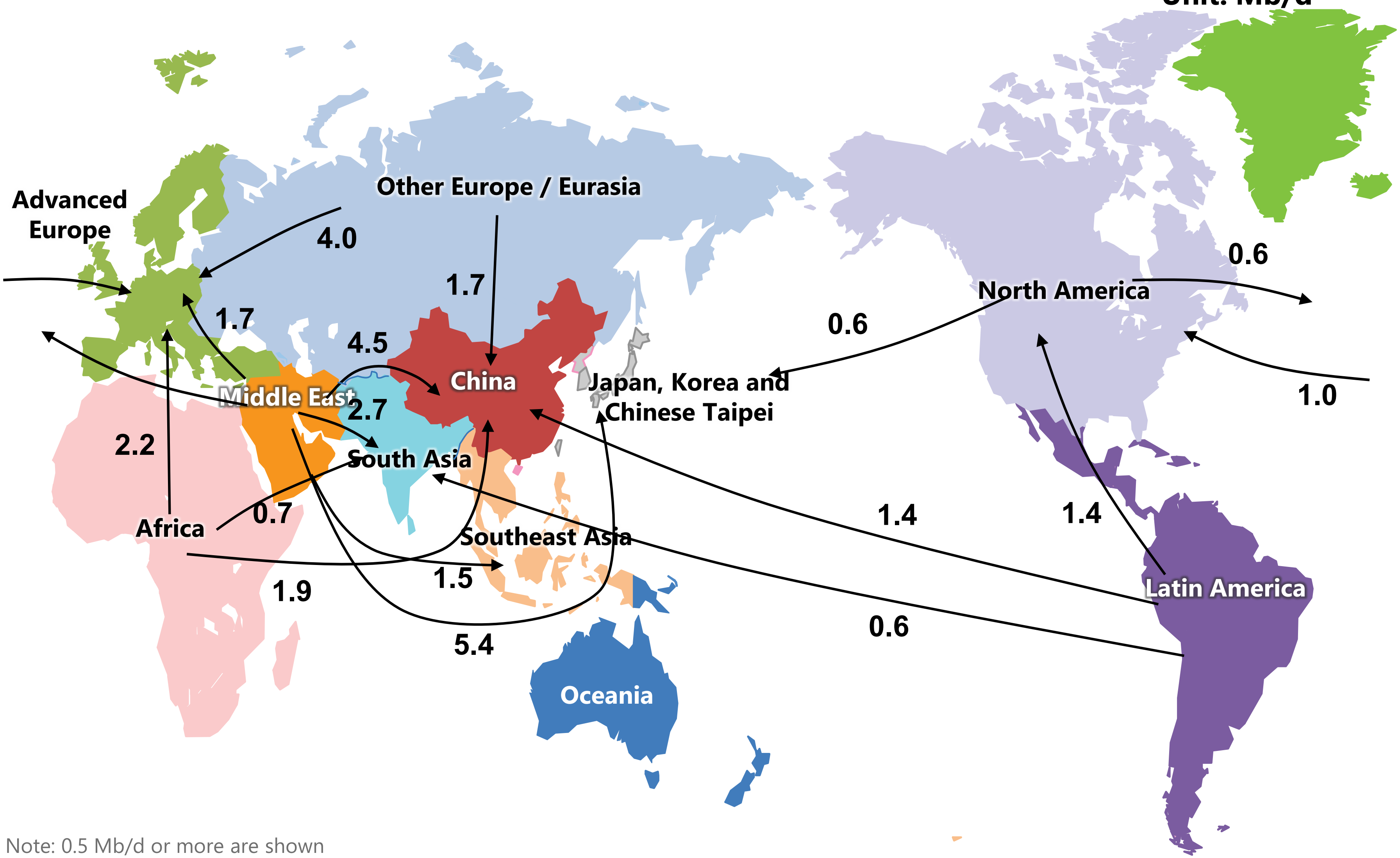
Net exports and imports of oil



Petroleum product consumption



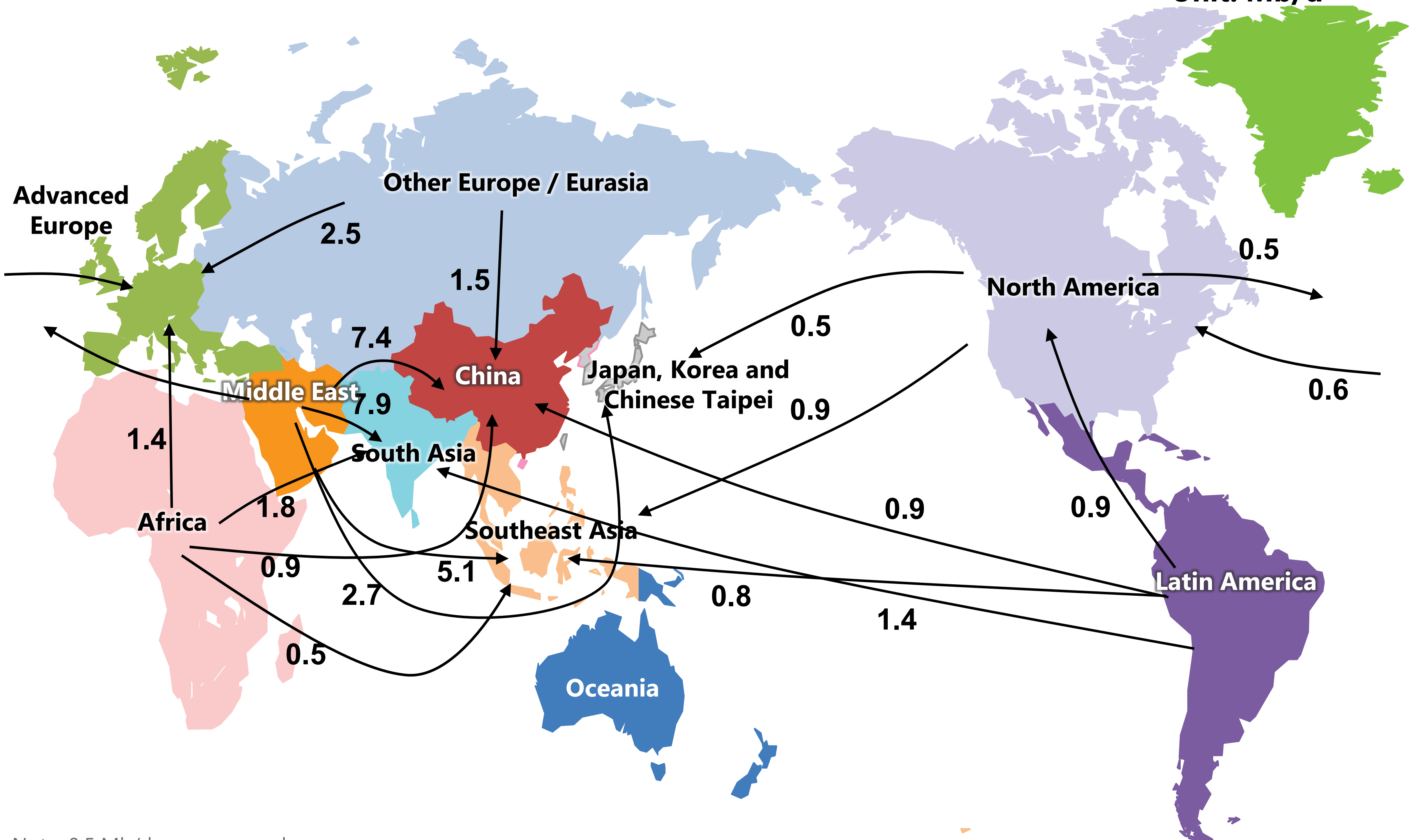
Major trade flows of crude oil (2019)



Note: 0.5 Mb/d or more are shown

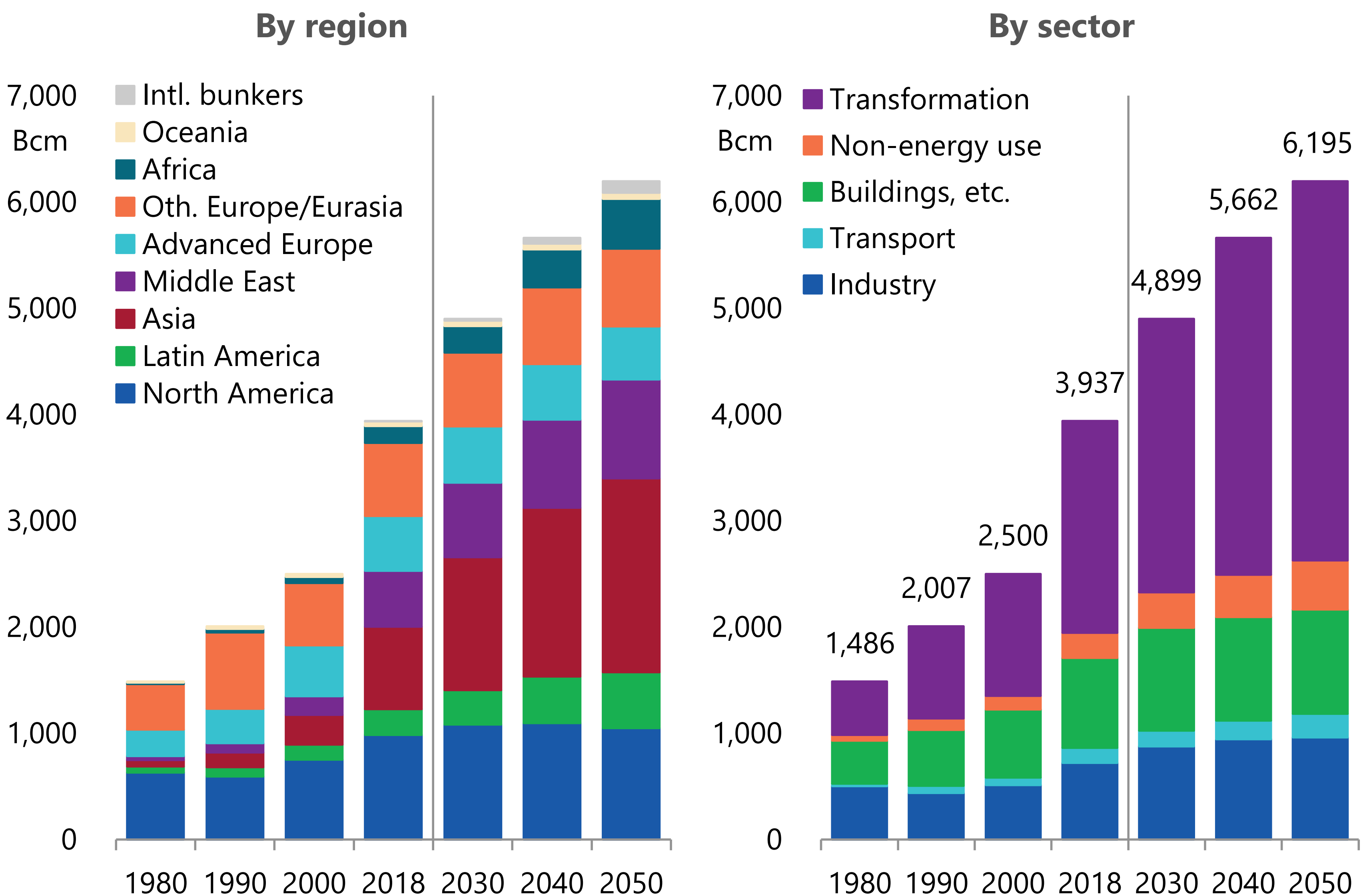
Reference Scenario

Major trade flows of crude oil (2050)



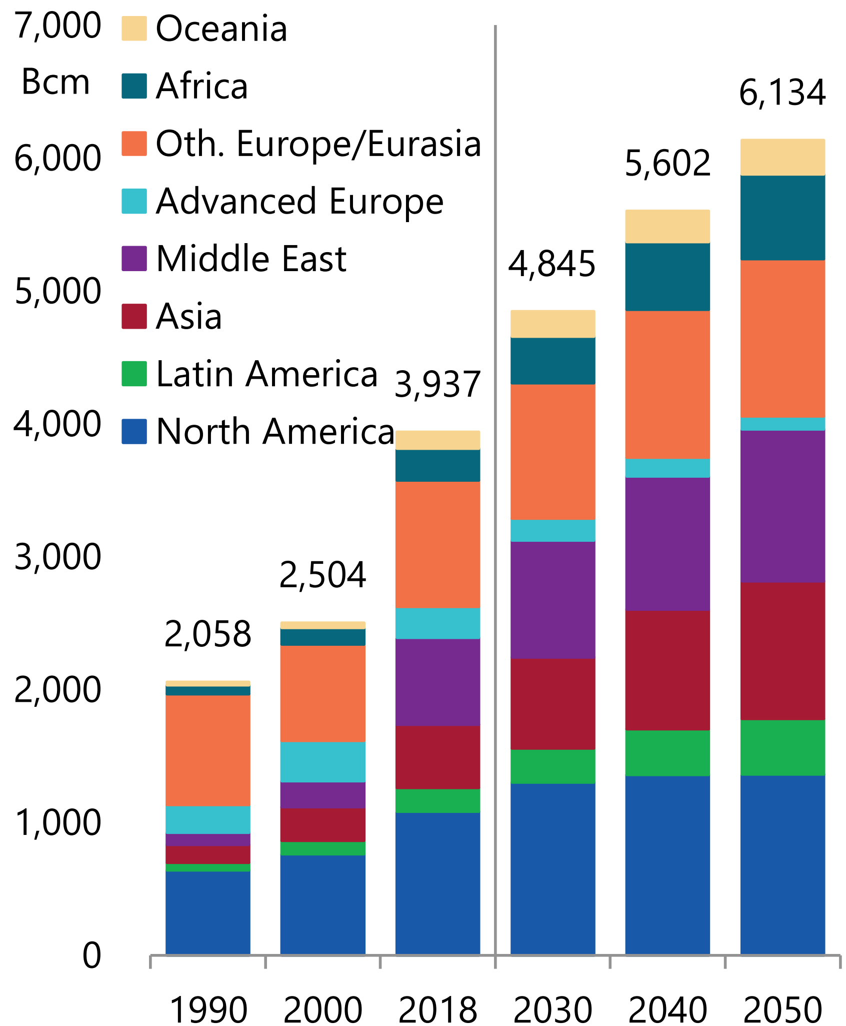
Note: 0.5 Mb/d or more are shown

Natural gas consumption

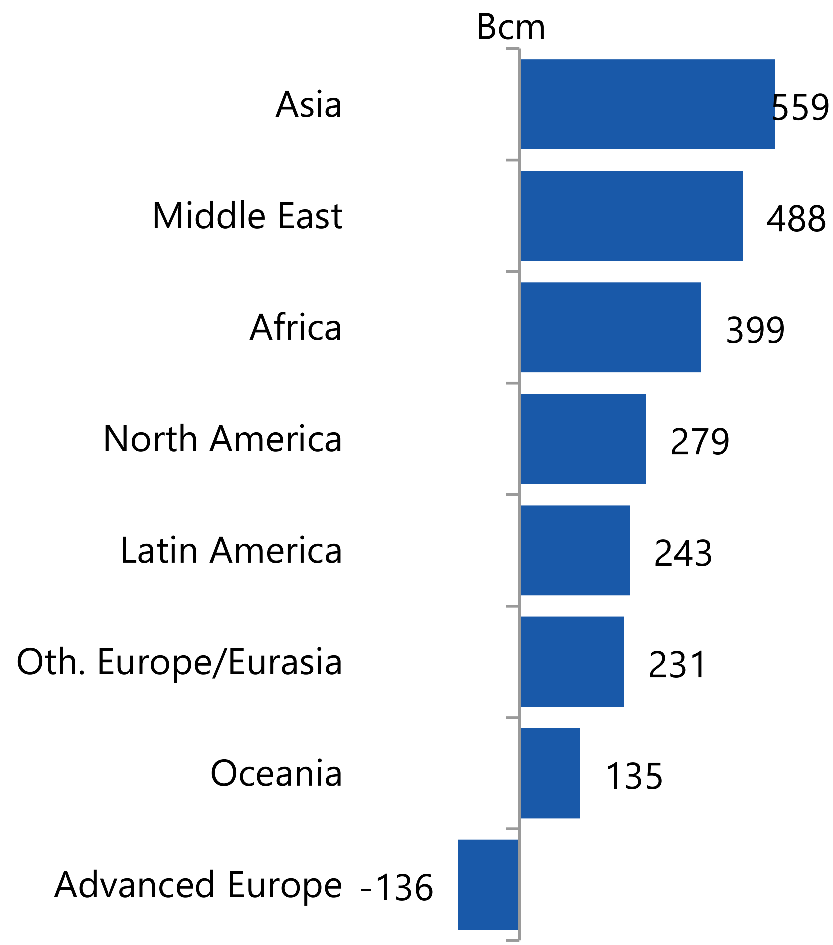


Natural gas production

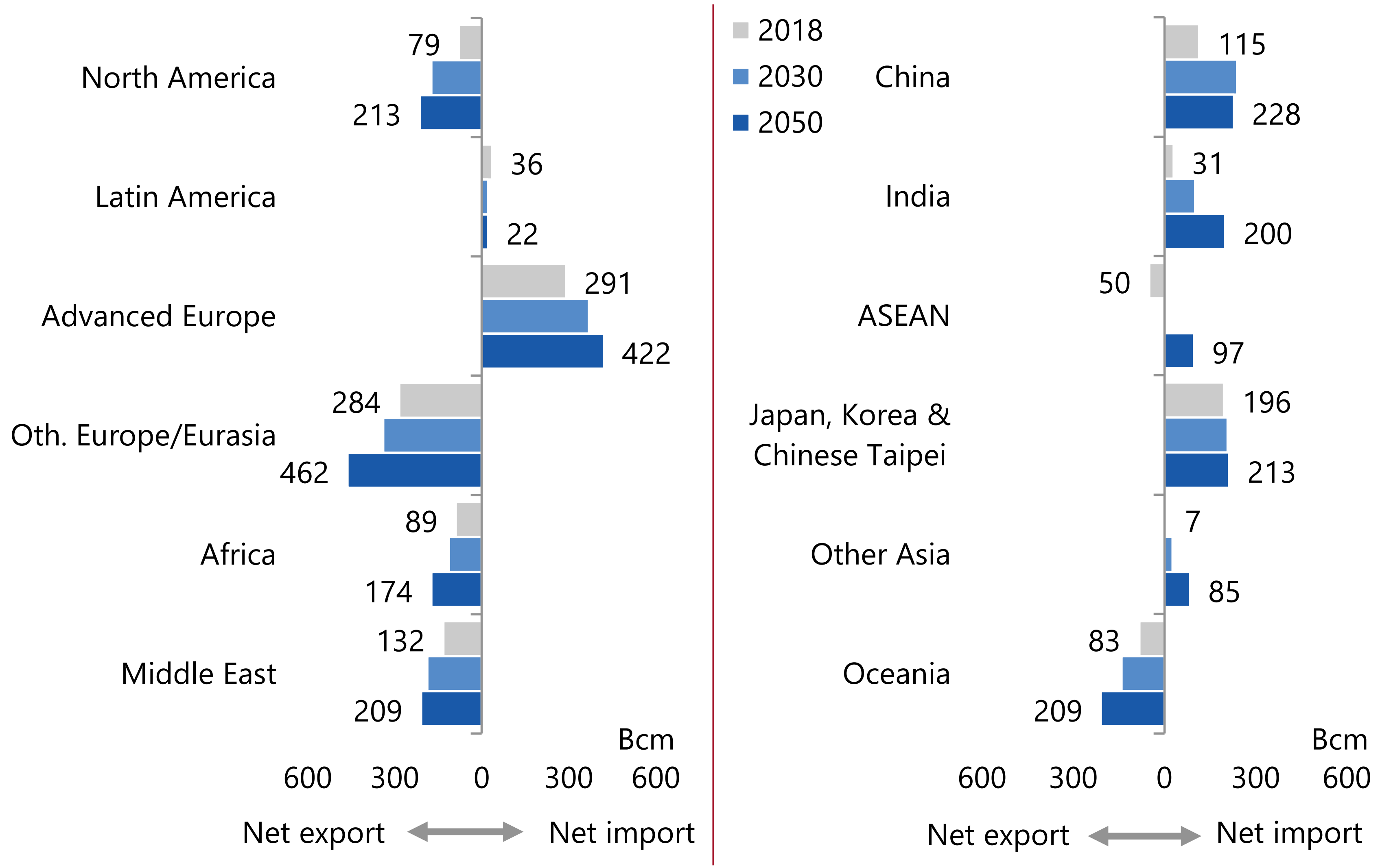
By region



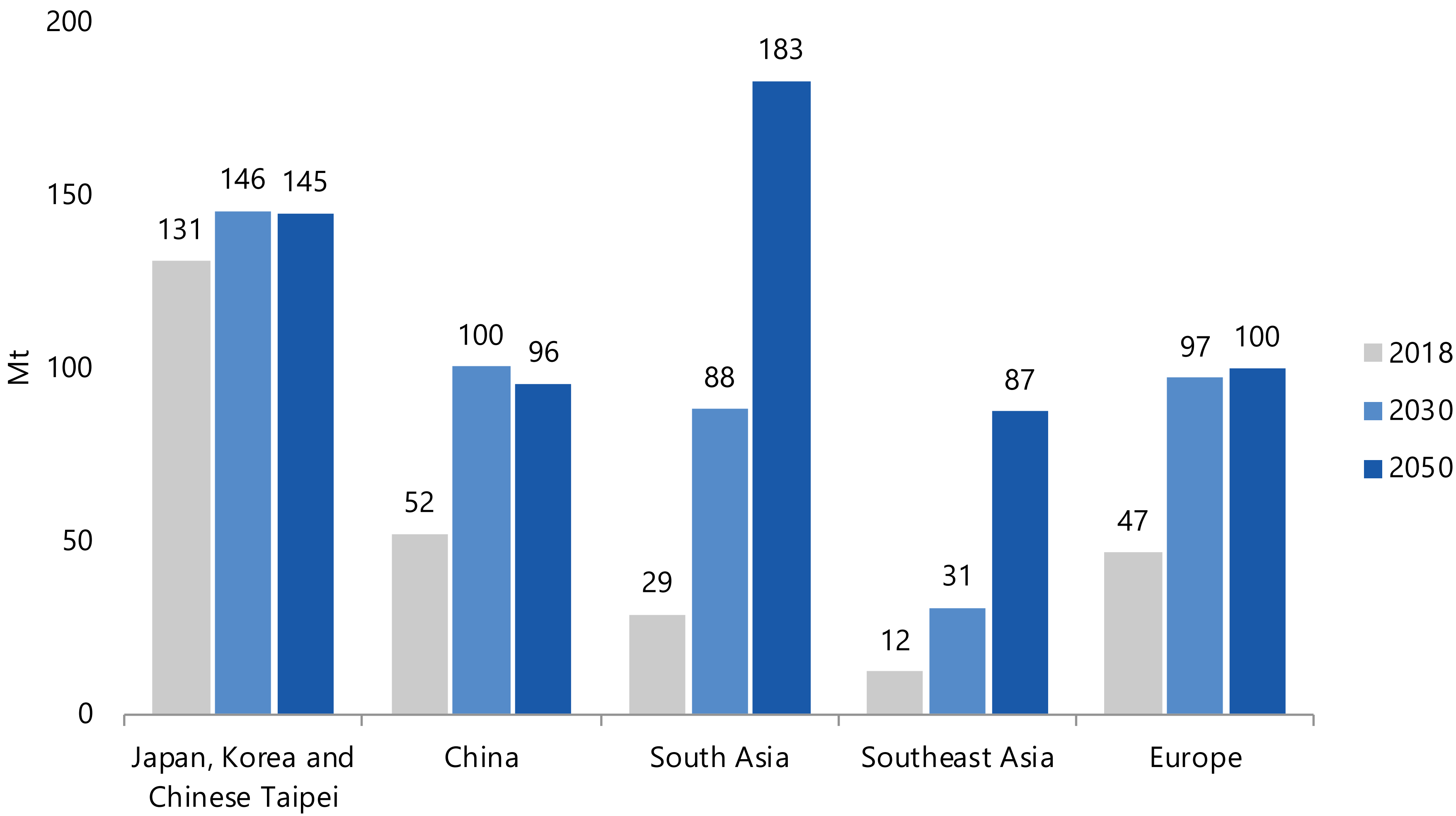
Changes (2018-2050)



Net exports and imports of natural gas

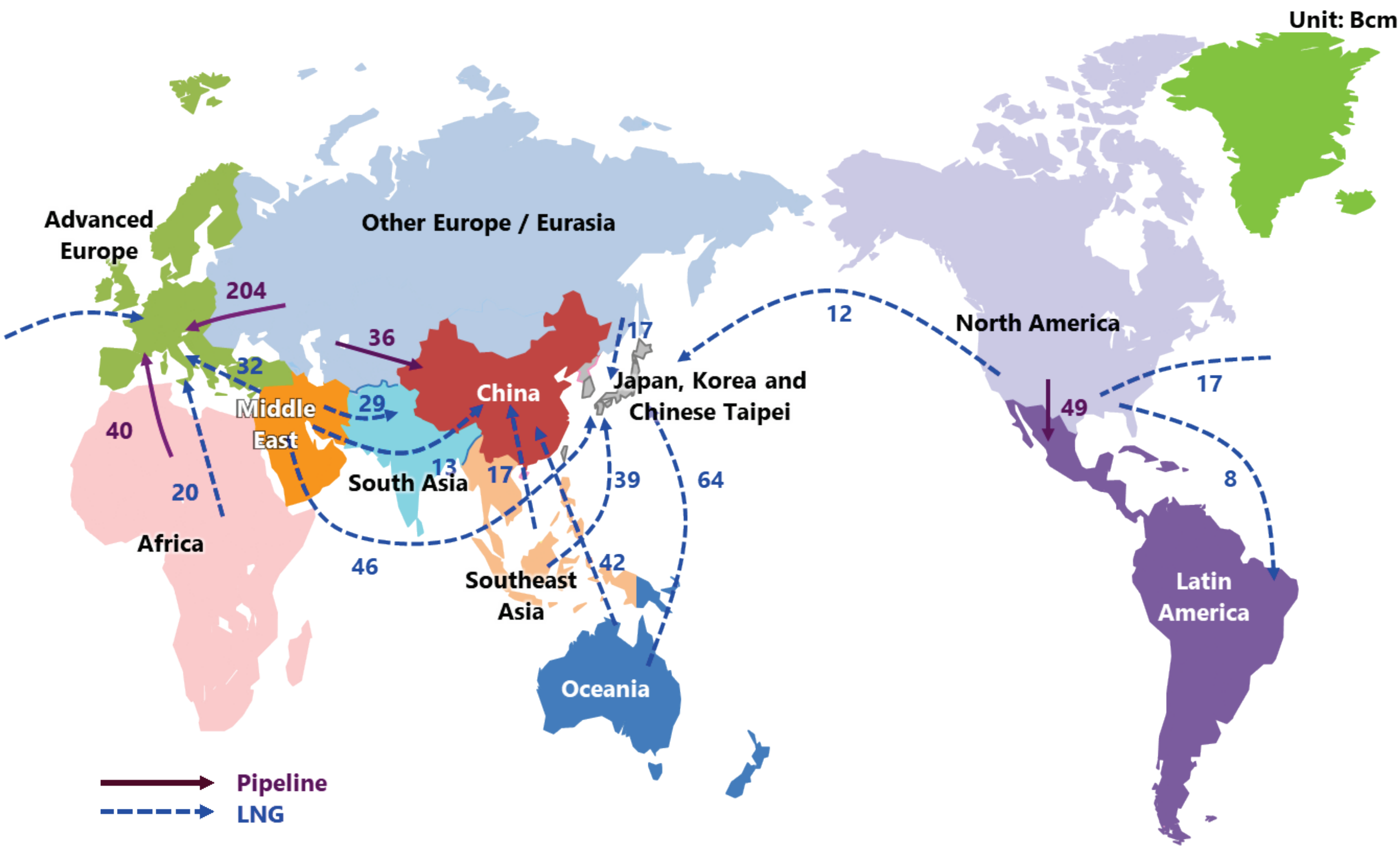


Net LNG imports in selected regions

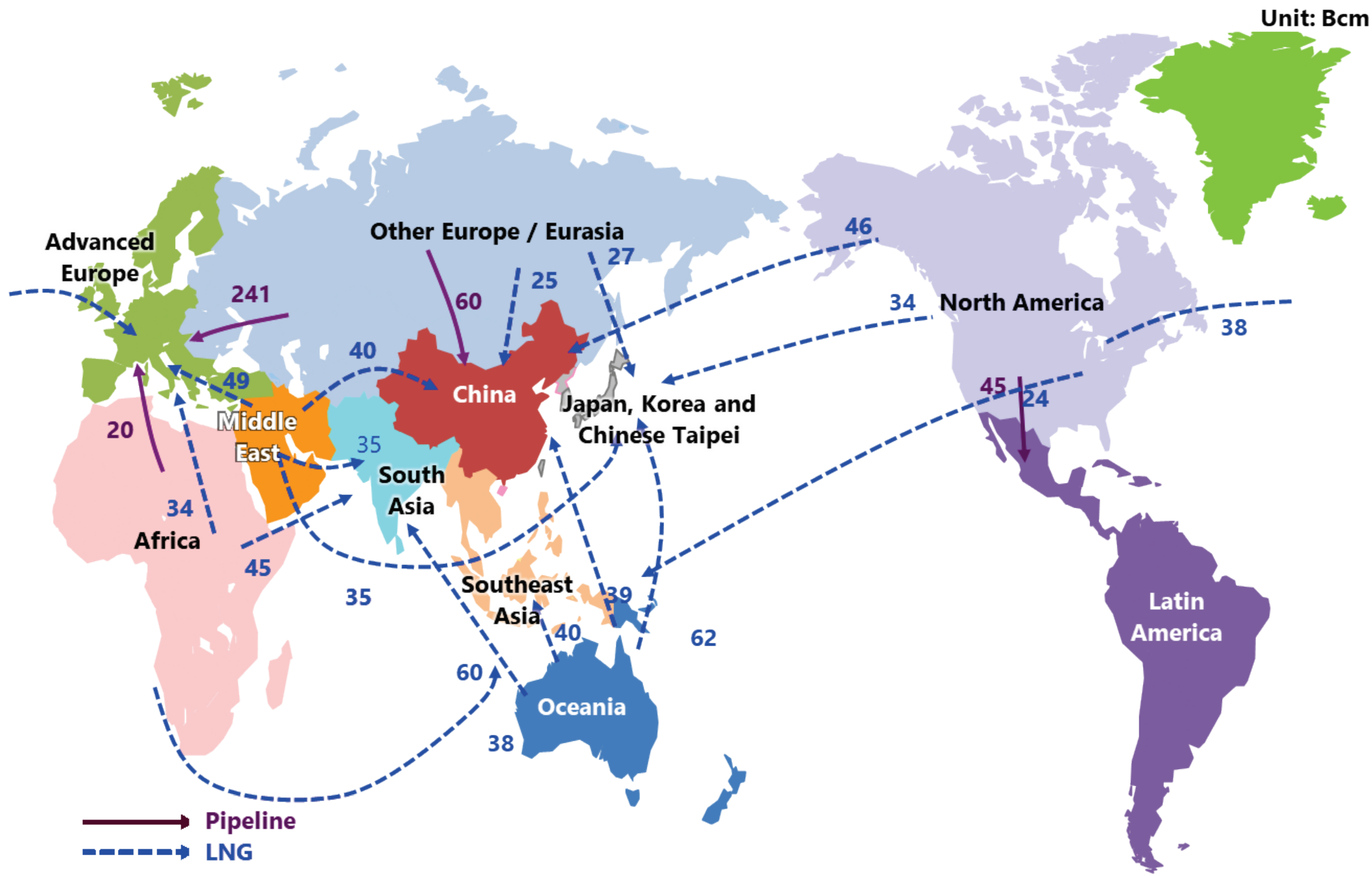


Note: does not include intra-regional trade

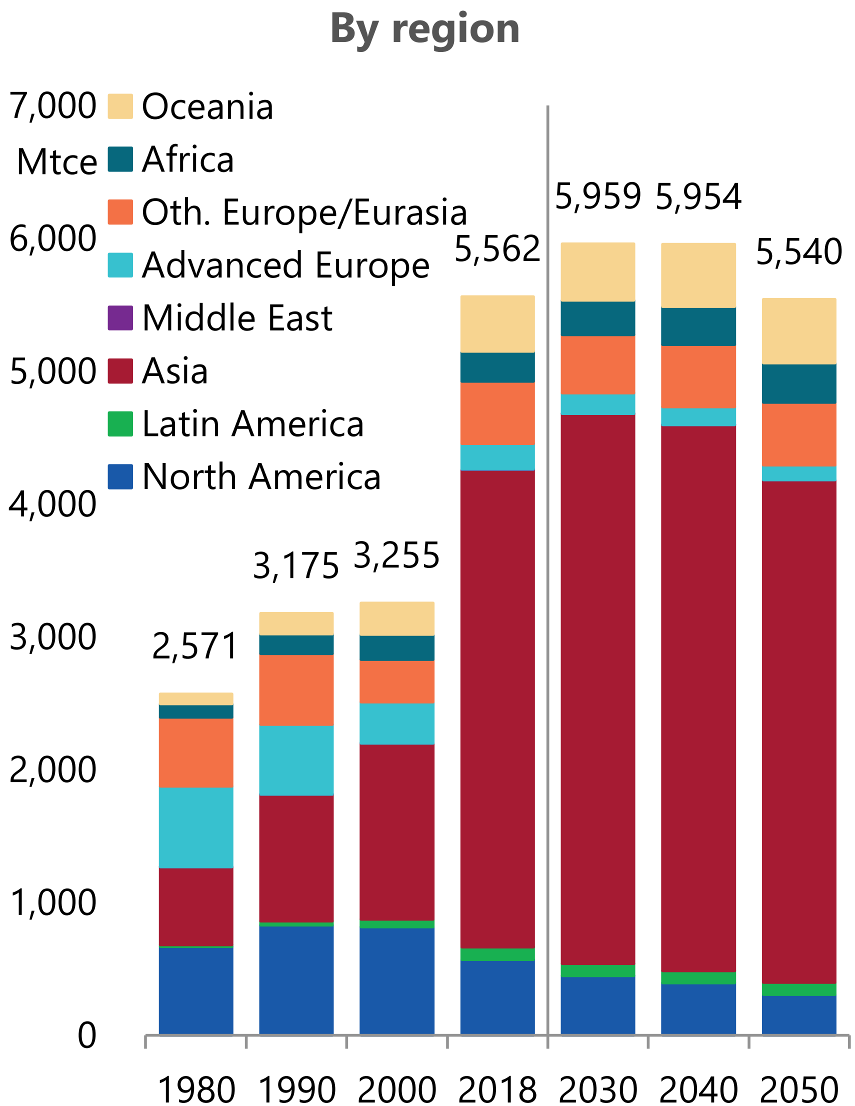
Major trade flows of natural gas (2019)

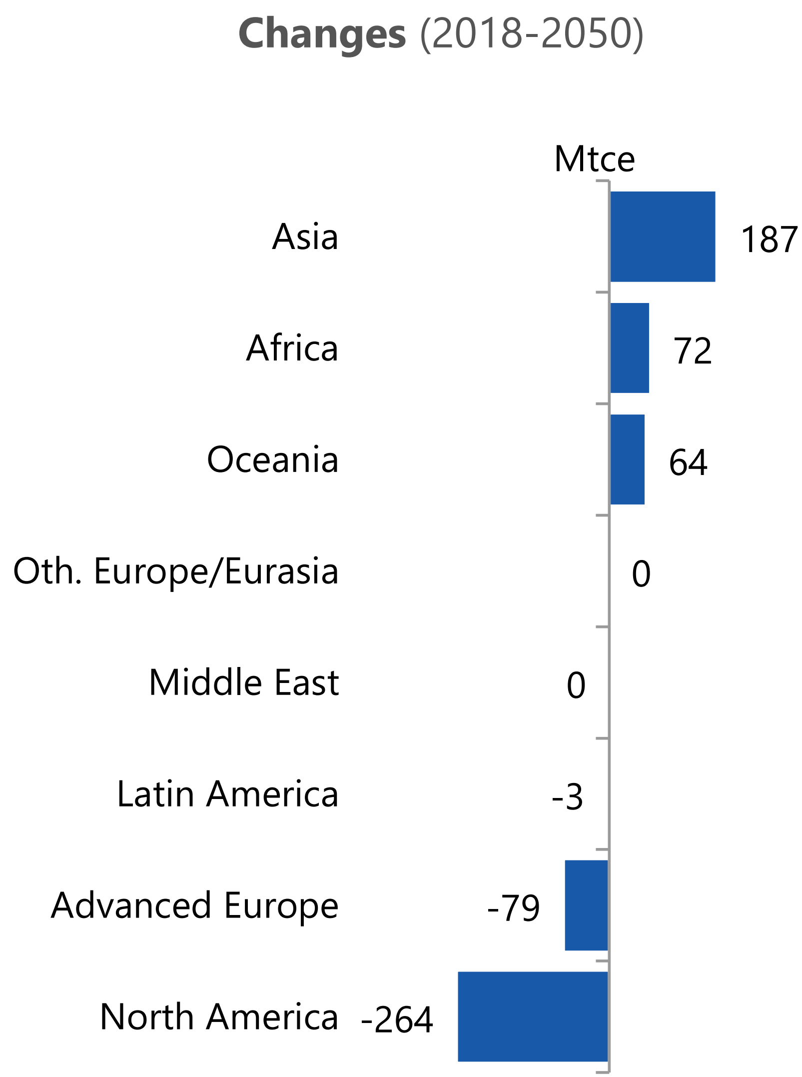


Major trade flows of natural gas (2050)

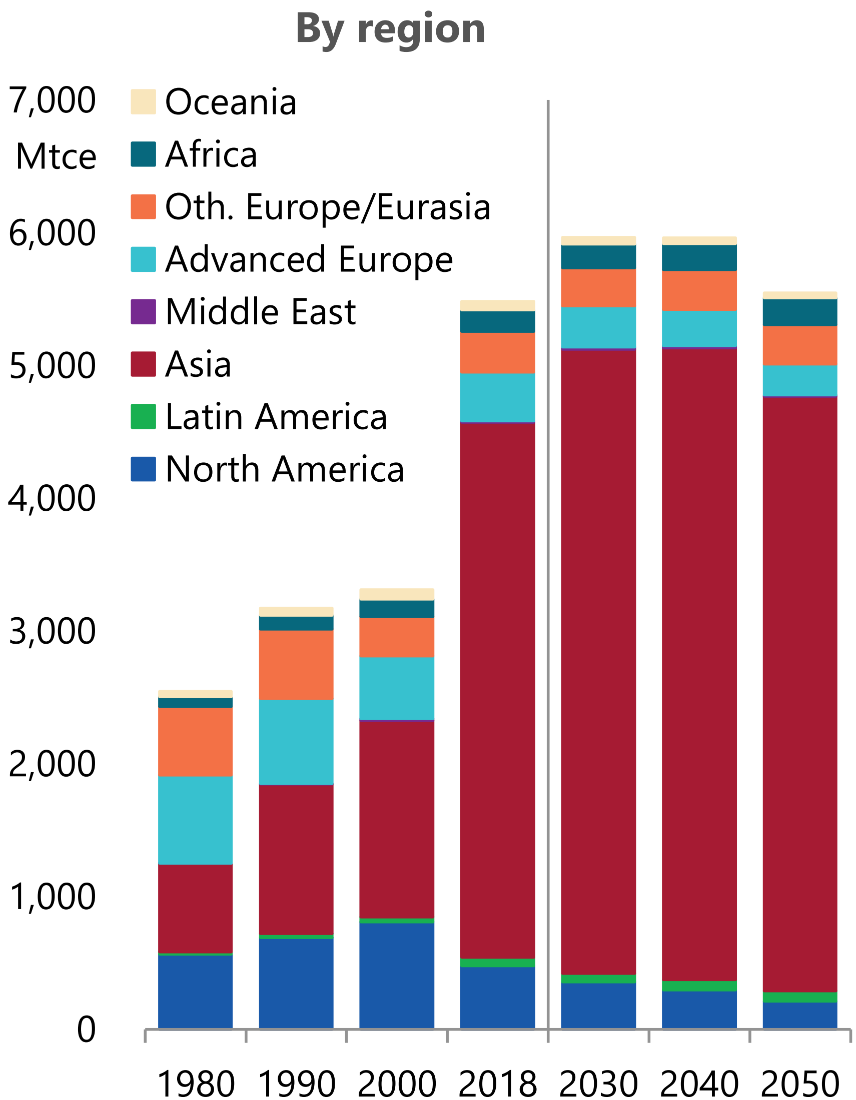


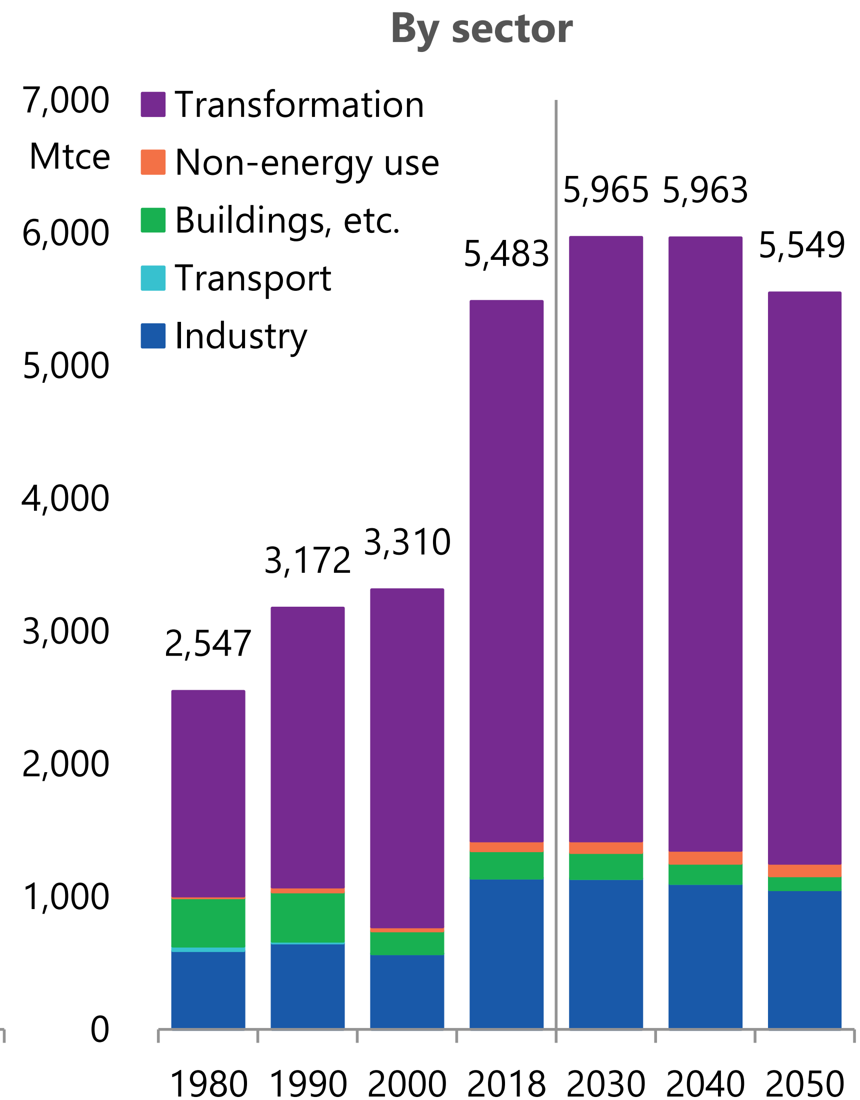
Coal production



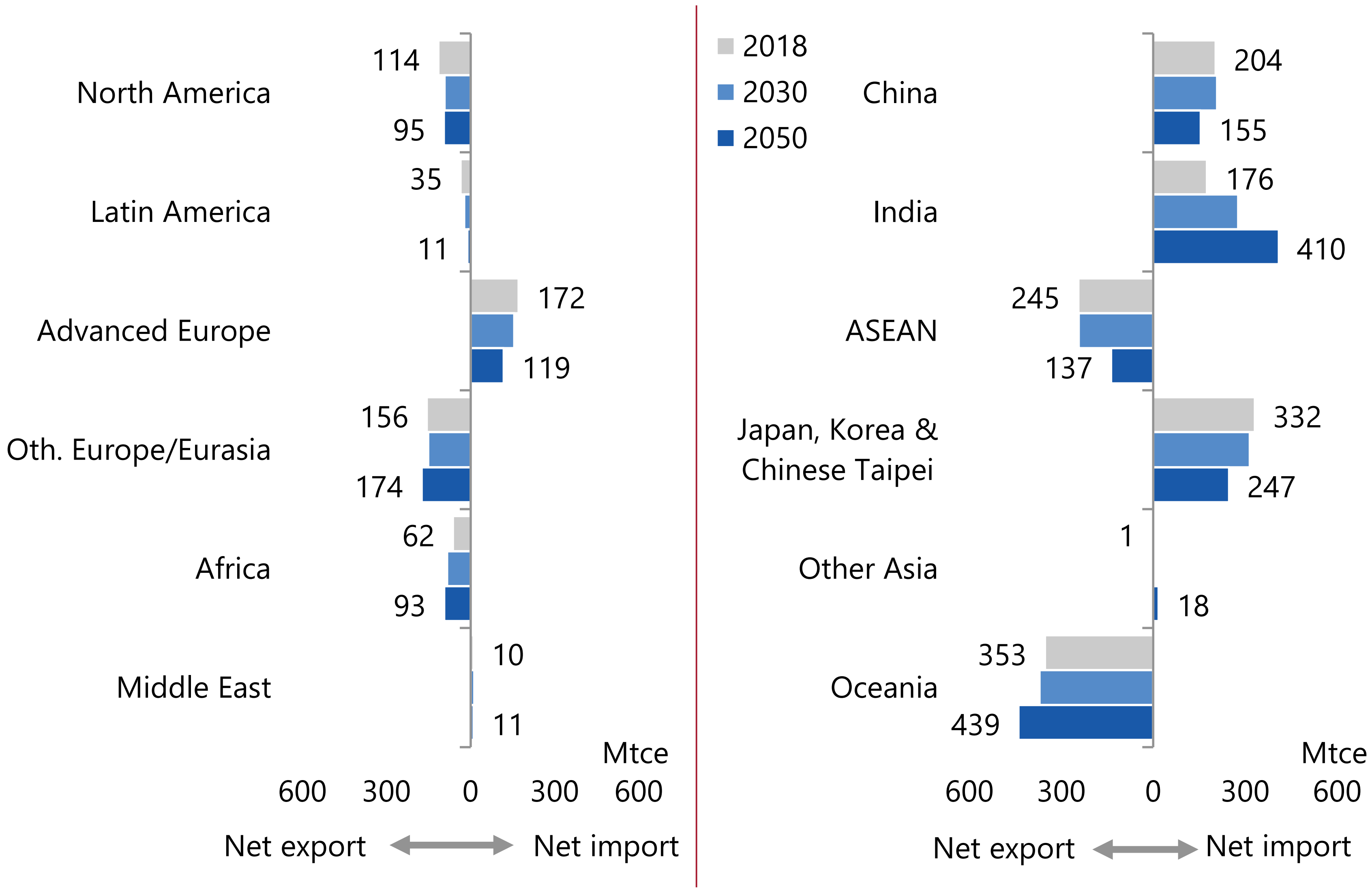


Coal consumption

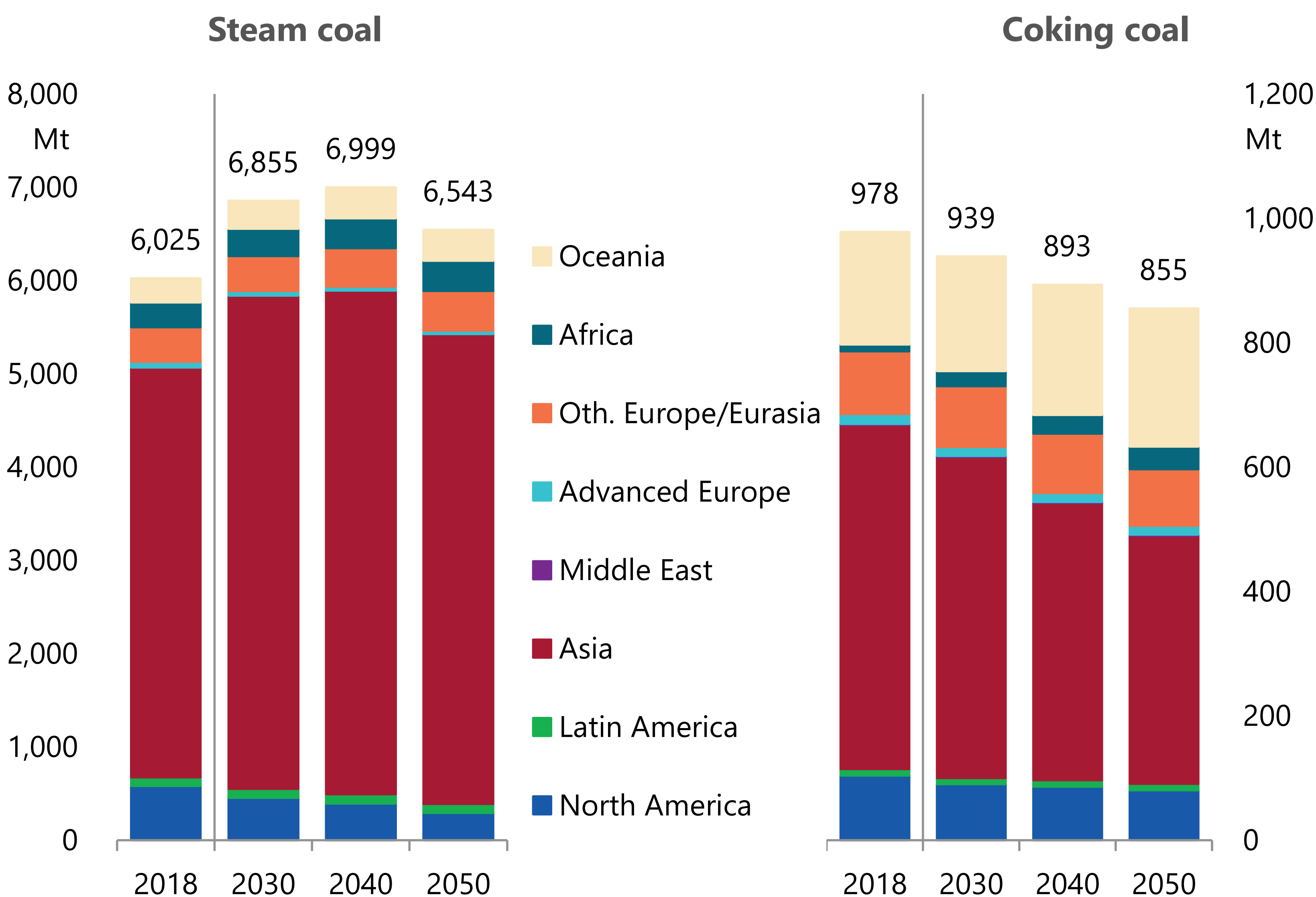




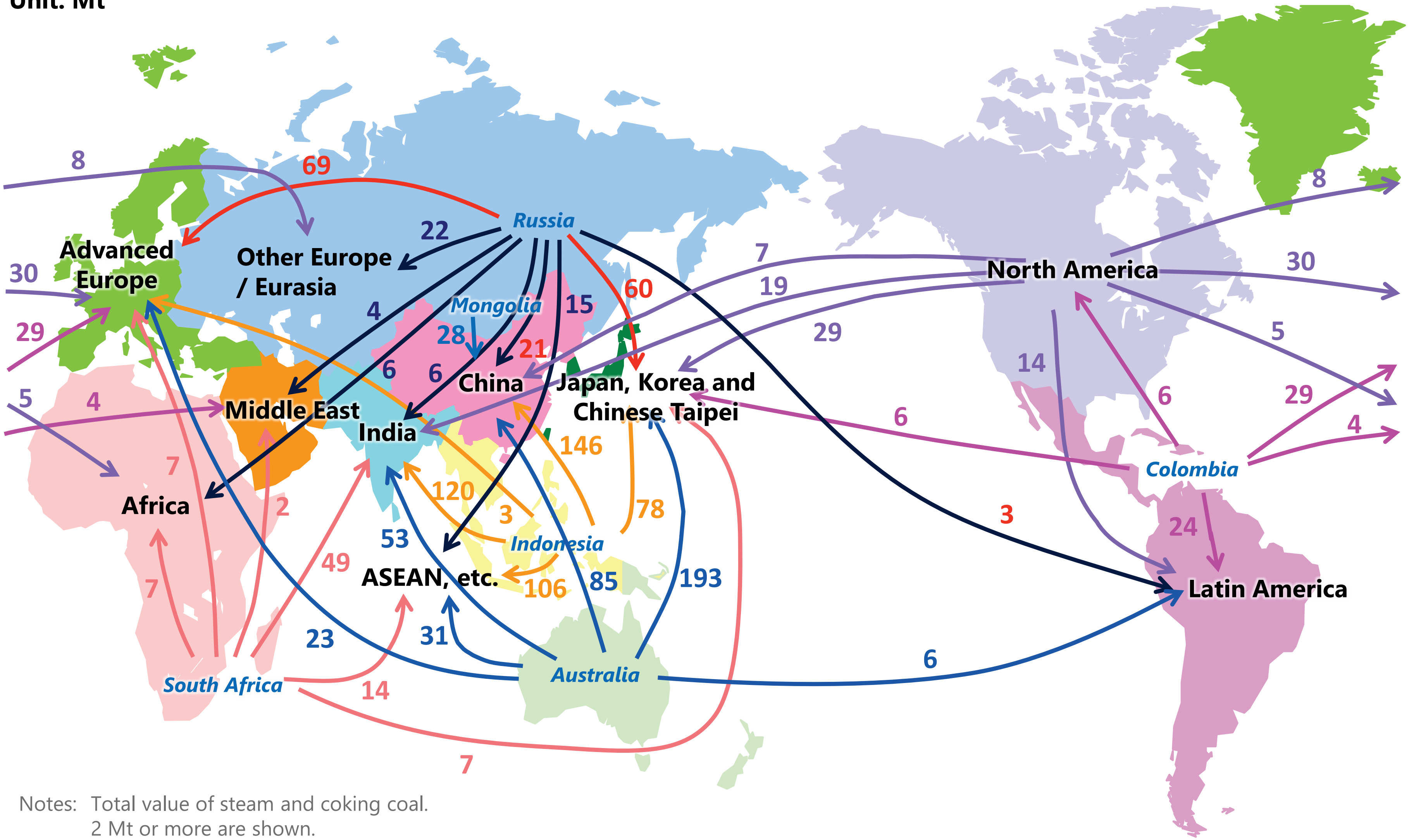
Net exports and imports of coal



Coal production (steam and coking coal)



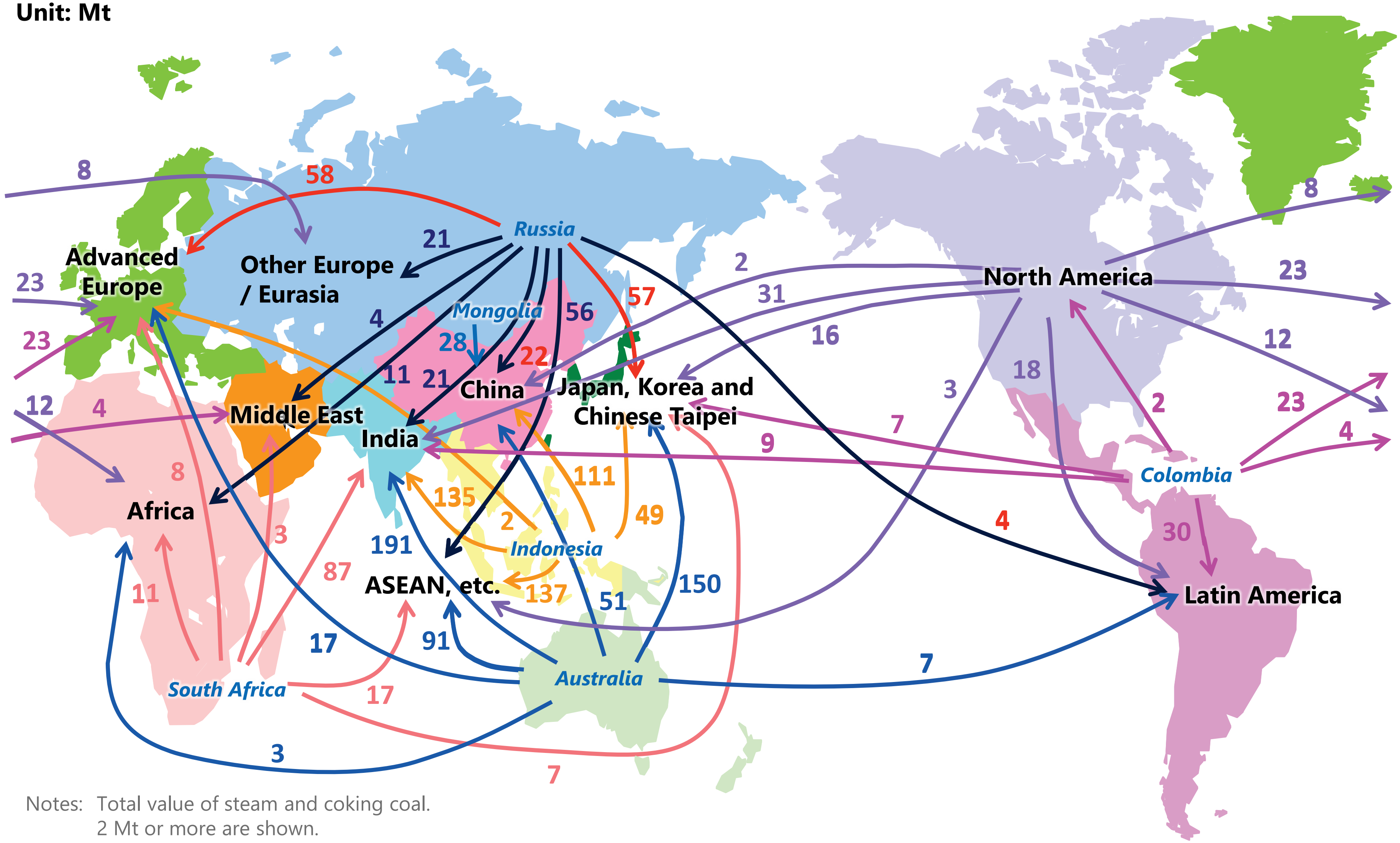
Major trade flows of steam and coking coal (2019)



Notes: Total value of steam and coking coal.
2 Mt or more are shown.
South Africa includes Mozambique.

Major trade flows of steam and coking coal (2050)

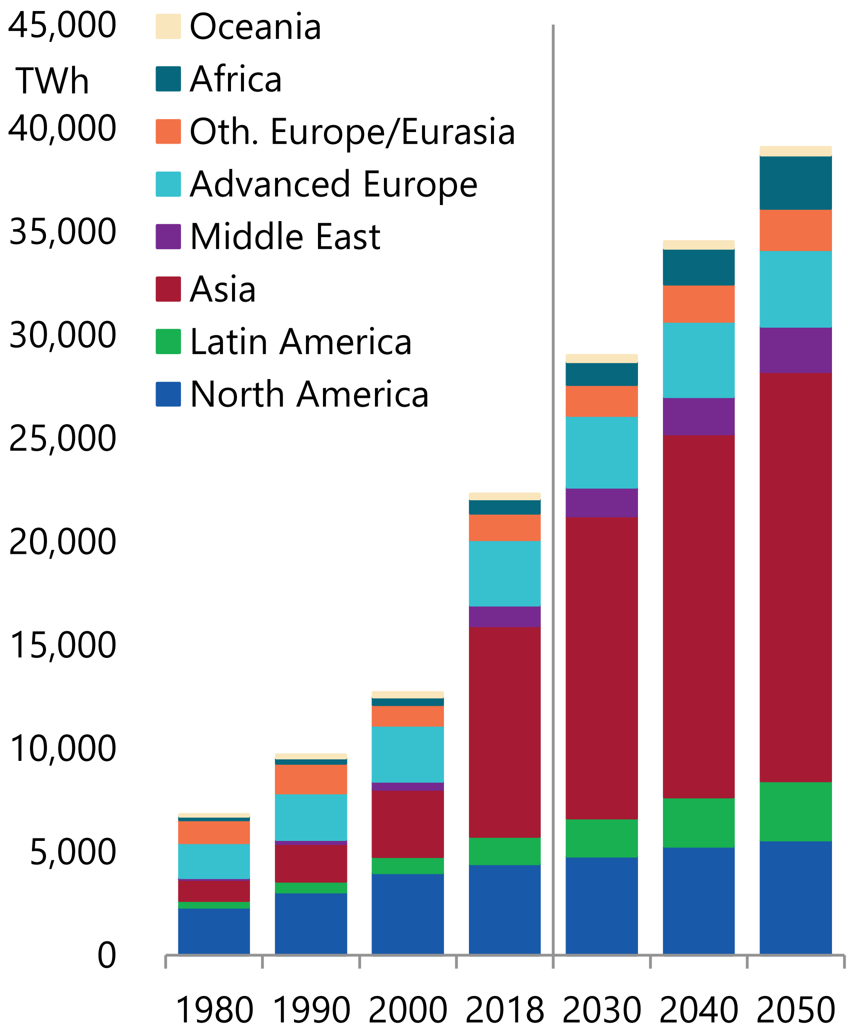
Unit: Mt



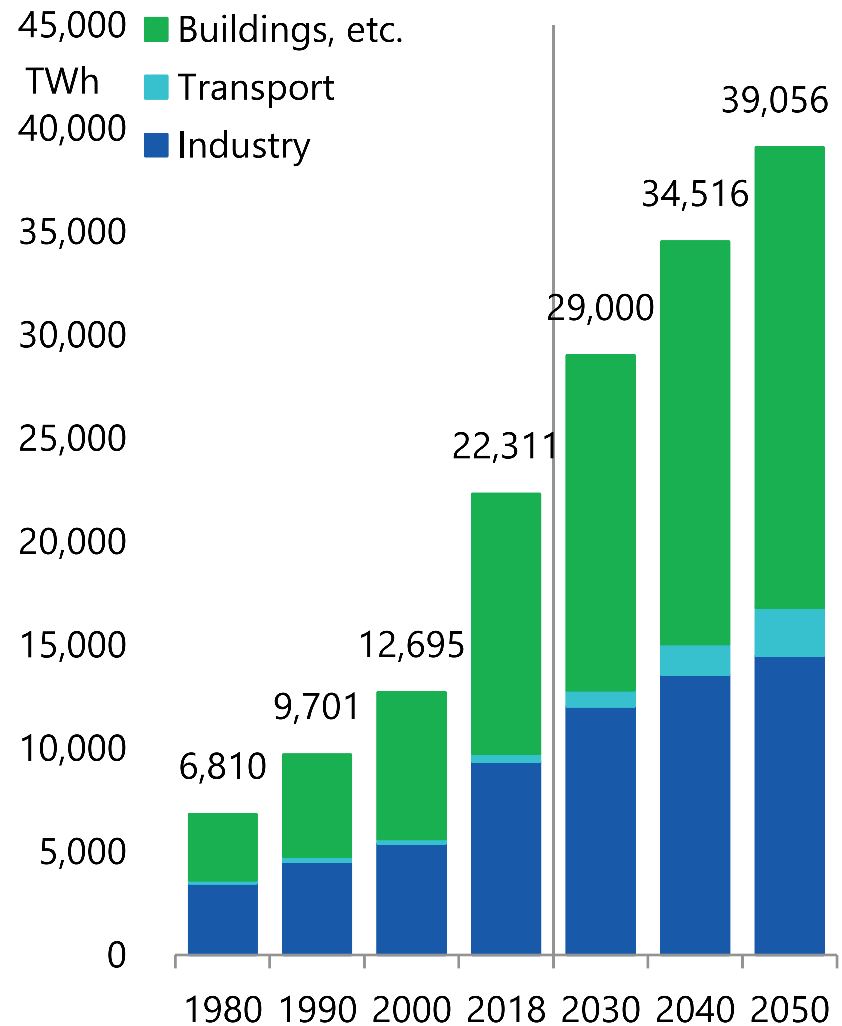
Notes: Total value of steam and coking coal.
2 Mt or more are shown.
South Africa includes Mozambique.

Final consumption of electricity

By region

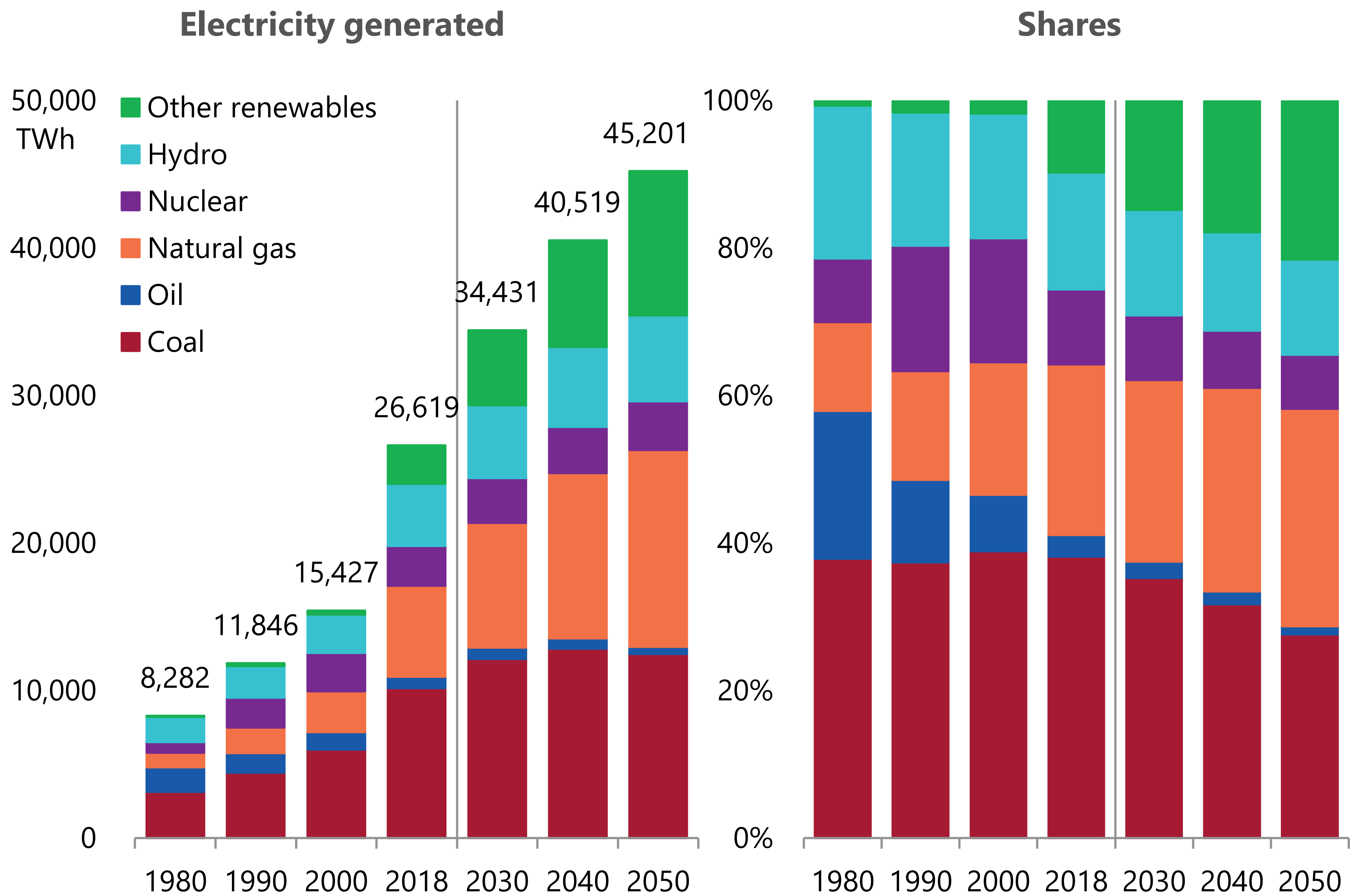


By sector



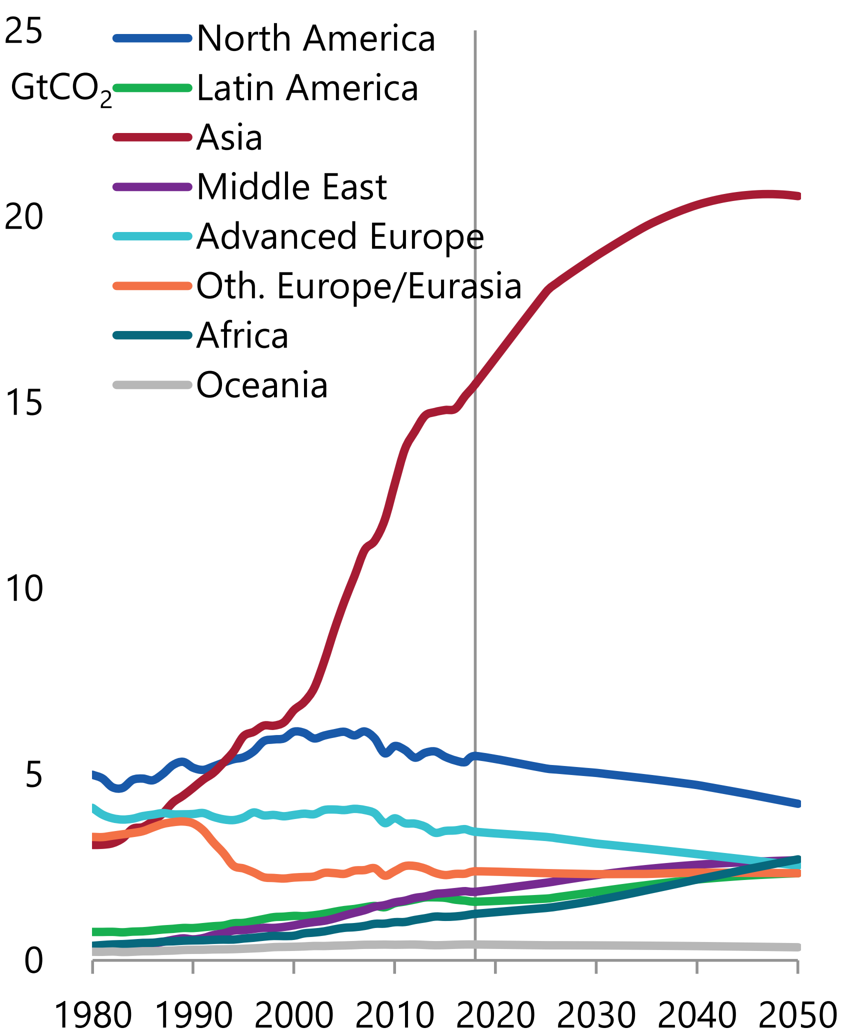
Power generation mix

IEE JAPAN

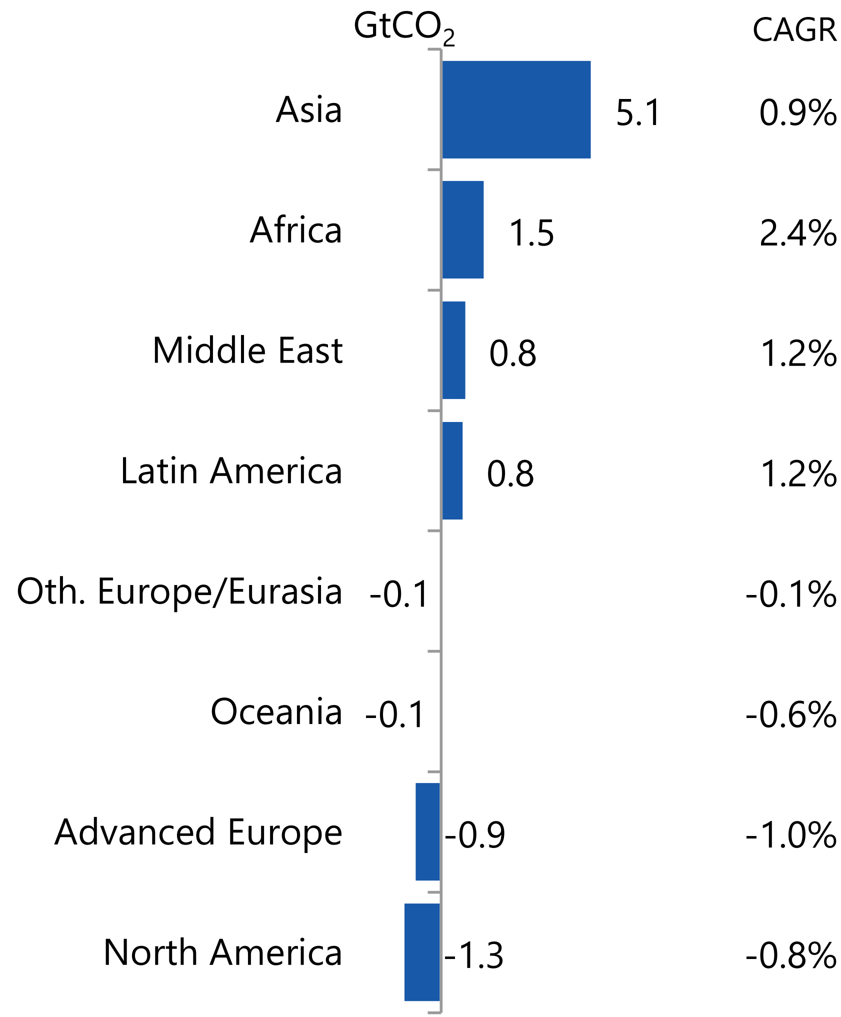


Energy-related CO_2 emissions

Emissions



Changes (2018-2050)

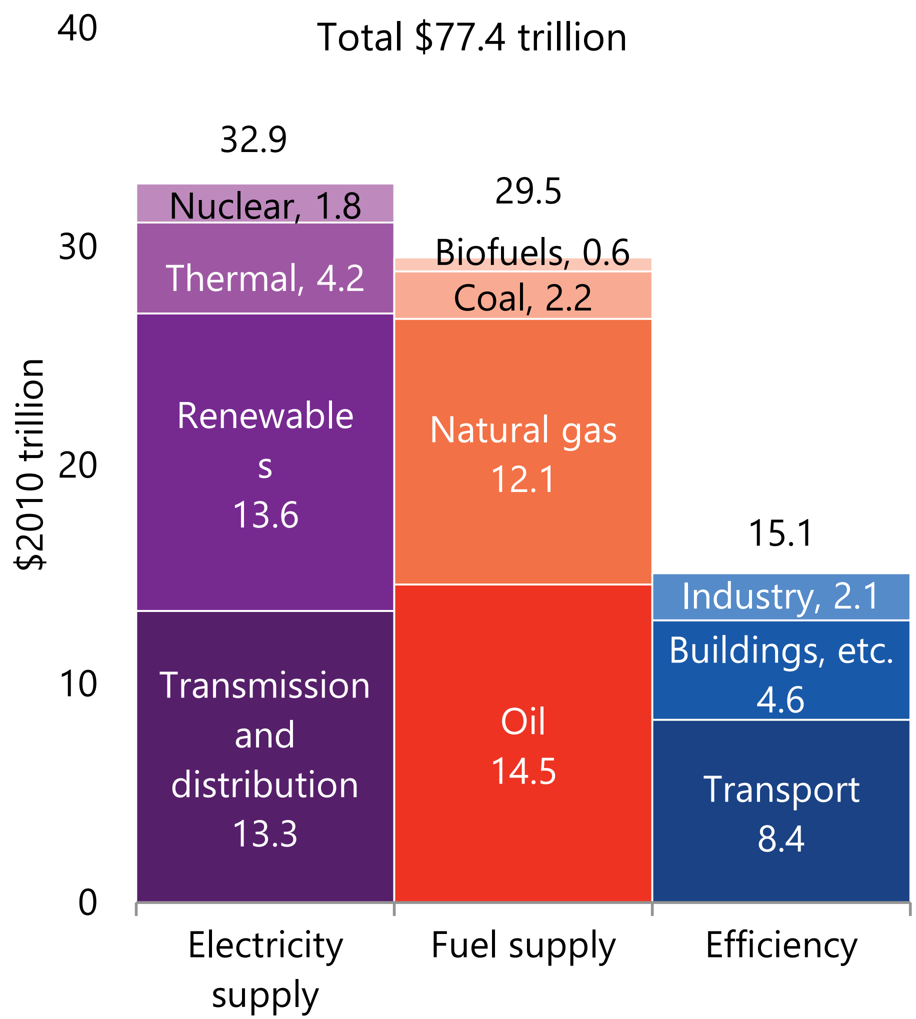


Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.

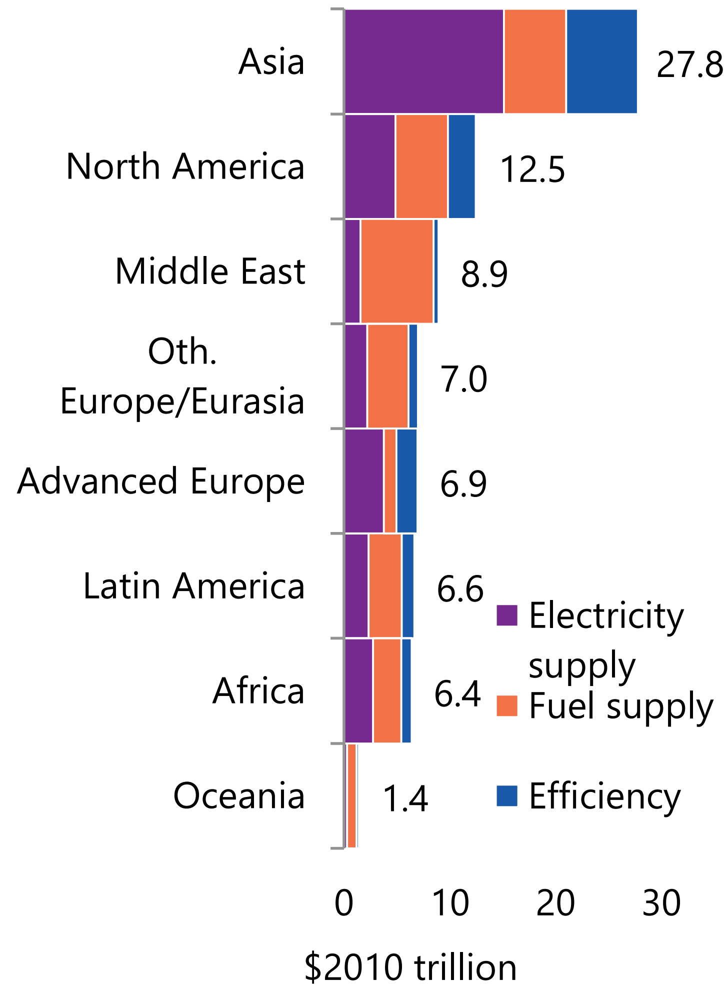
Reference Scenario

Energy-related investments (2019 – 2050)

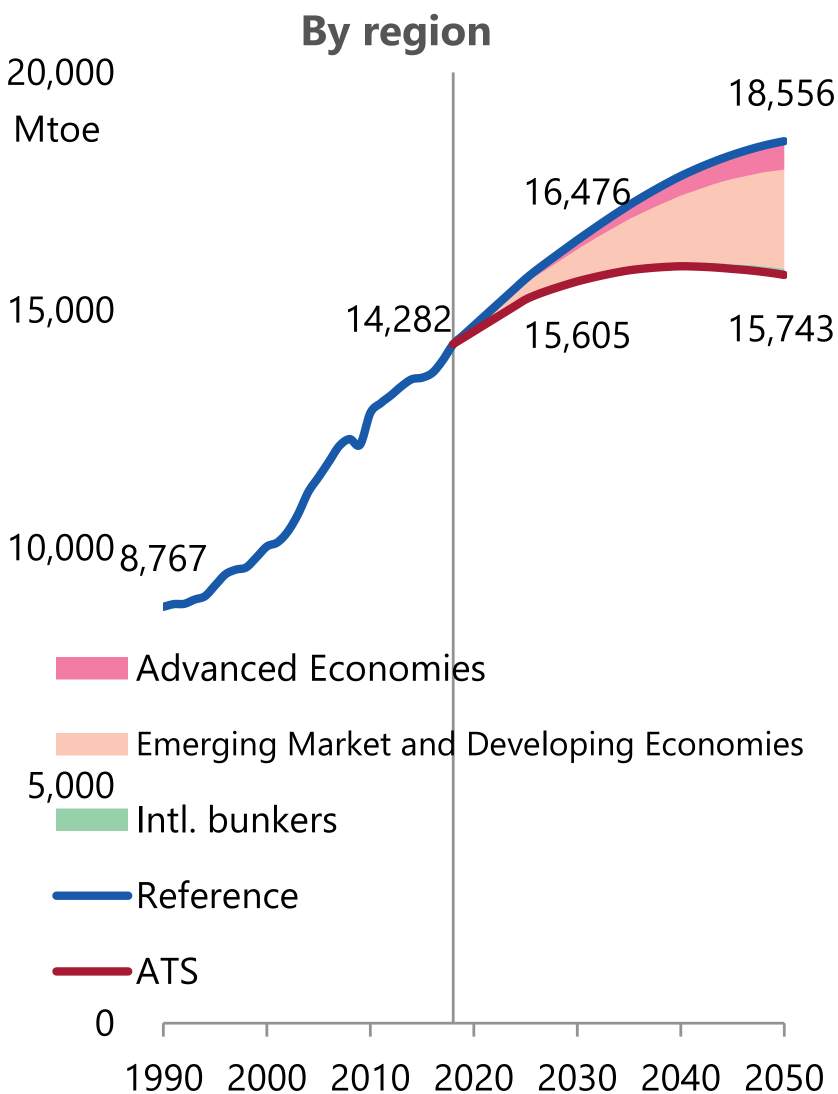
By sector



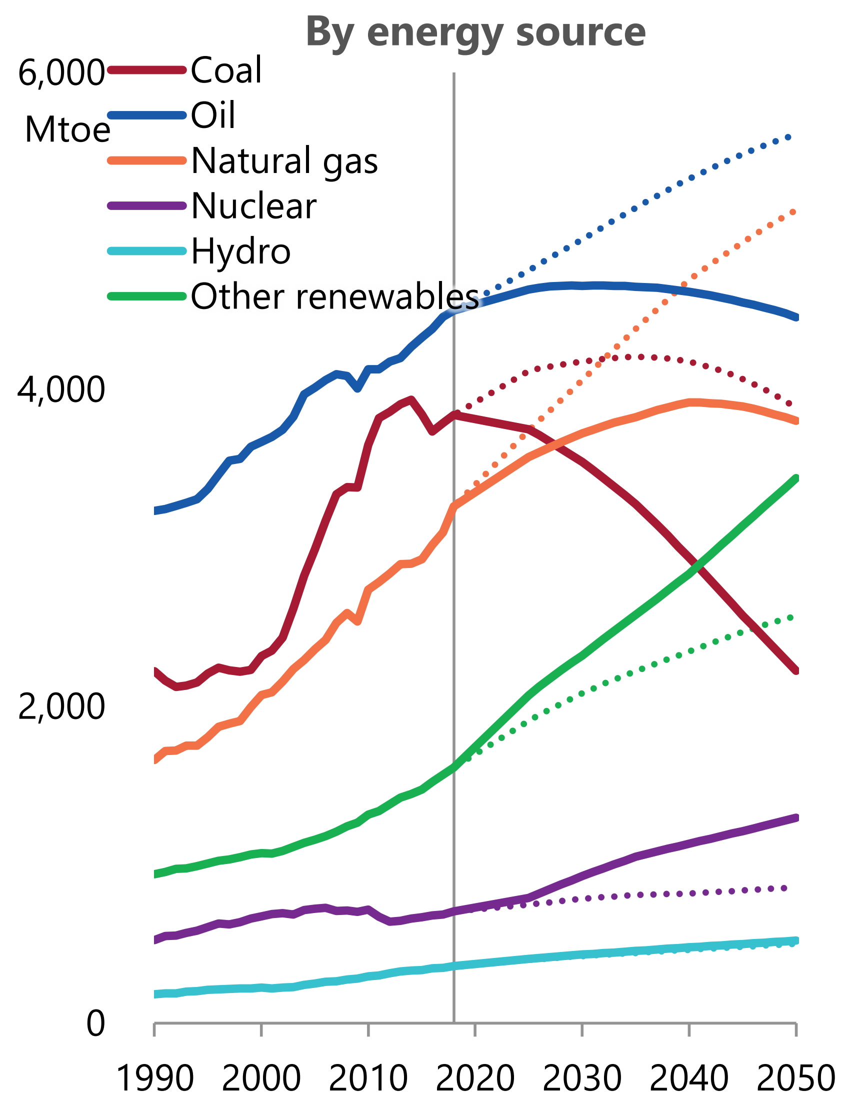
By region



Primary energy consumption

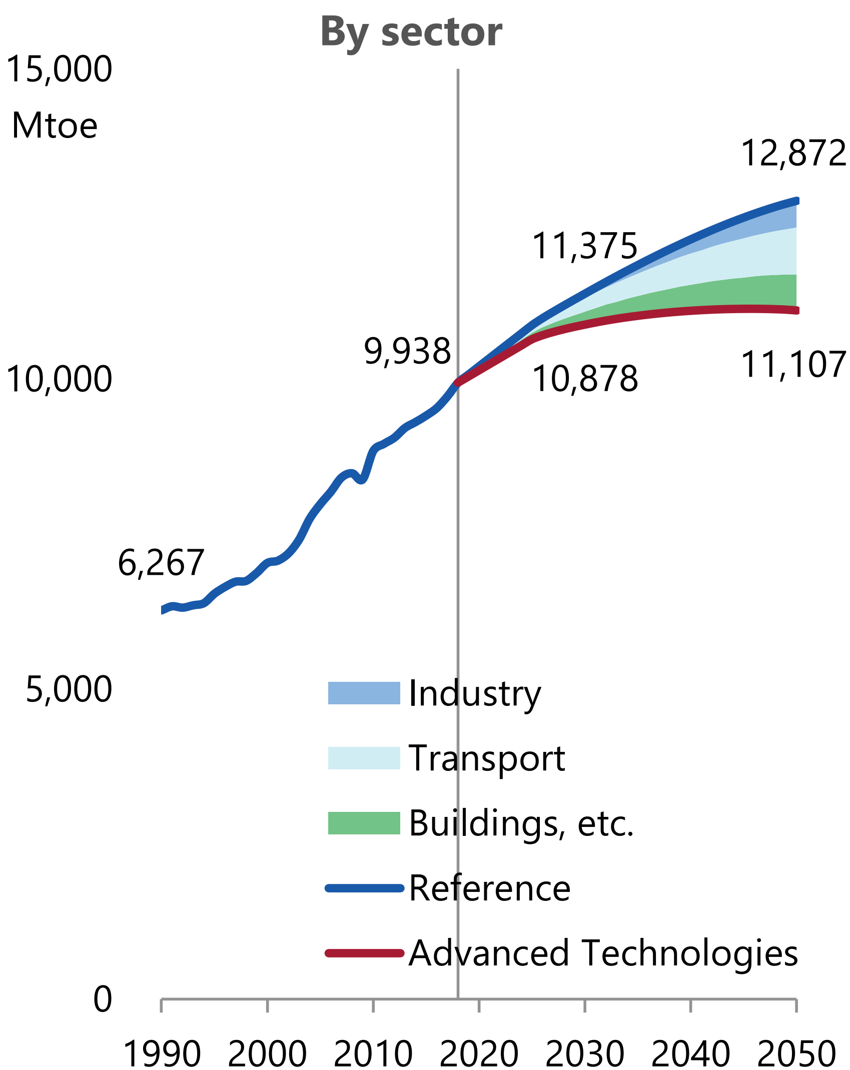


Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.

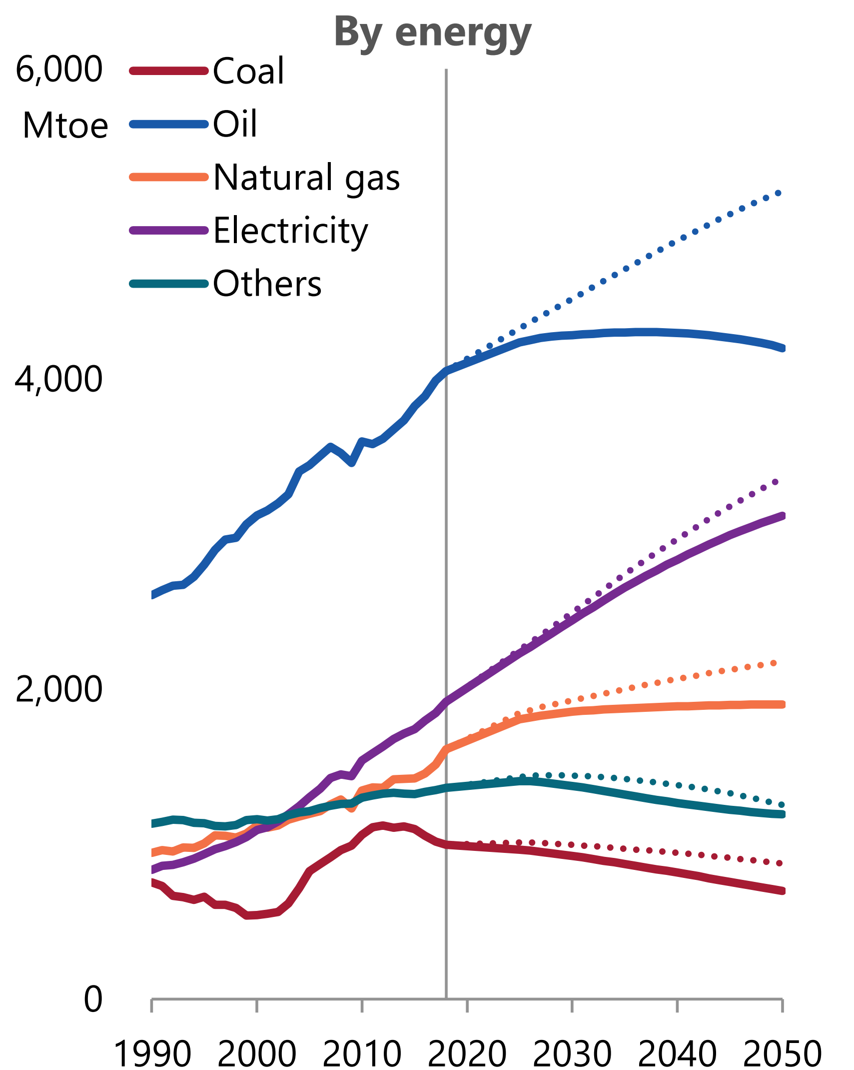


Note: Solid lines stand for Advanced Technologies Scenario and dotted lines stand for Reference Scenario.

Final energy consumption

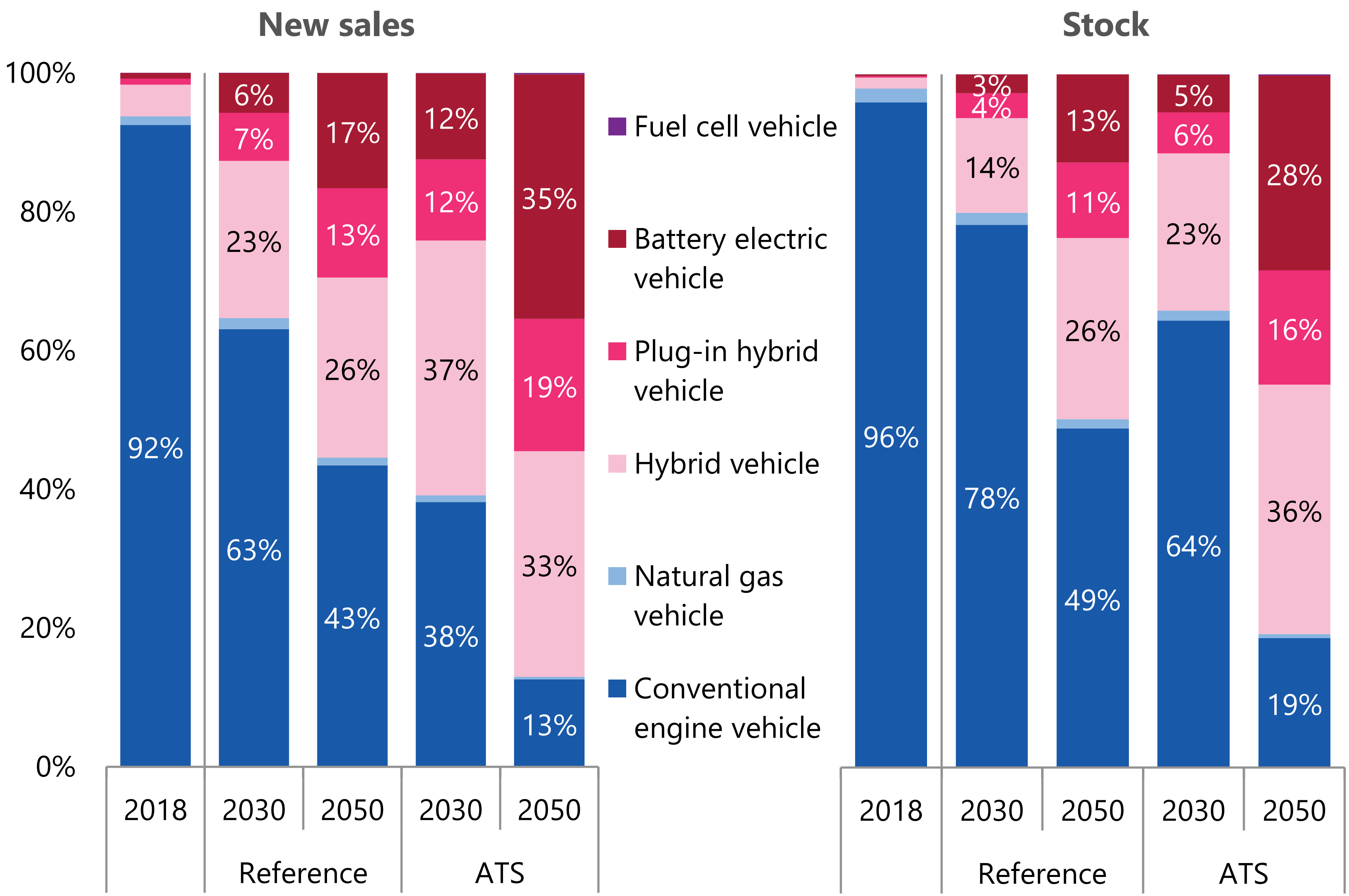


Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.

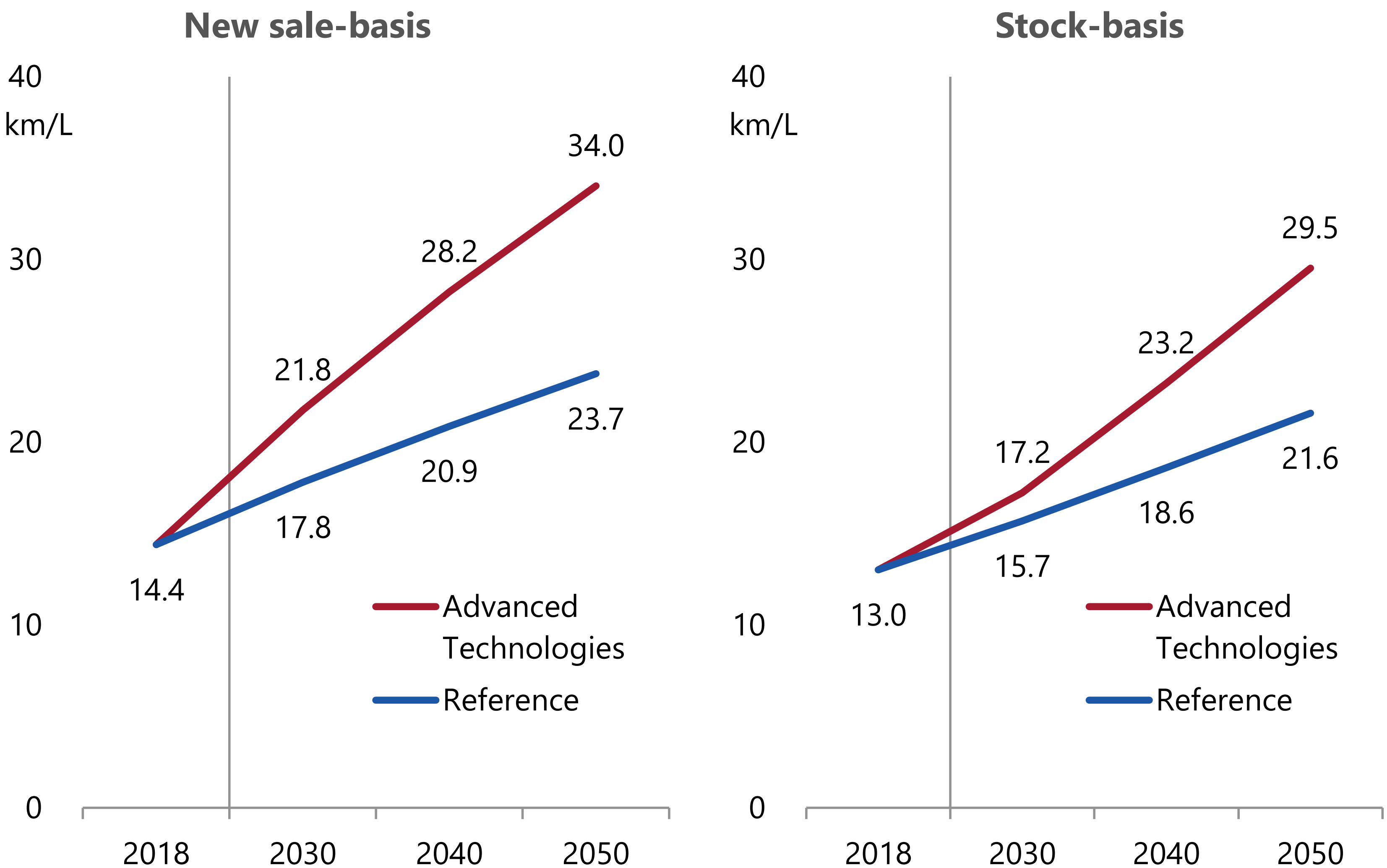


Note: Solid lines stand for Advanced Technologies Scenario and dotted lines stand for Reference Scenario.

Share of passenger vehicle

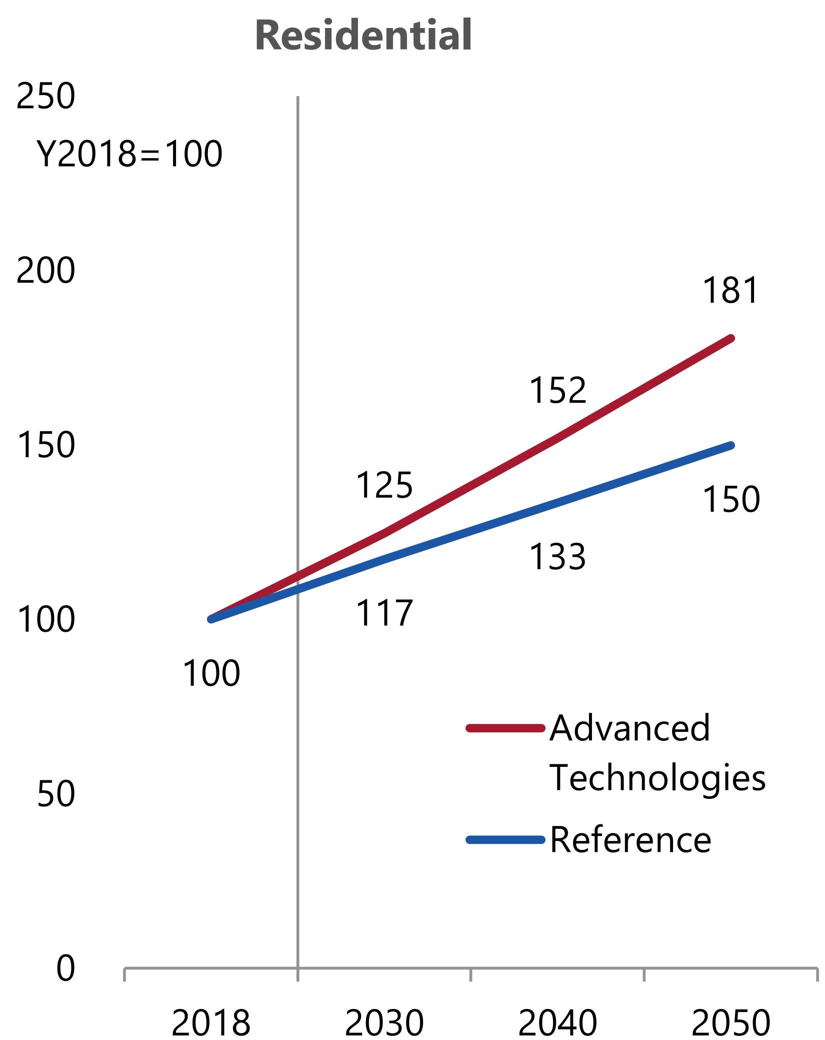


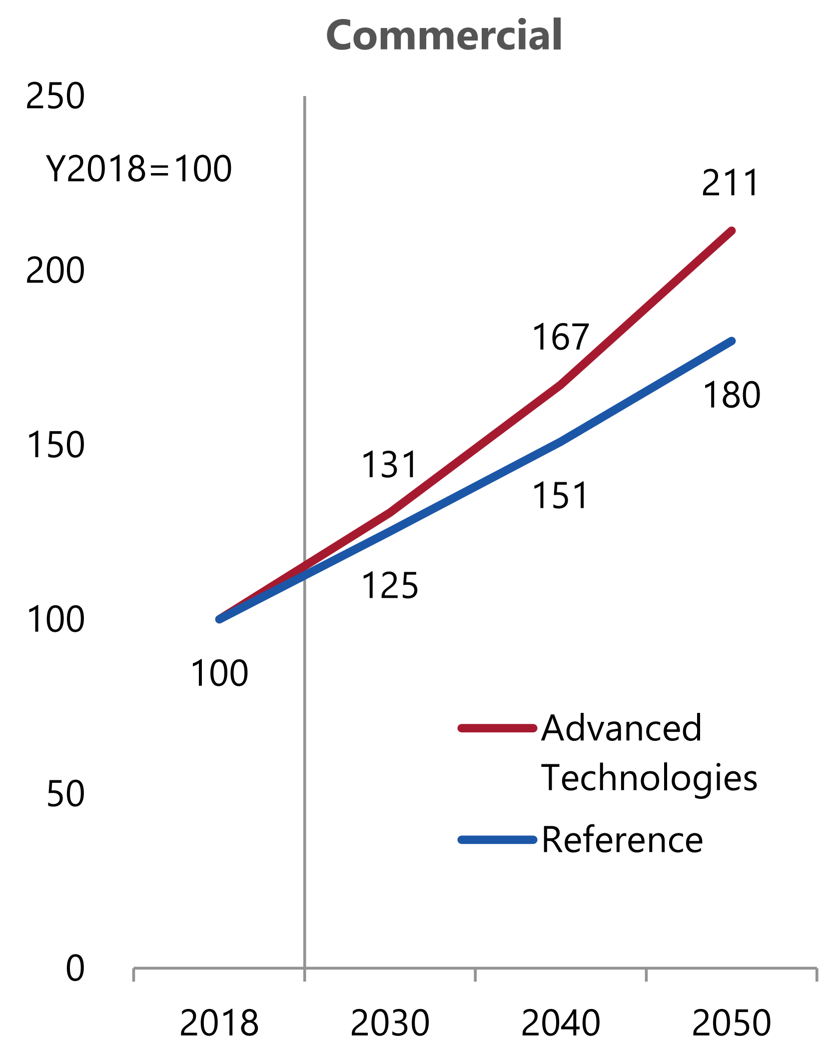
Fuel efficiency of passenger vehicle



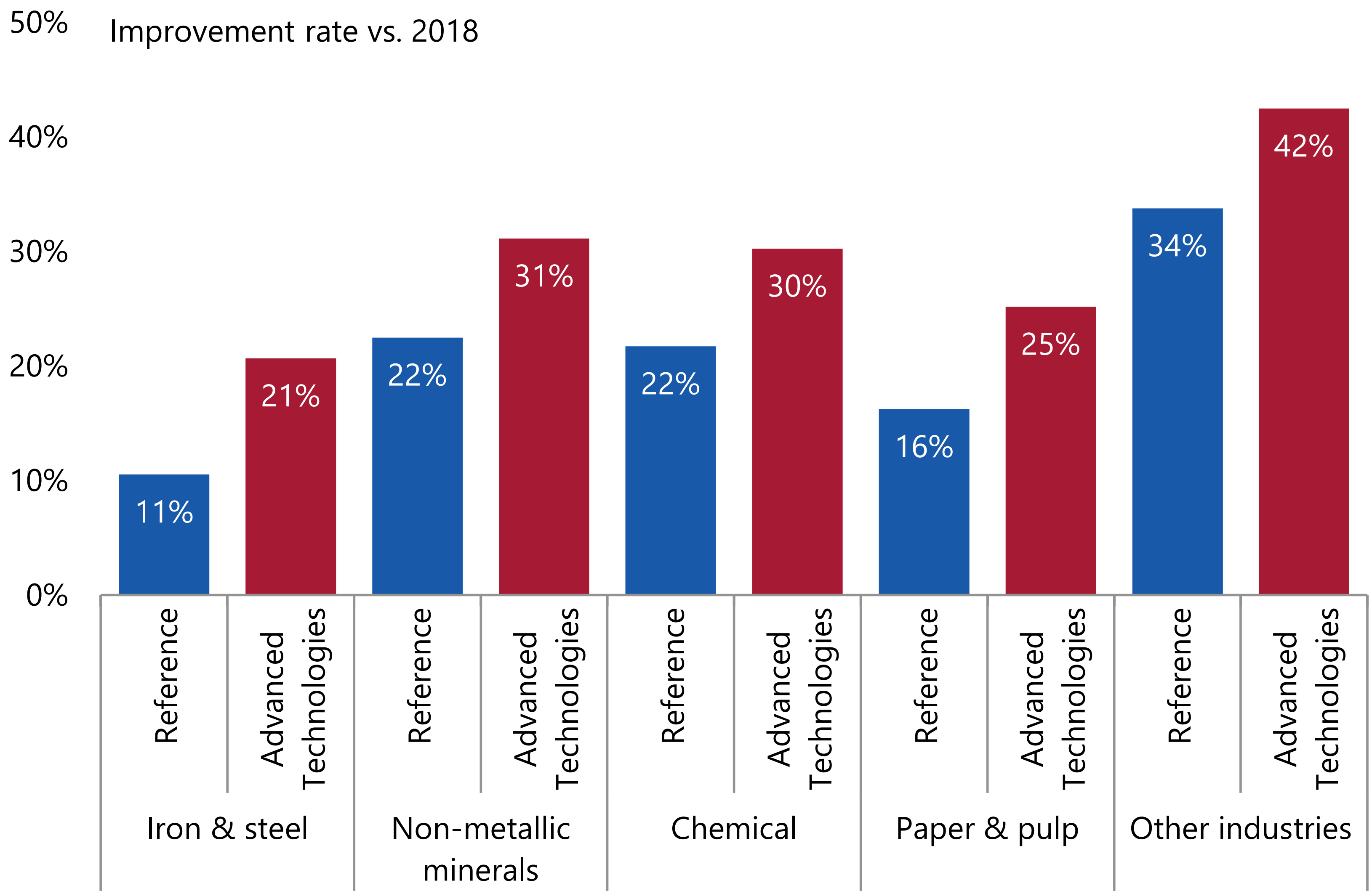
Note: Litres of gasoline equivalent

Energy efficiency in buildings sector

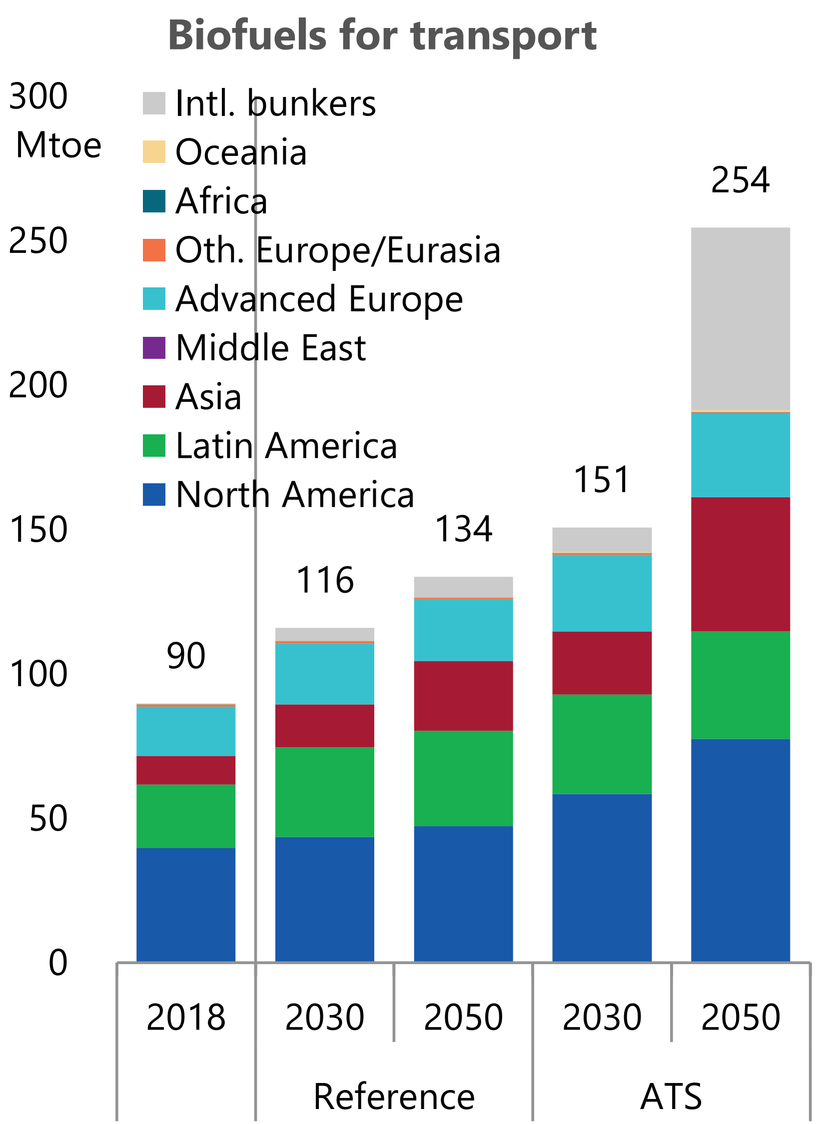


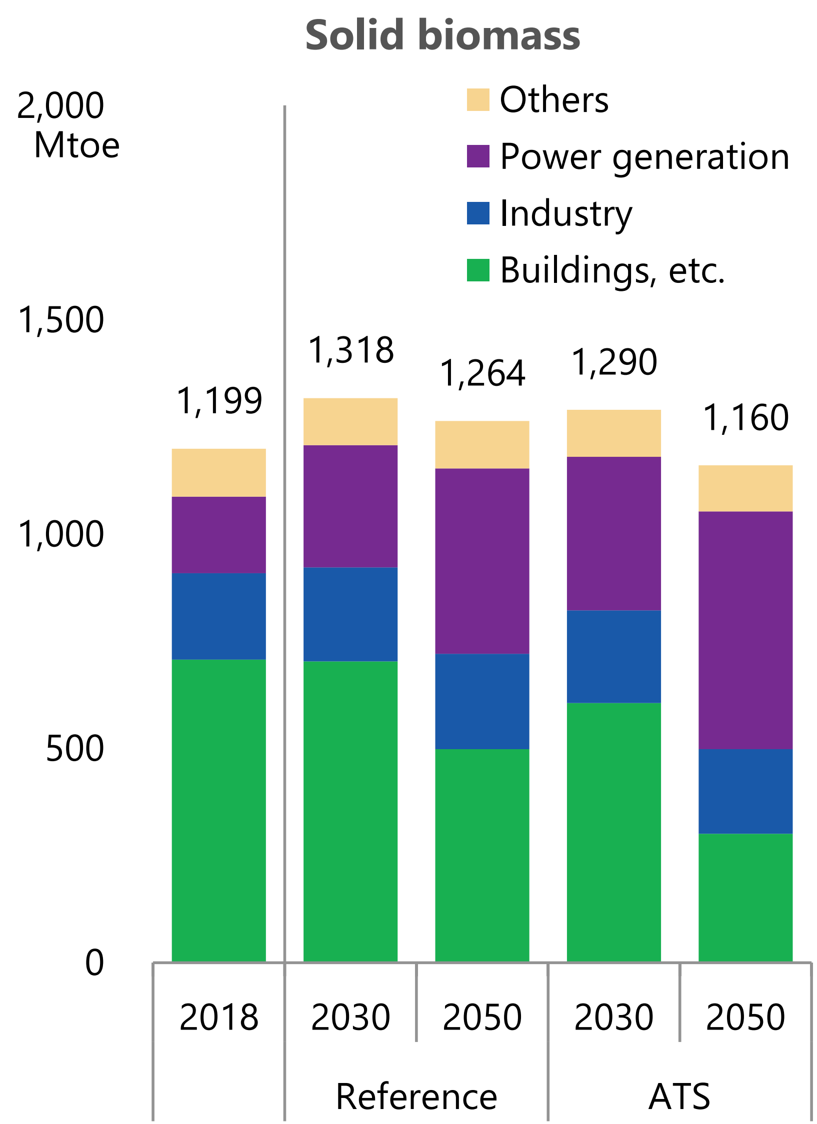


Energy intensity improvement in industry sector

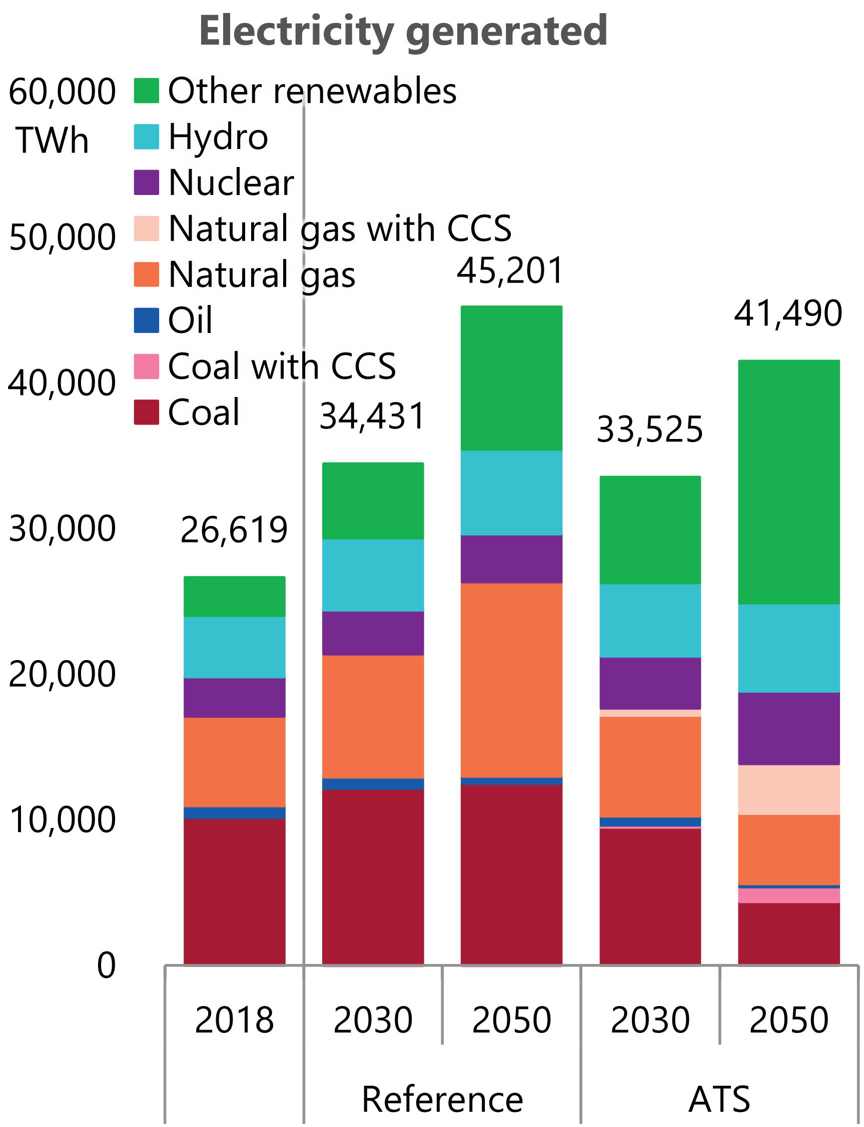


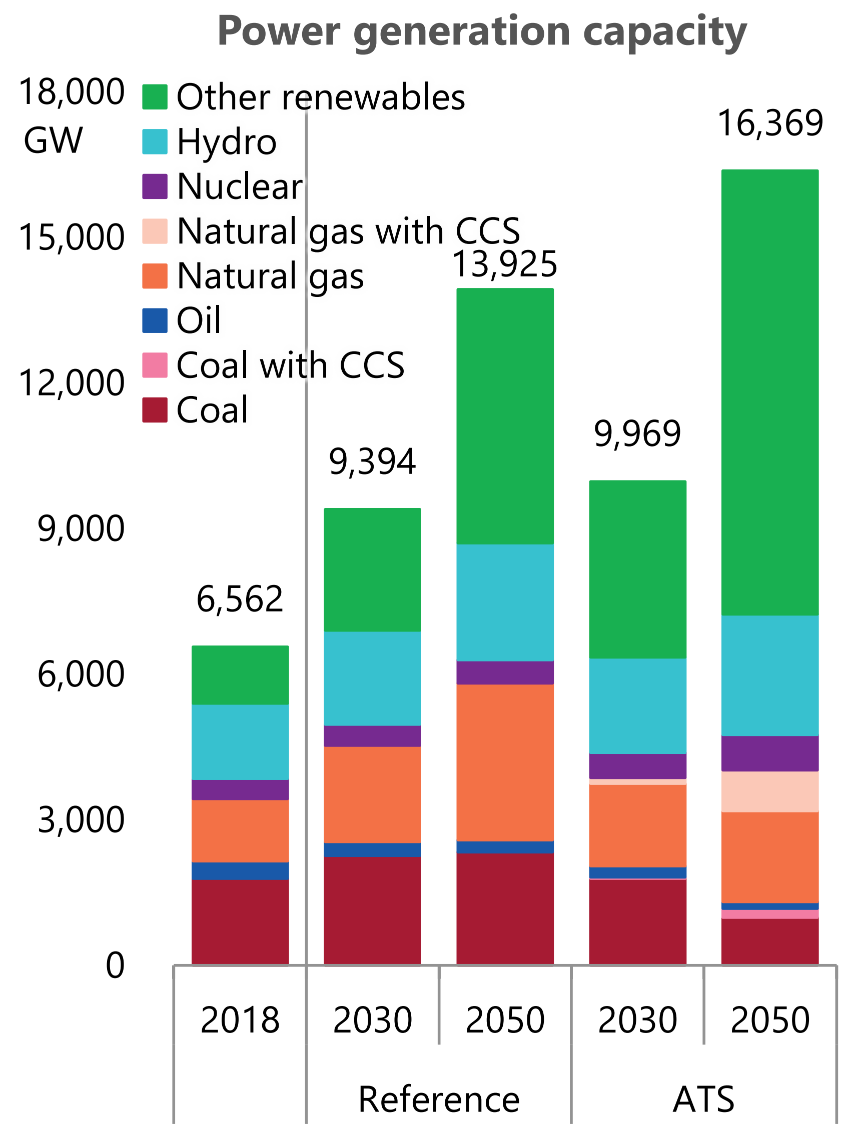
Biomass


Biofuels for transport
300
Mtoe
250
200
150
100
50
0
Intl. bunkers
Oceania
Africa
Oth. Europe/Eurasia
Advanced Europe
Middle East
Asia
Latin America
North America
90
116
134
151
254
2018
2030
2050
2030
2050
Reference
ATS

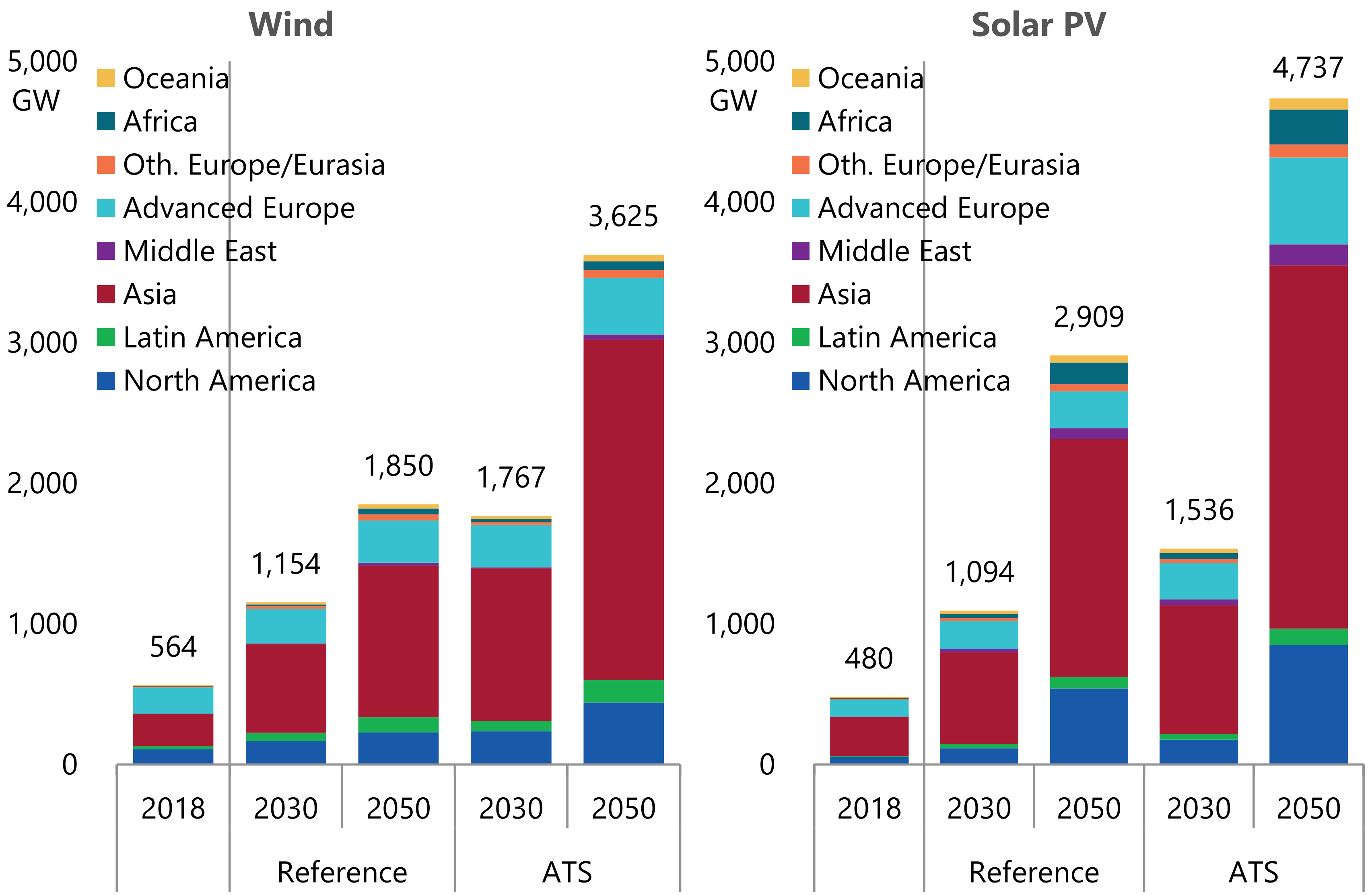

Solid biomass
2,000
Mtoe
1,500
1,000
500
0
Others
Power generation
Industry
Buildings, etc.
1,199
1,318
1,264
1,290
1,160
2018
2030
2050
2030
2050
Reference
ATS

Power generation mix

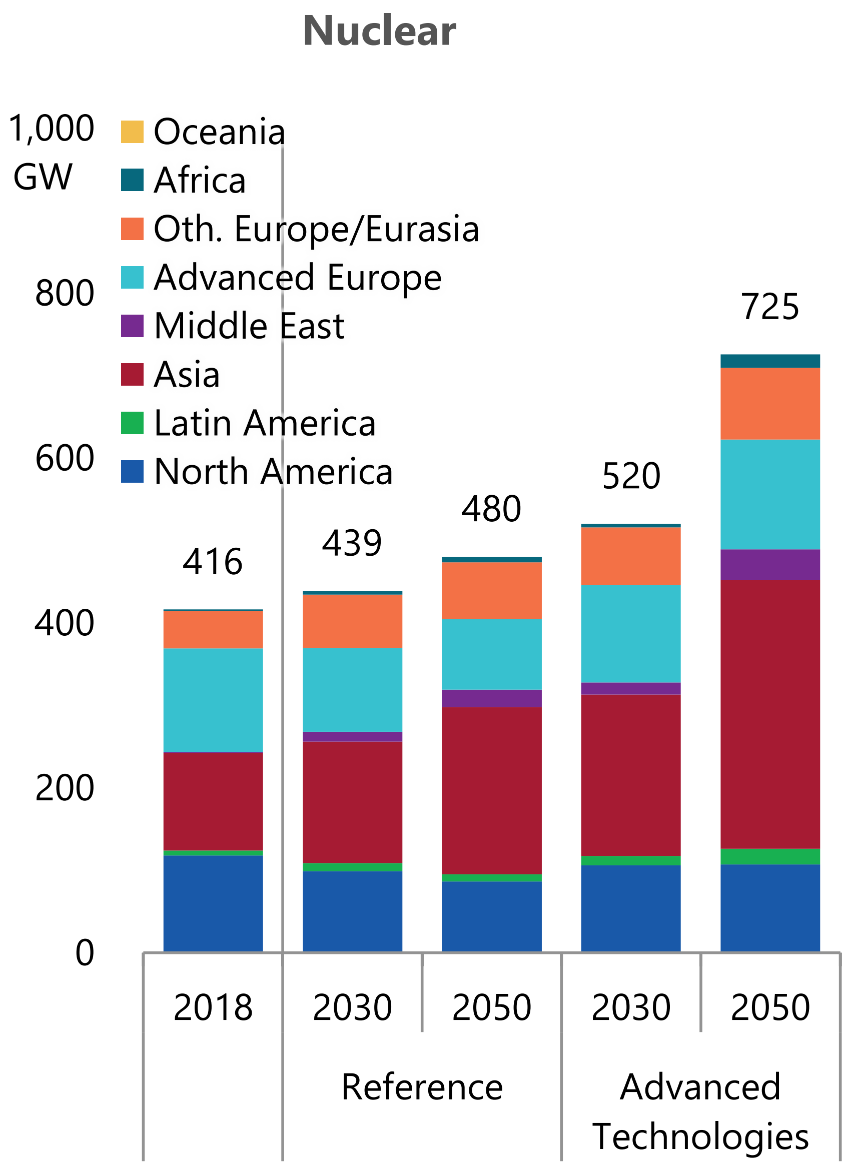


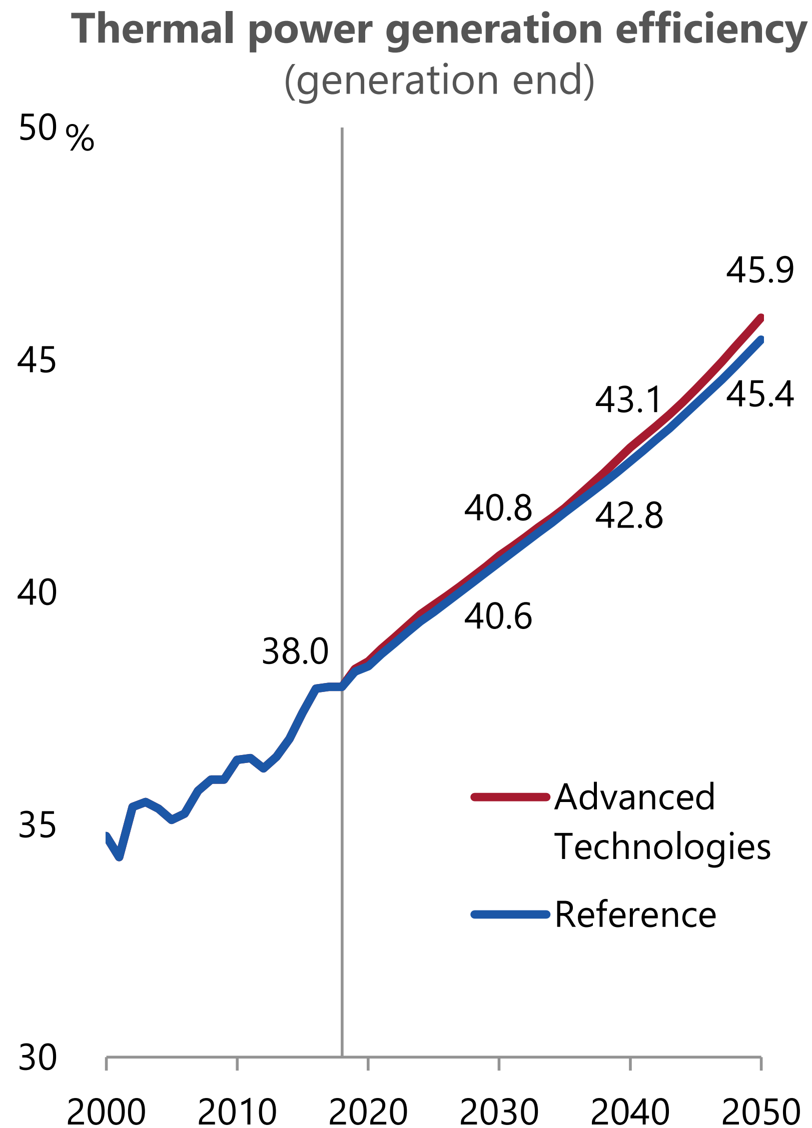


Wind and solar PV power generation capacity

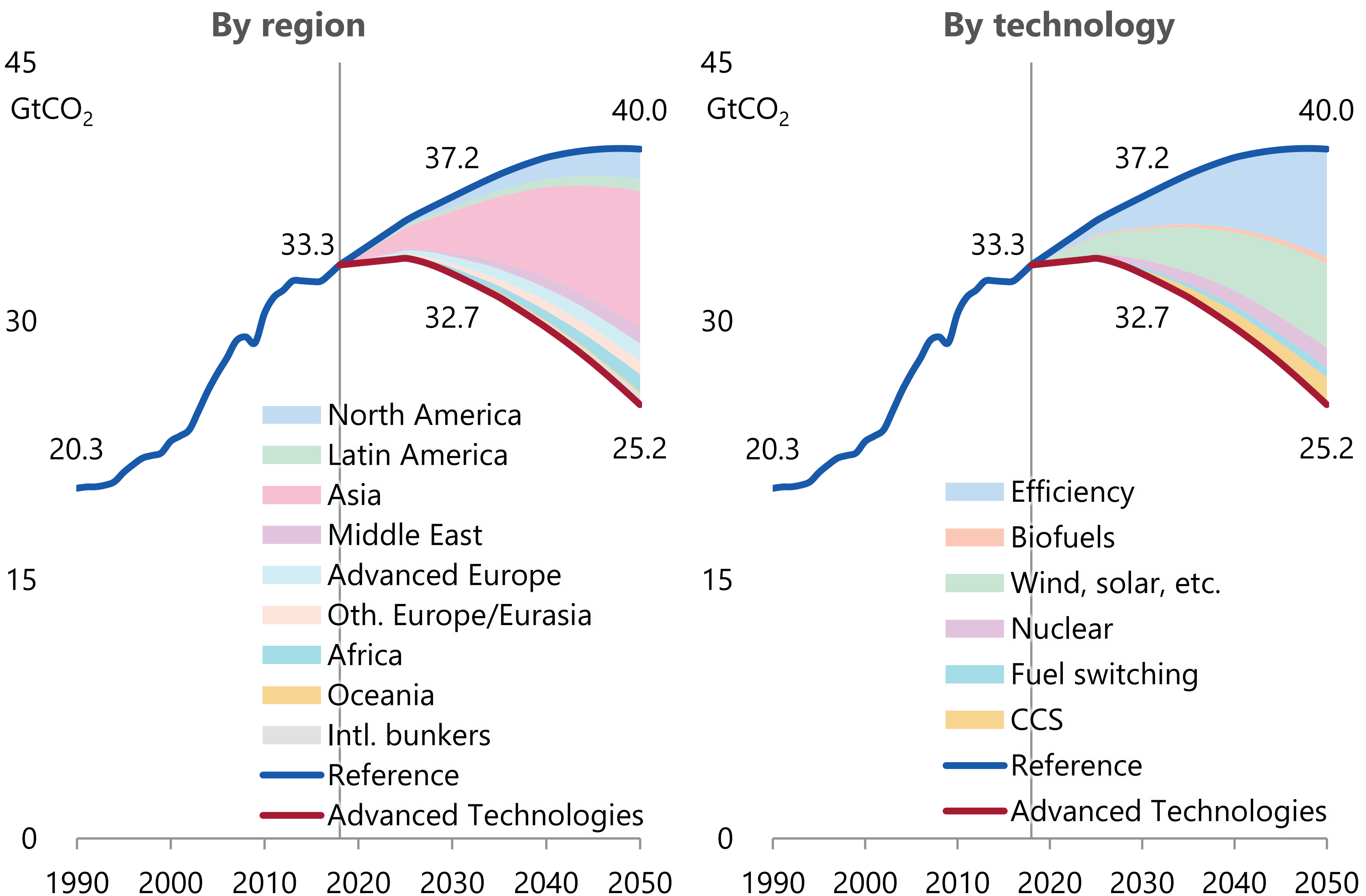


Nuclear power generation capacity and thermal power generation efficiency



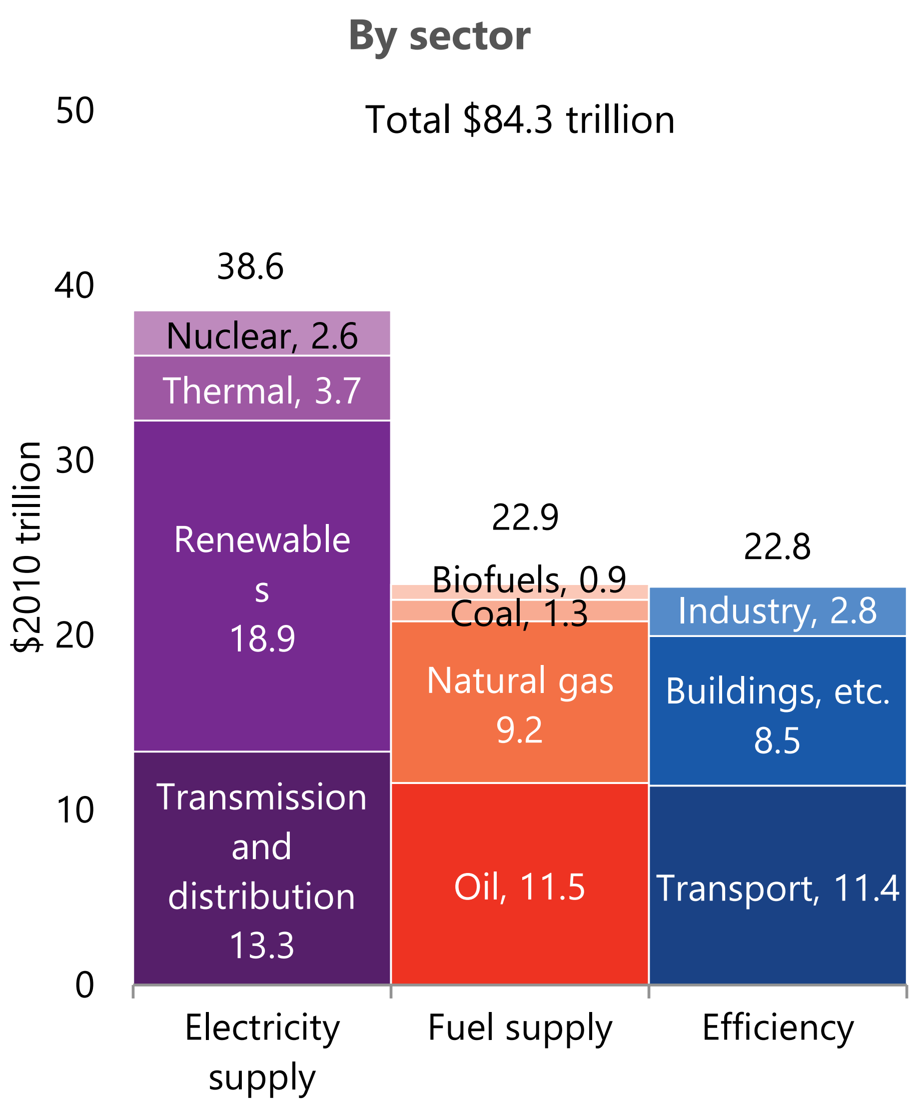


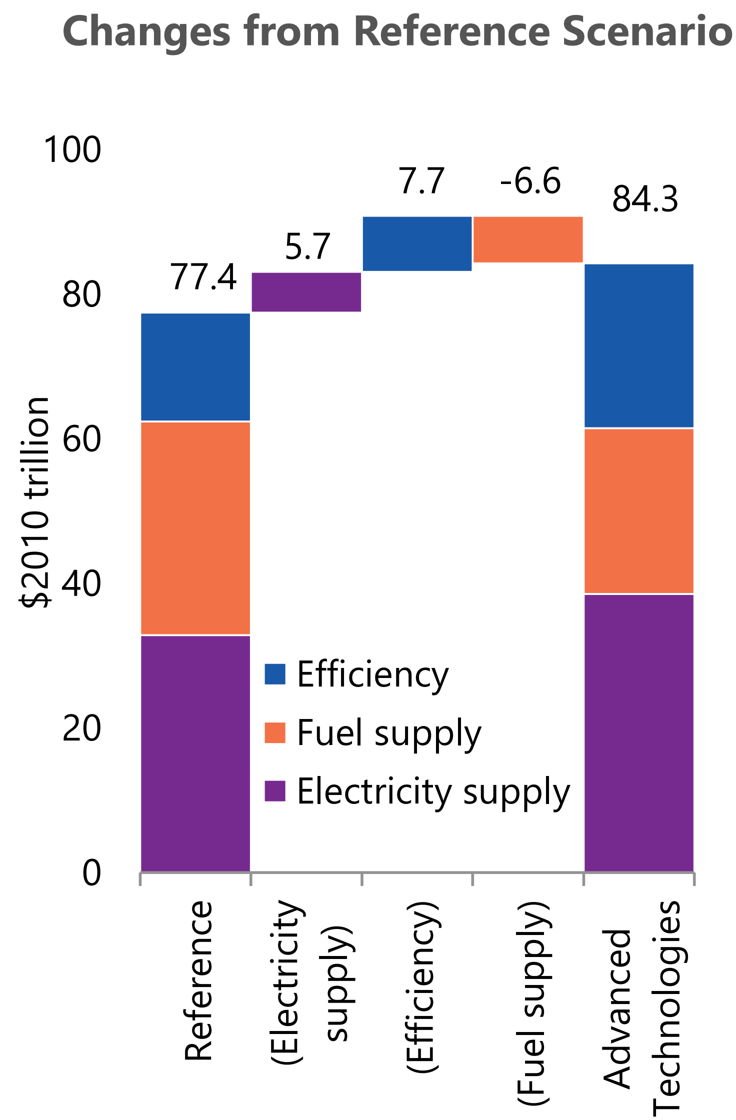
Energy-related CO_2 emissions



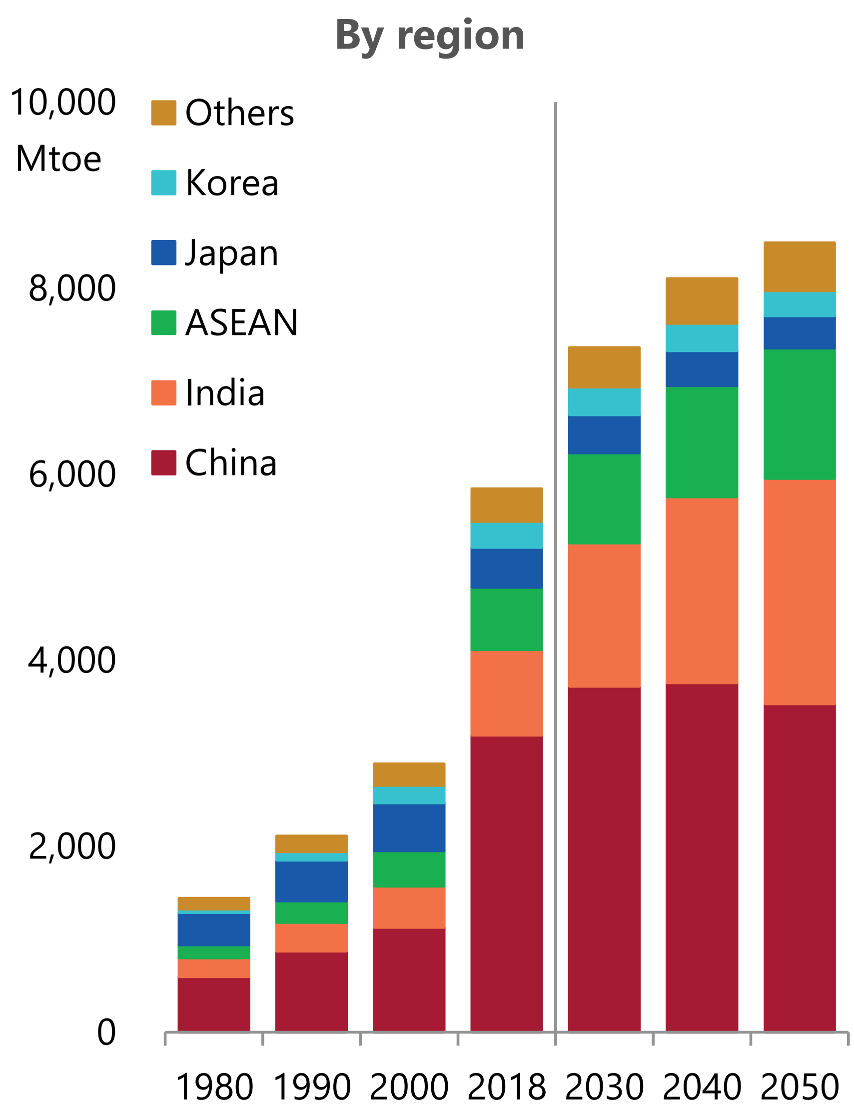
Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.

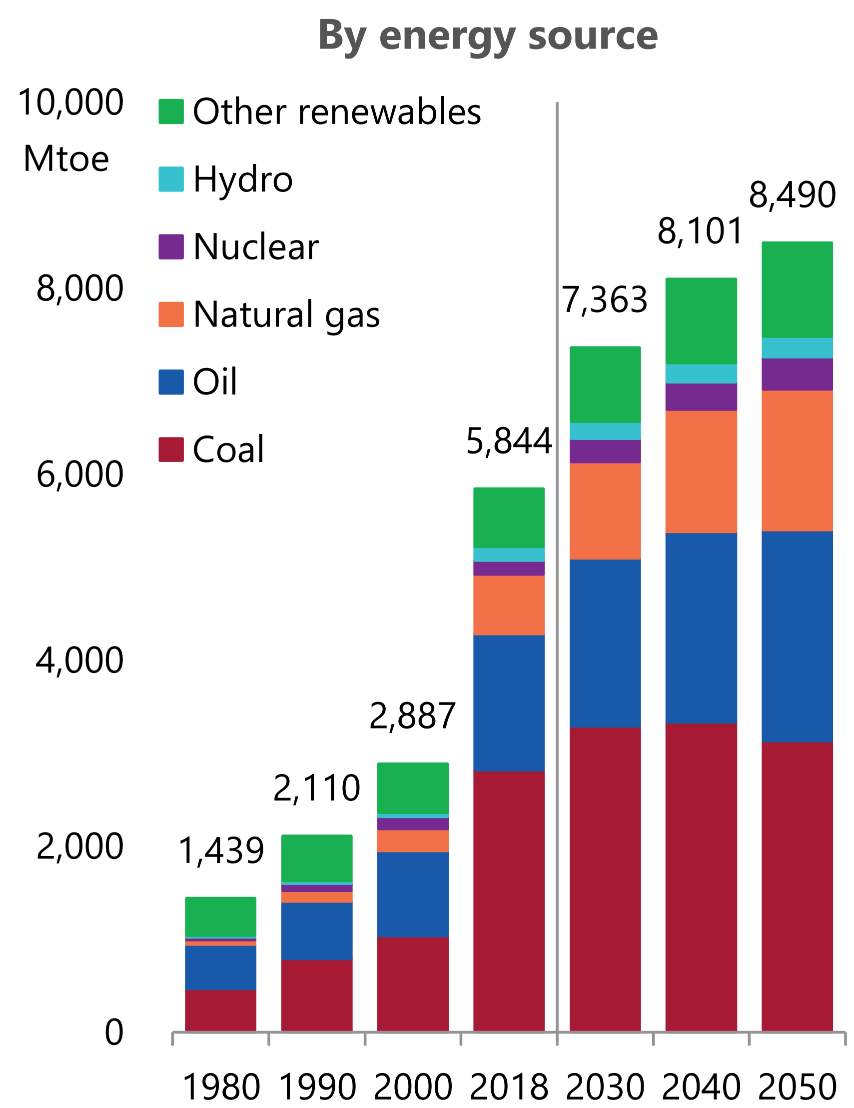
Energy-related investments (2019 – 2050)



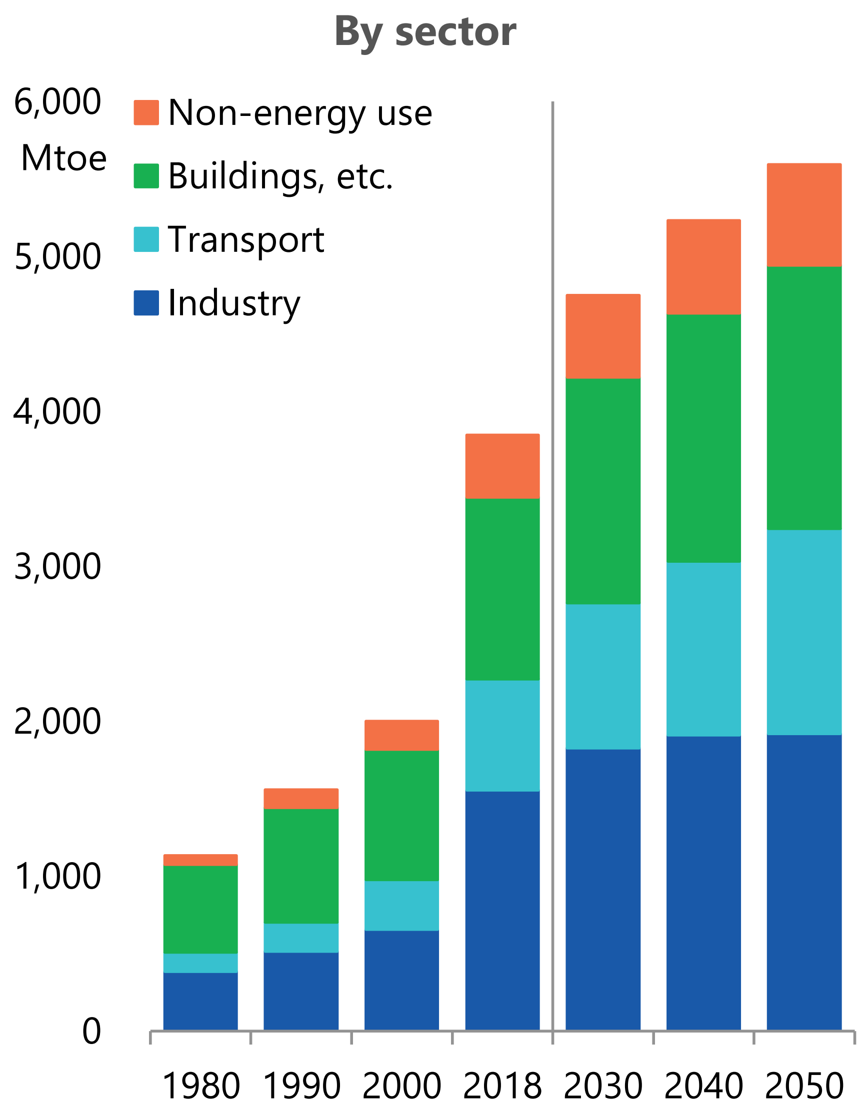


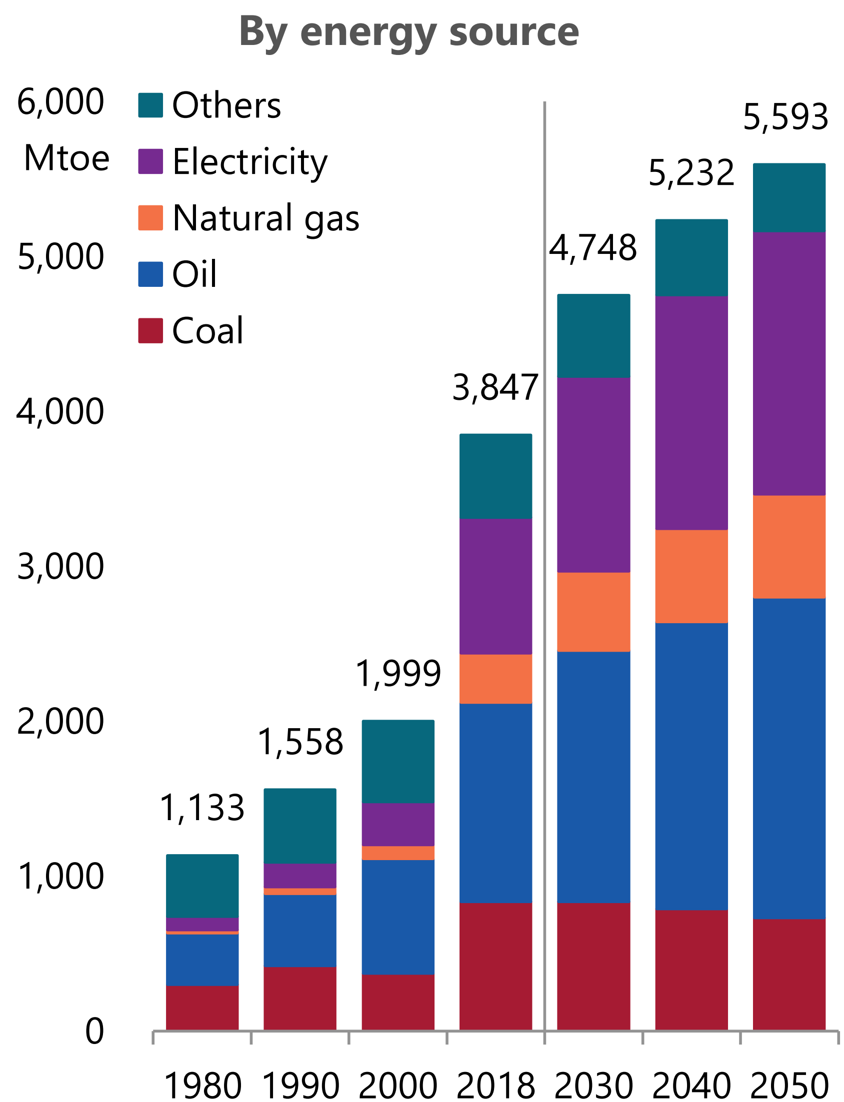
Primary energy consumption



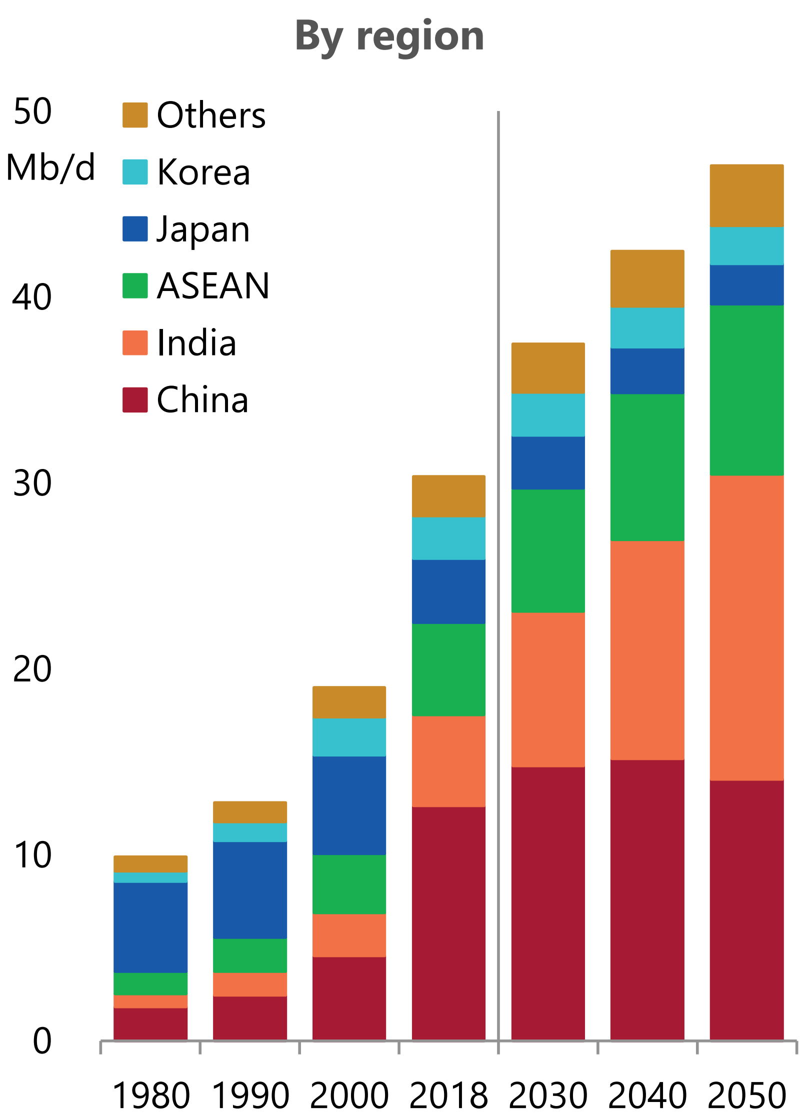


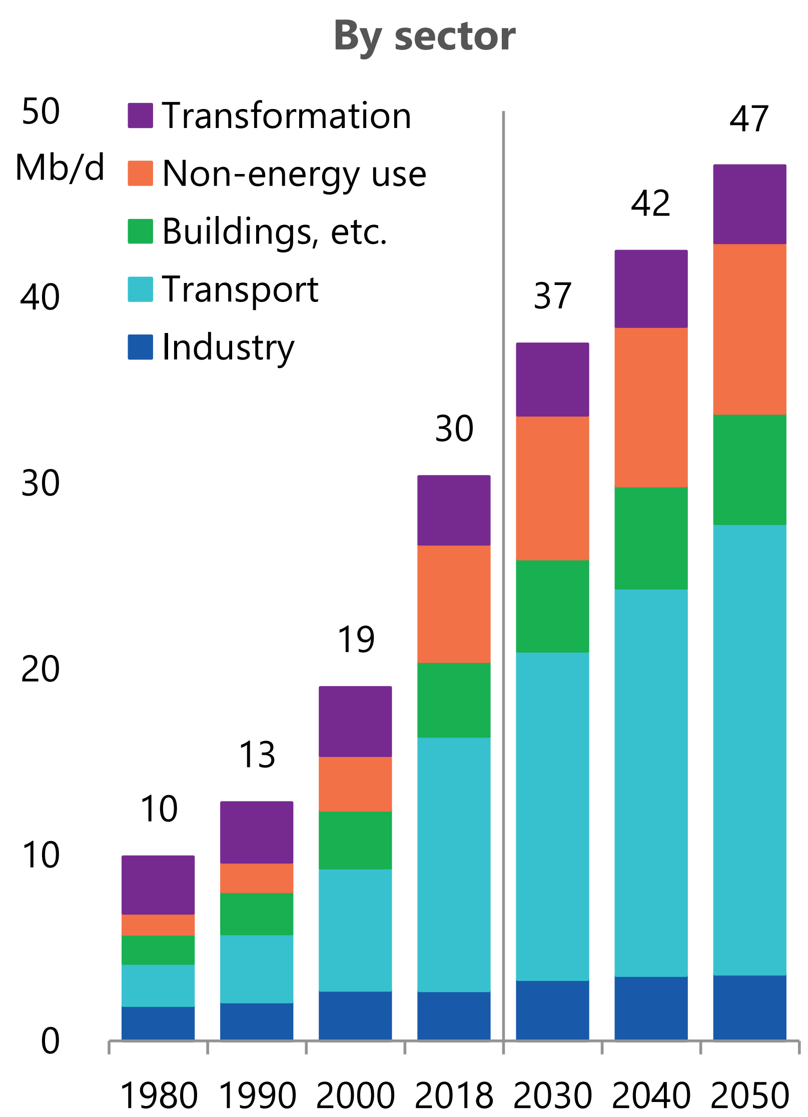
Final energy consumption





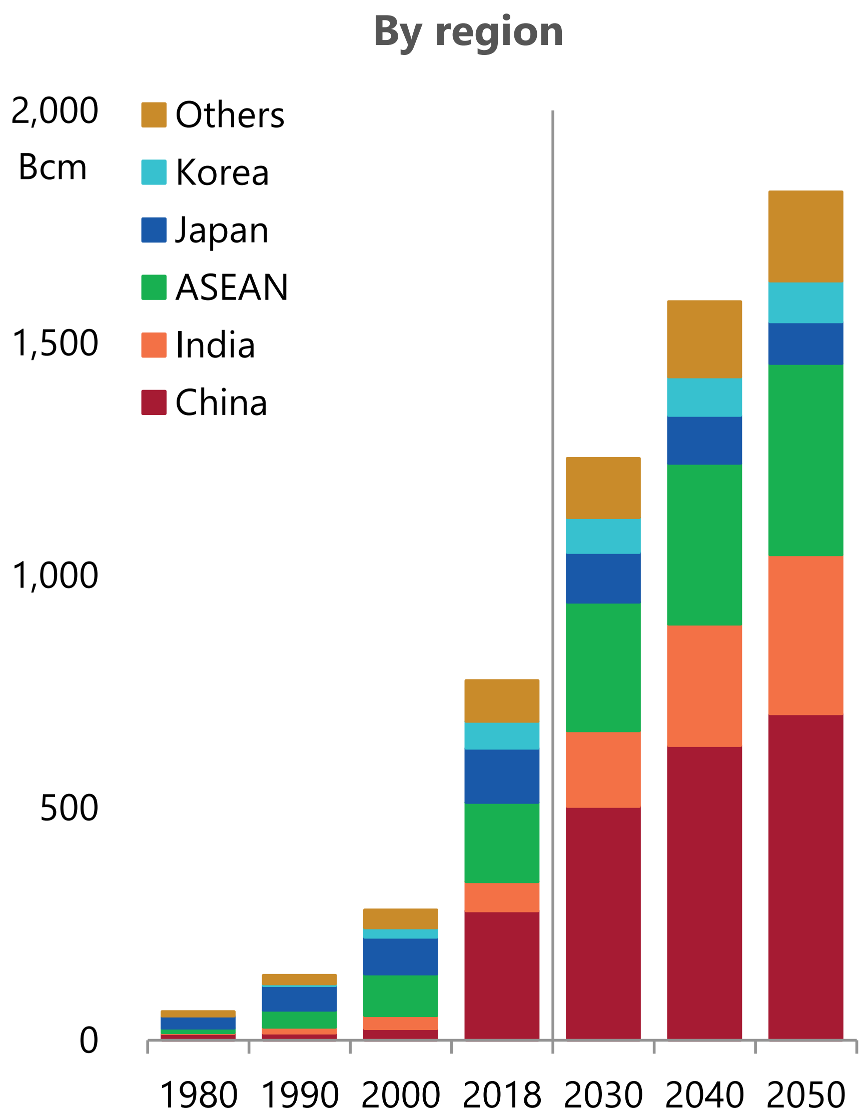
Oil consumption

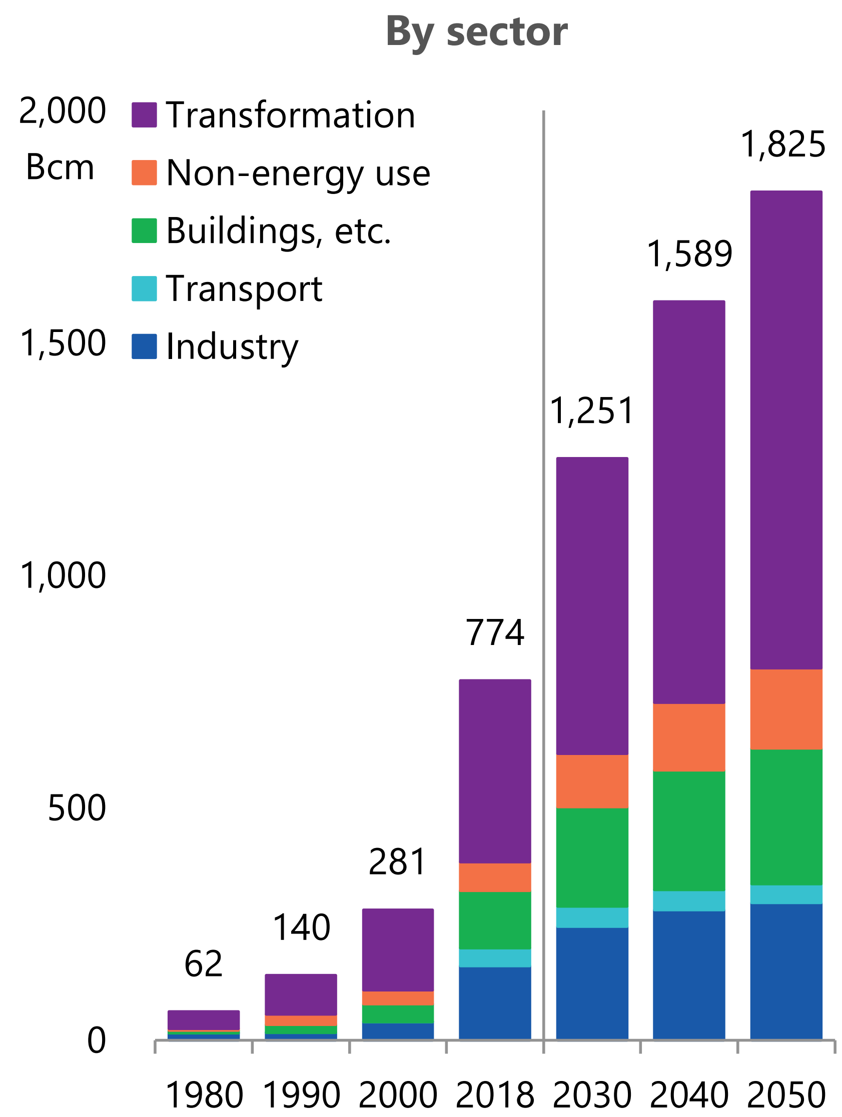




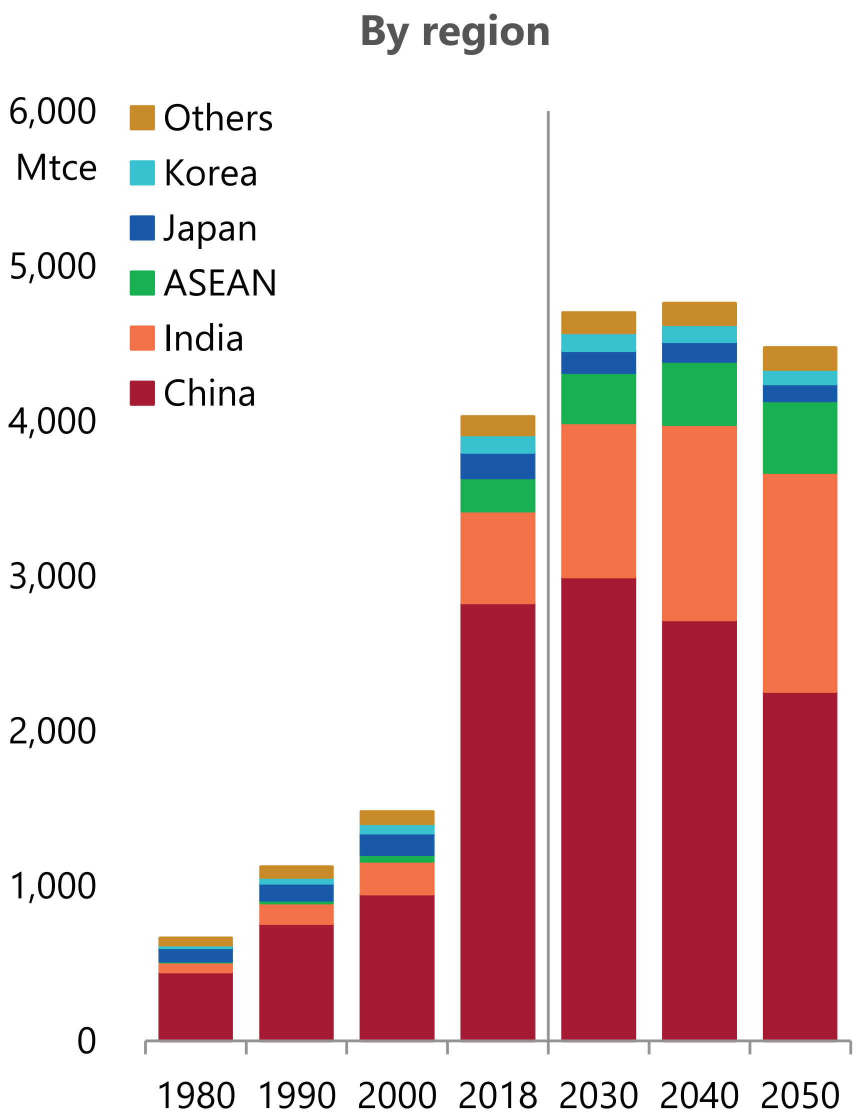
Asia | Reference Scenario

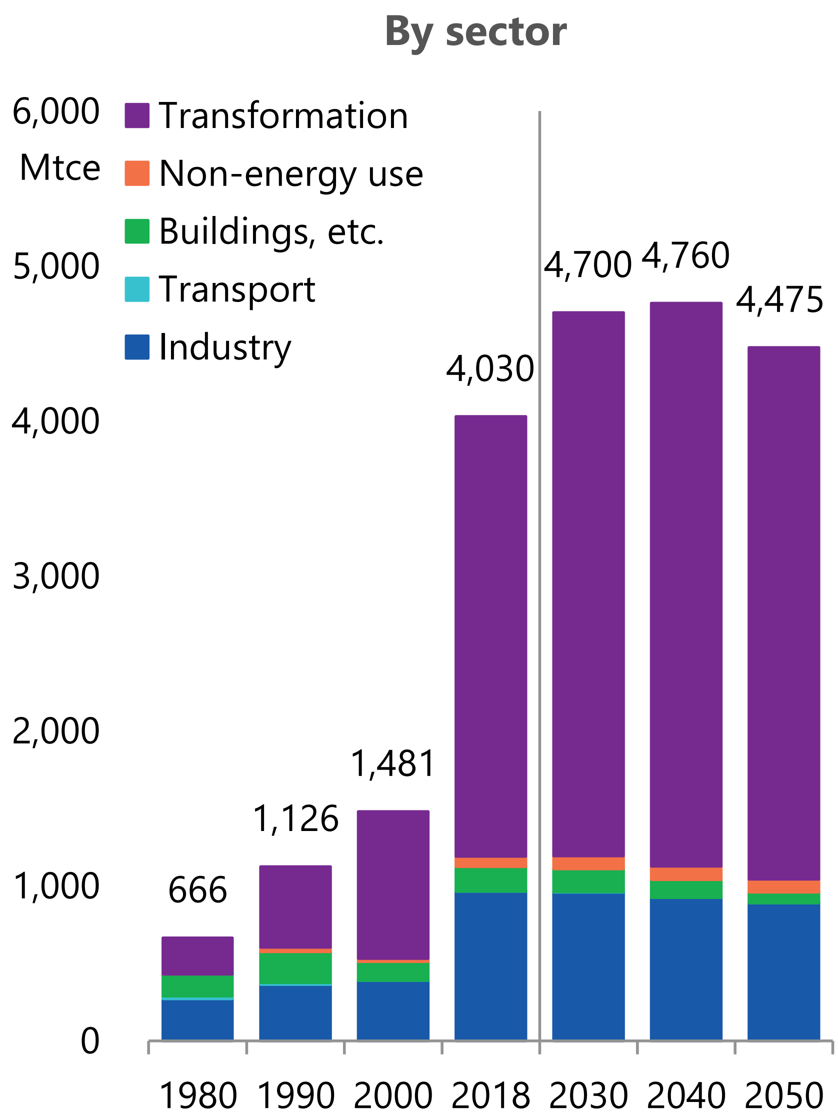
Natural gas consumption





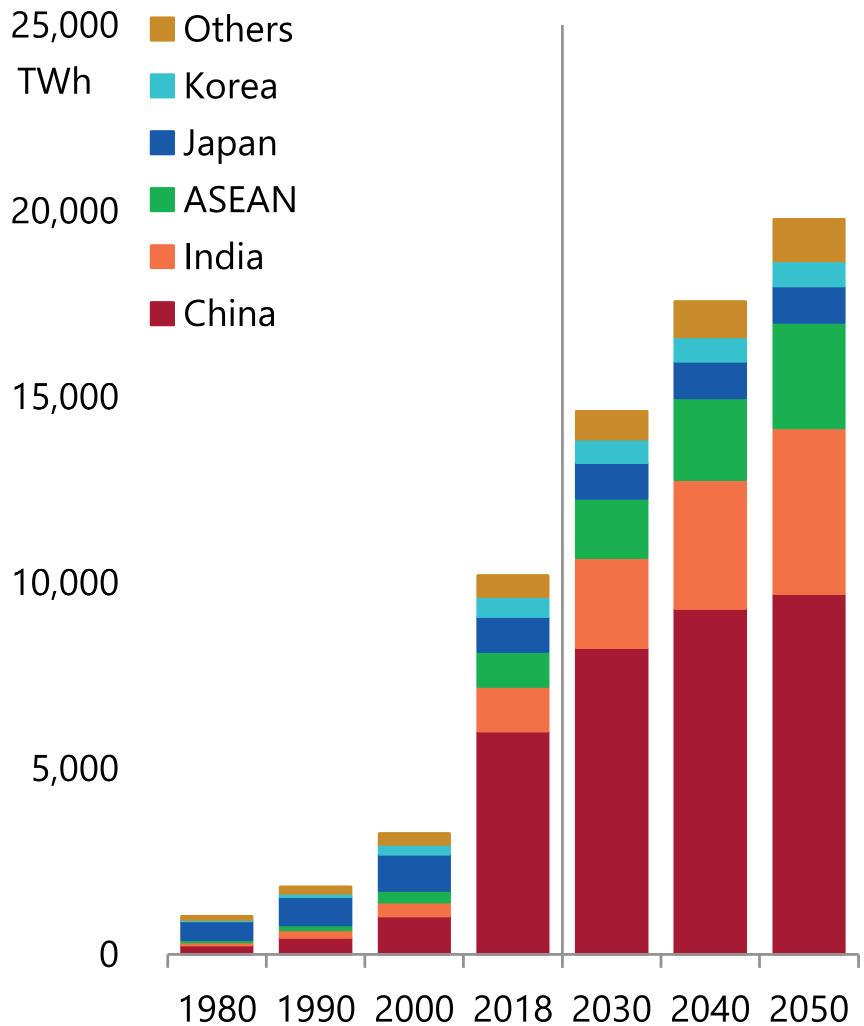
Coal consumption



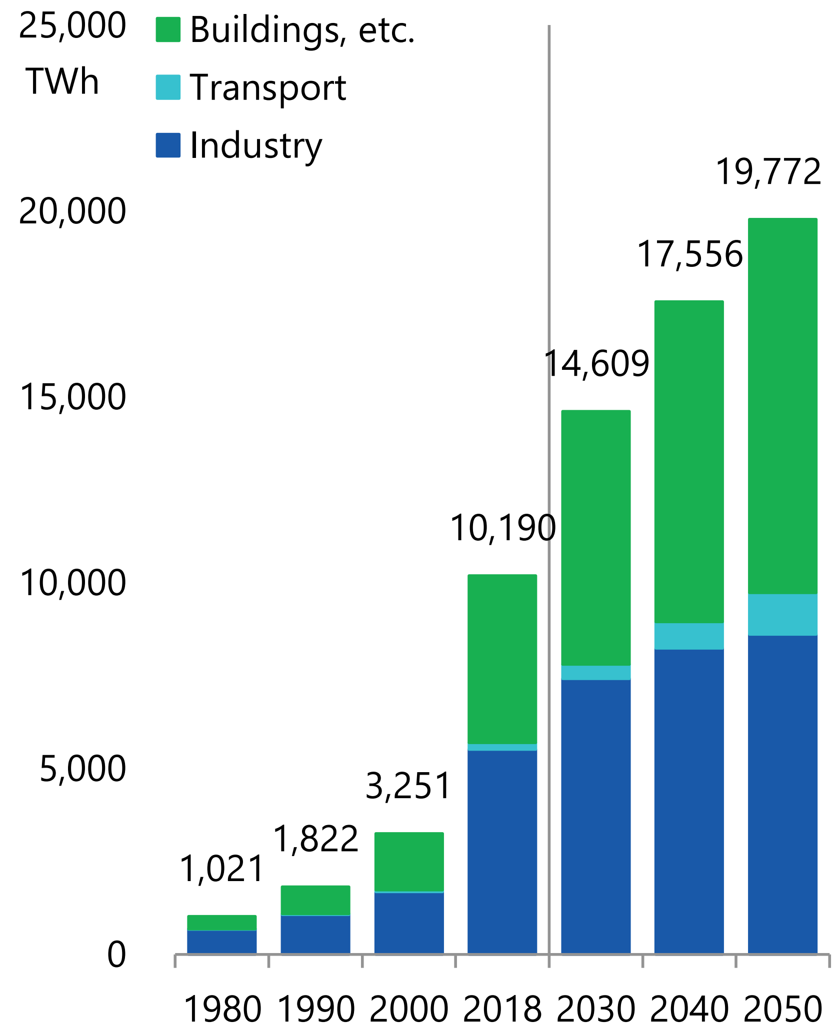


Final consumption of electricity

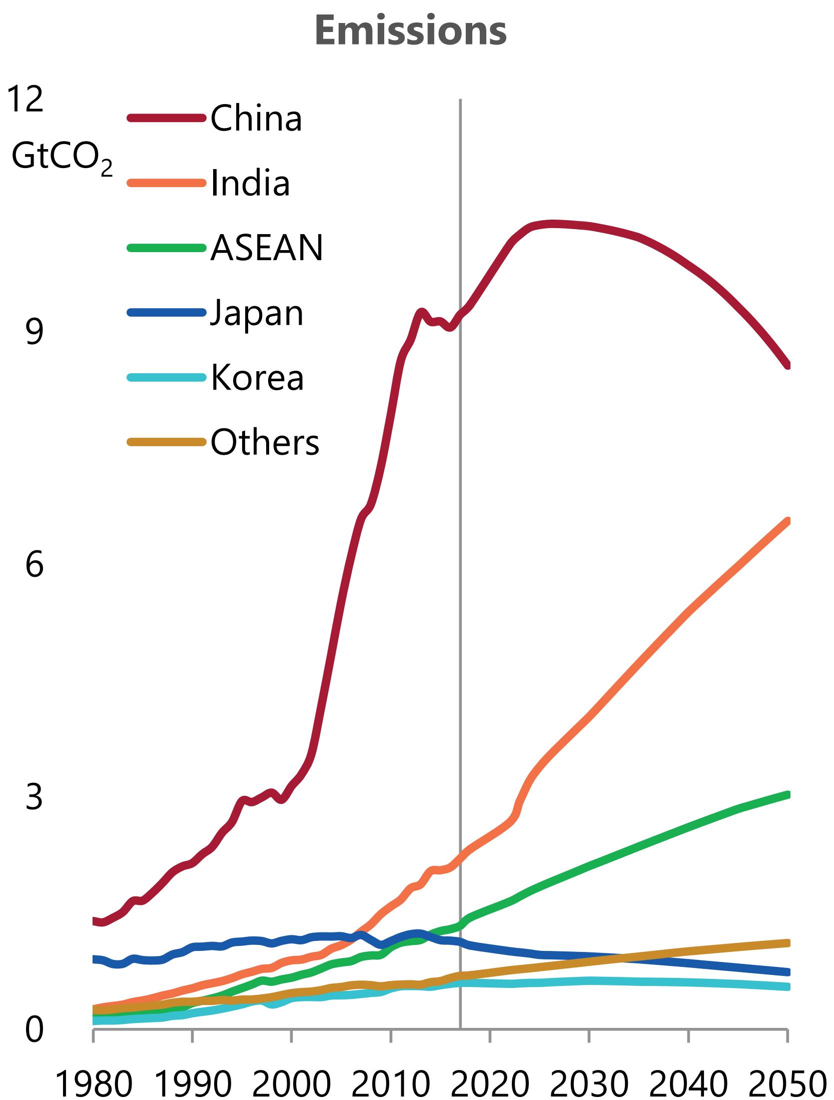
By region

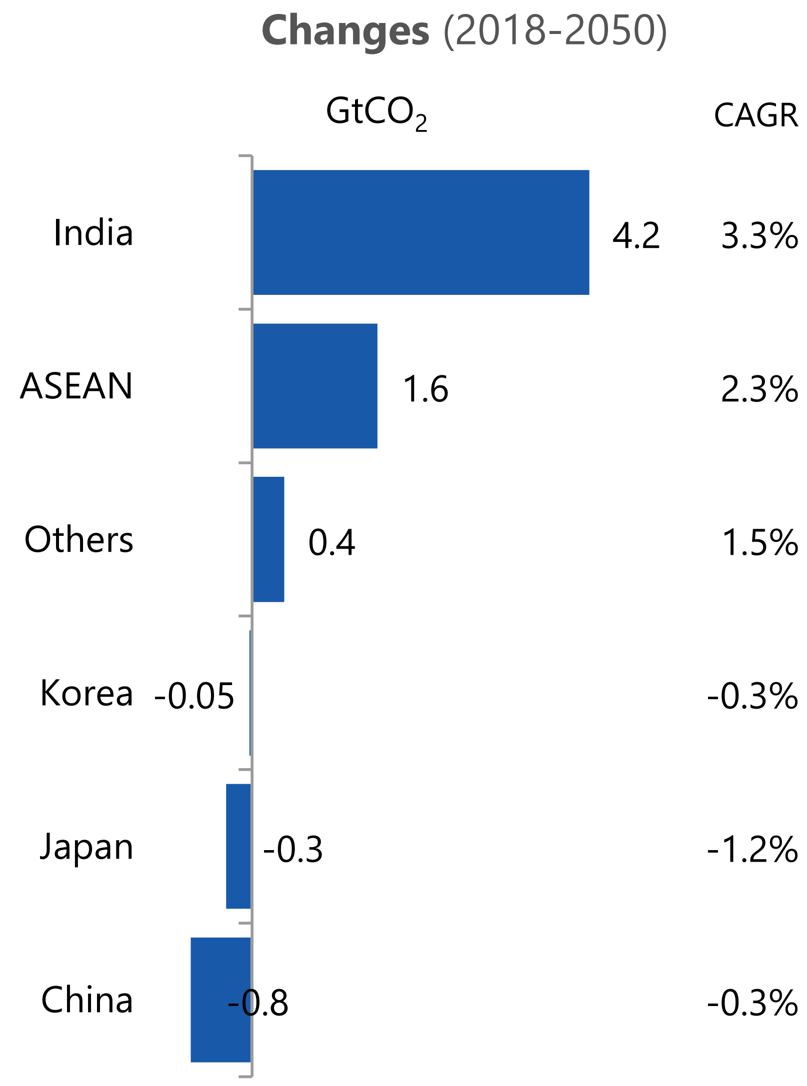


By sector



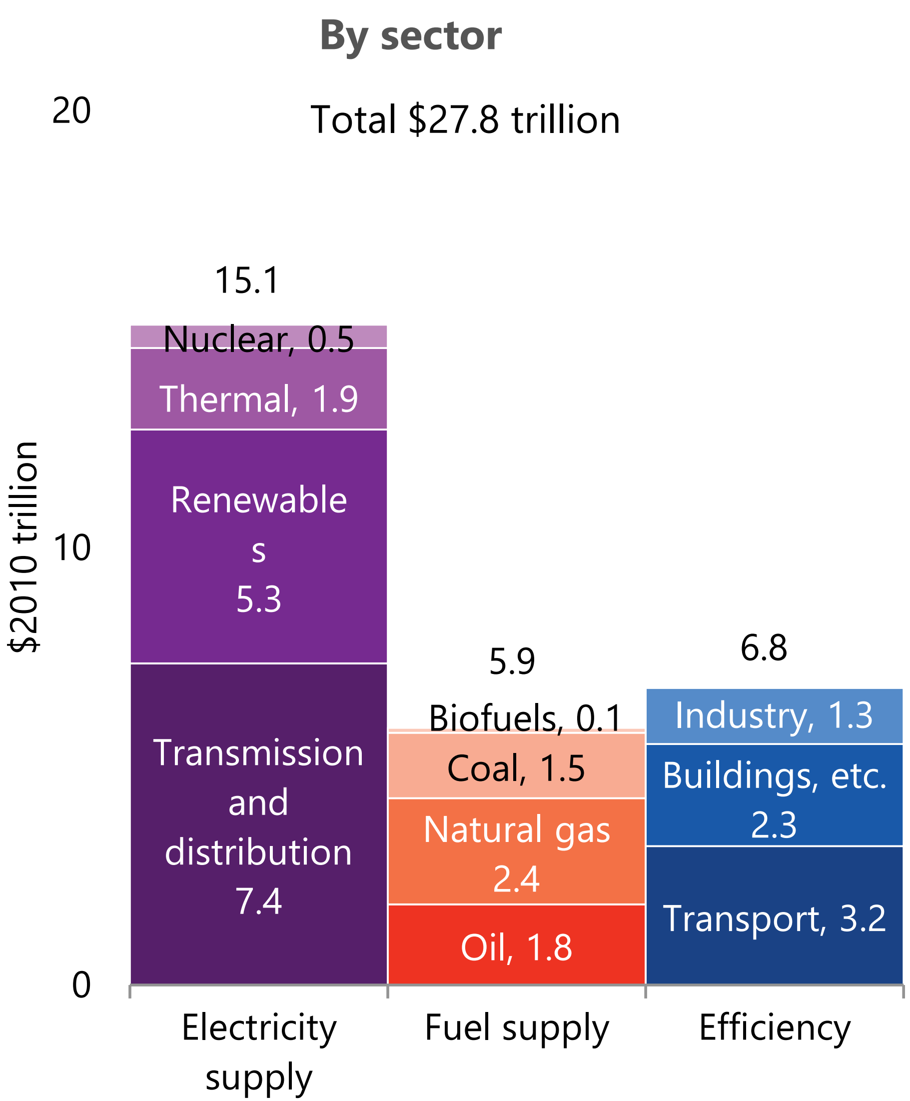
Energy-related CO_2 emissions

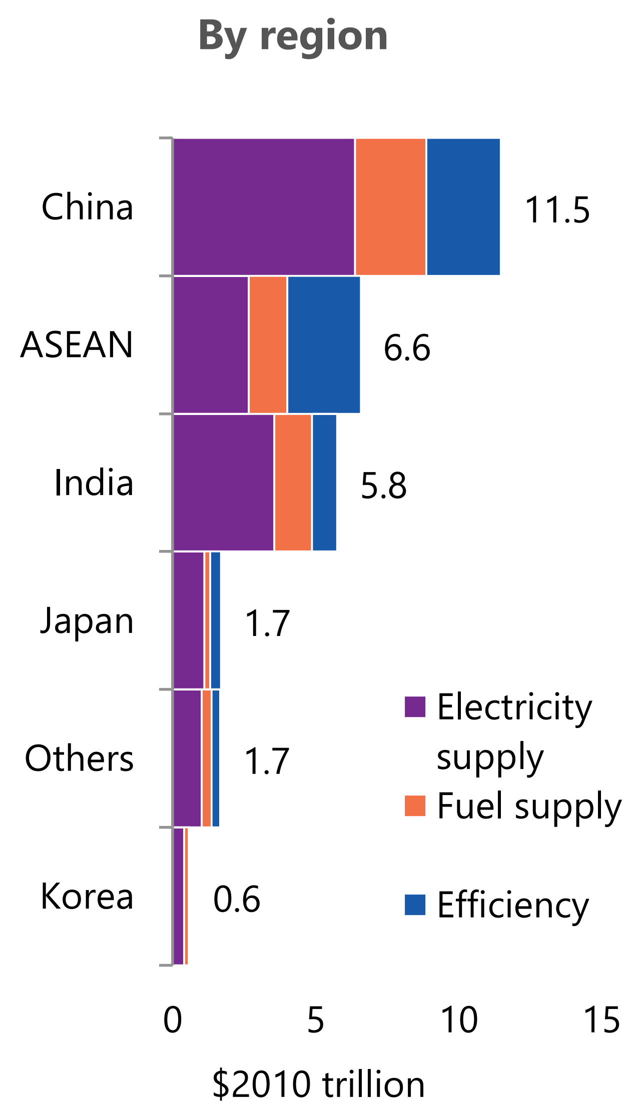




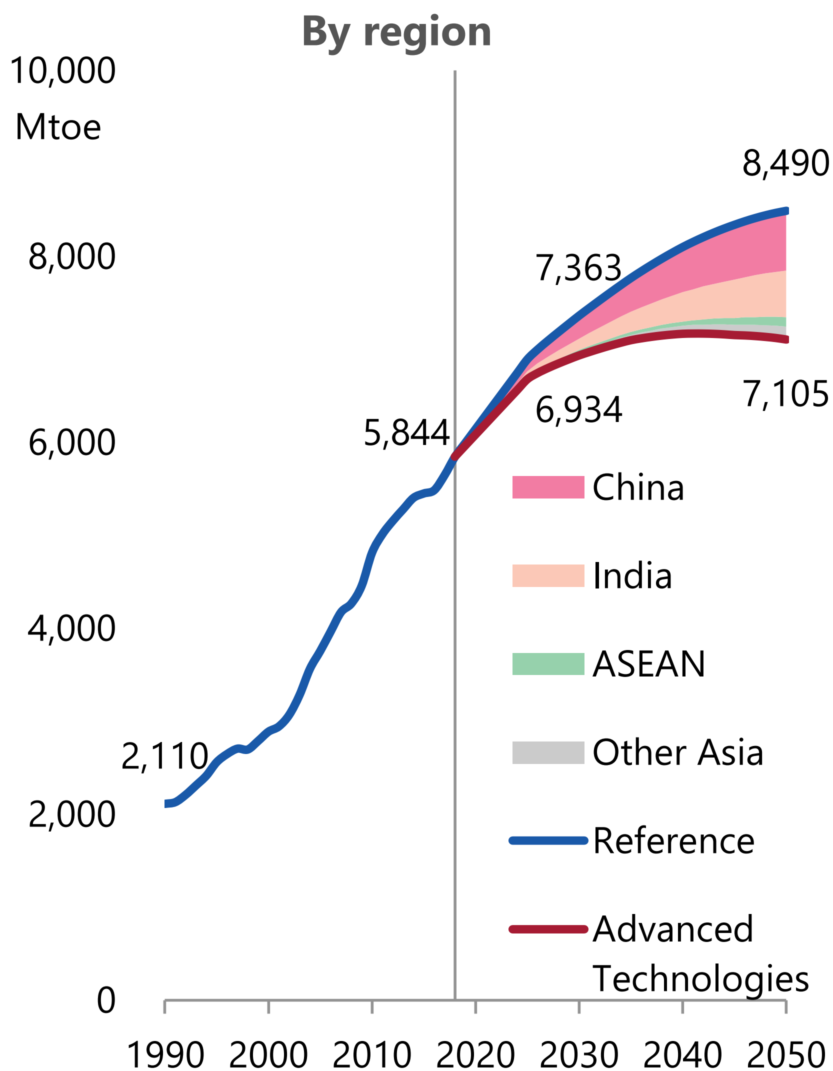
Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.

Energy-related investments (2019 – 2050)

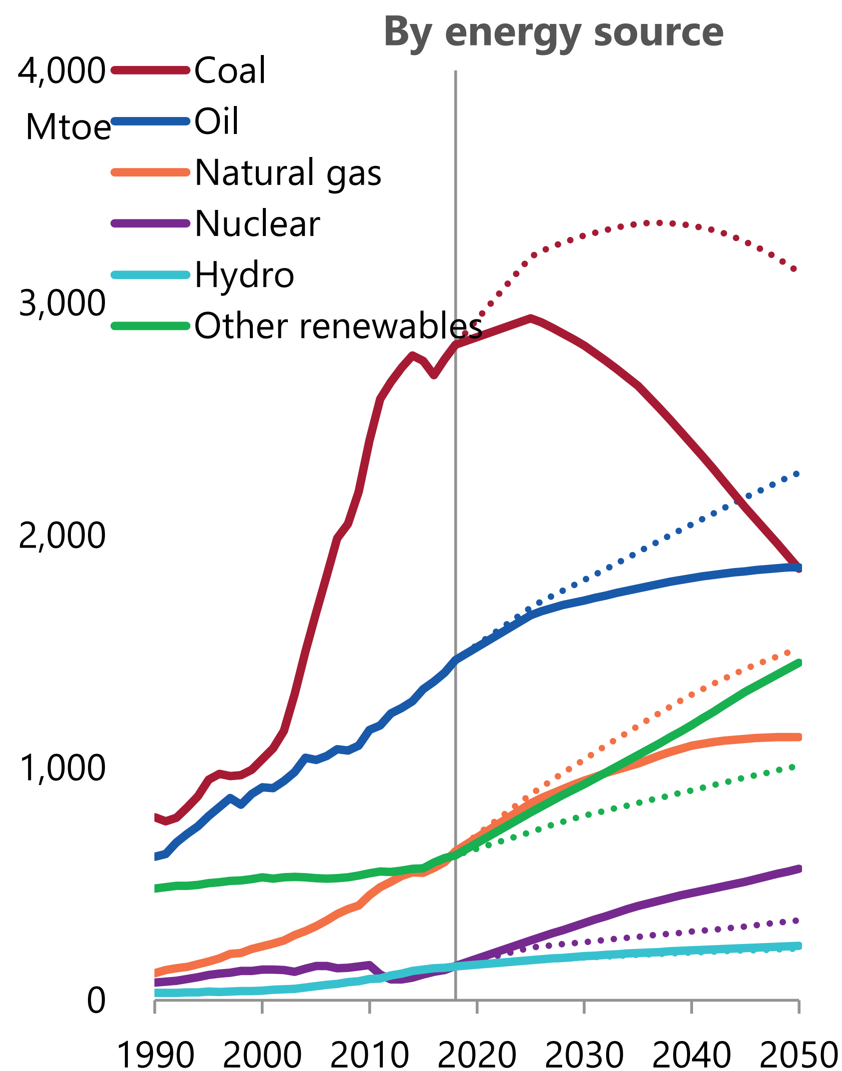




Primary energy consumption

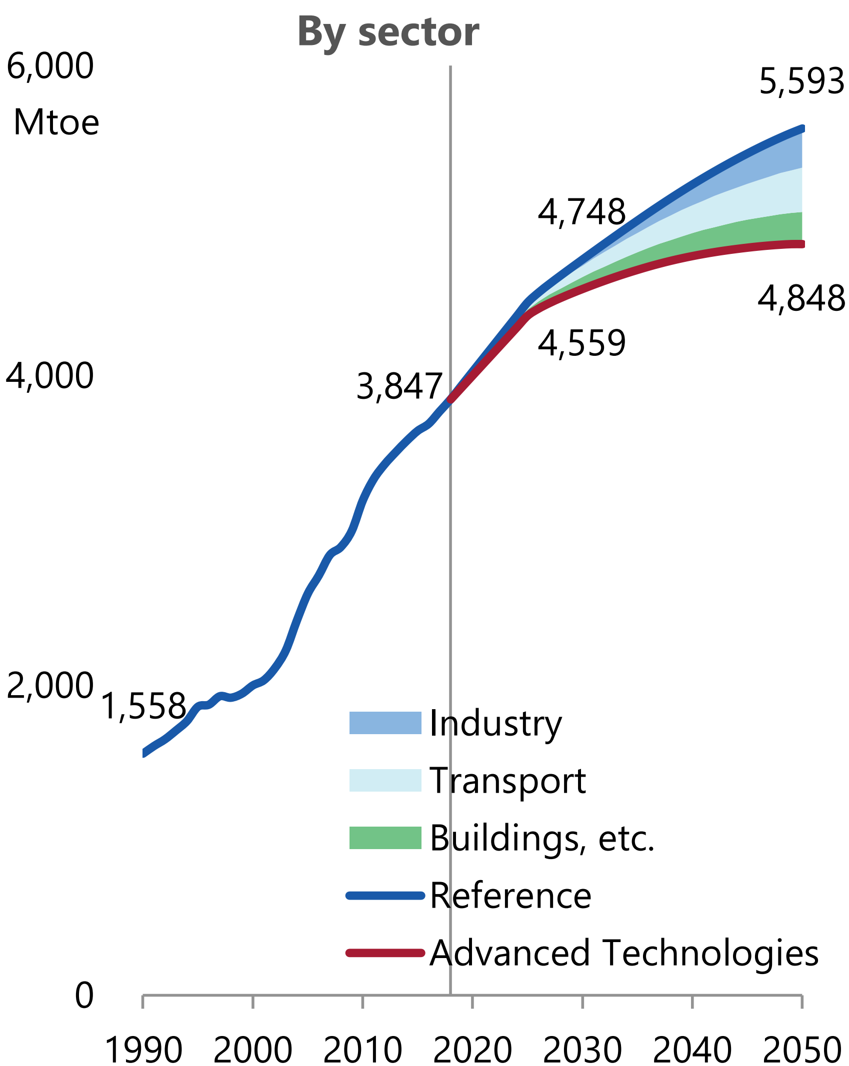


Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.

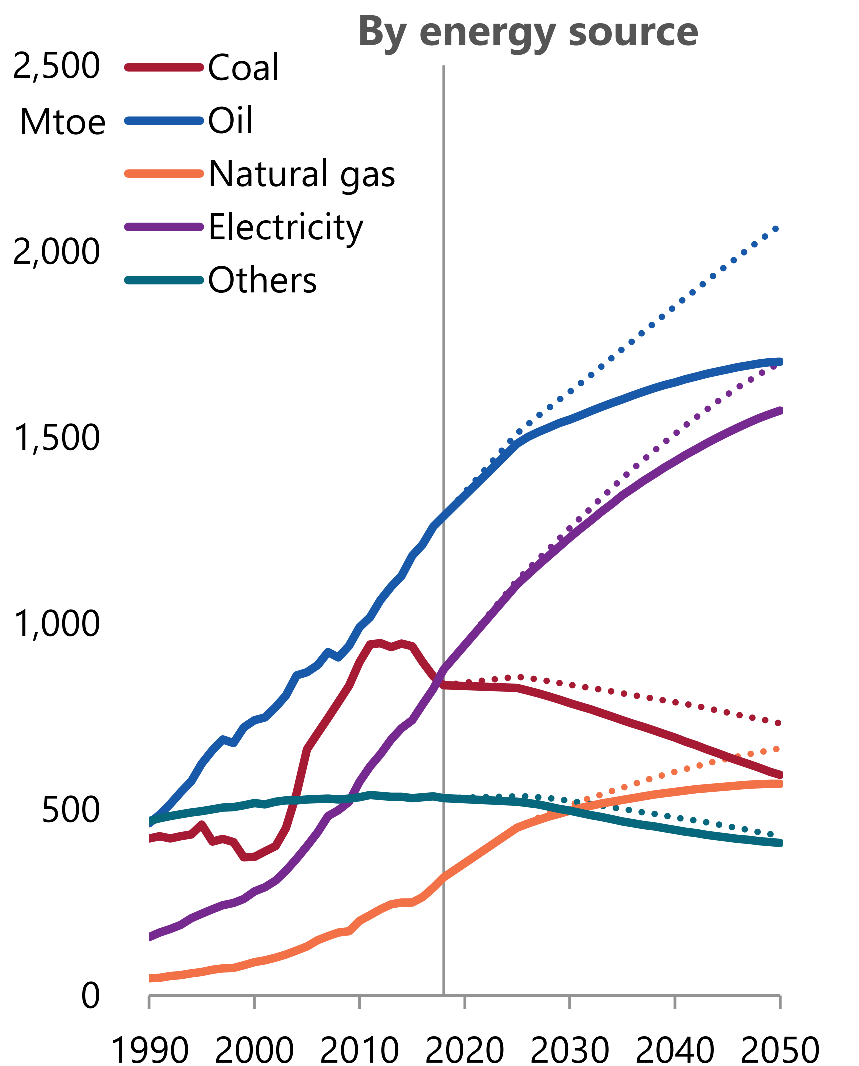


Note: Solid lines stand for Advanced Technologies Scenario and dotted lines stand for Reference Scenario.

Final energy consumption

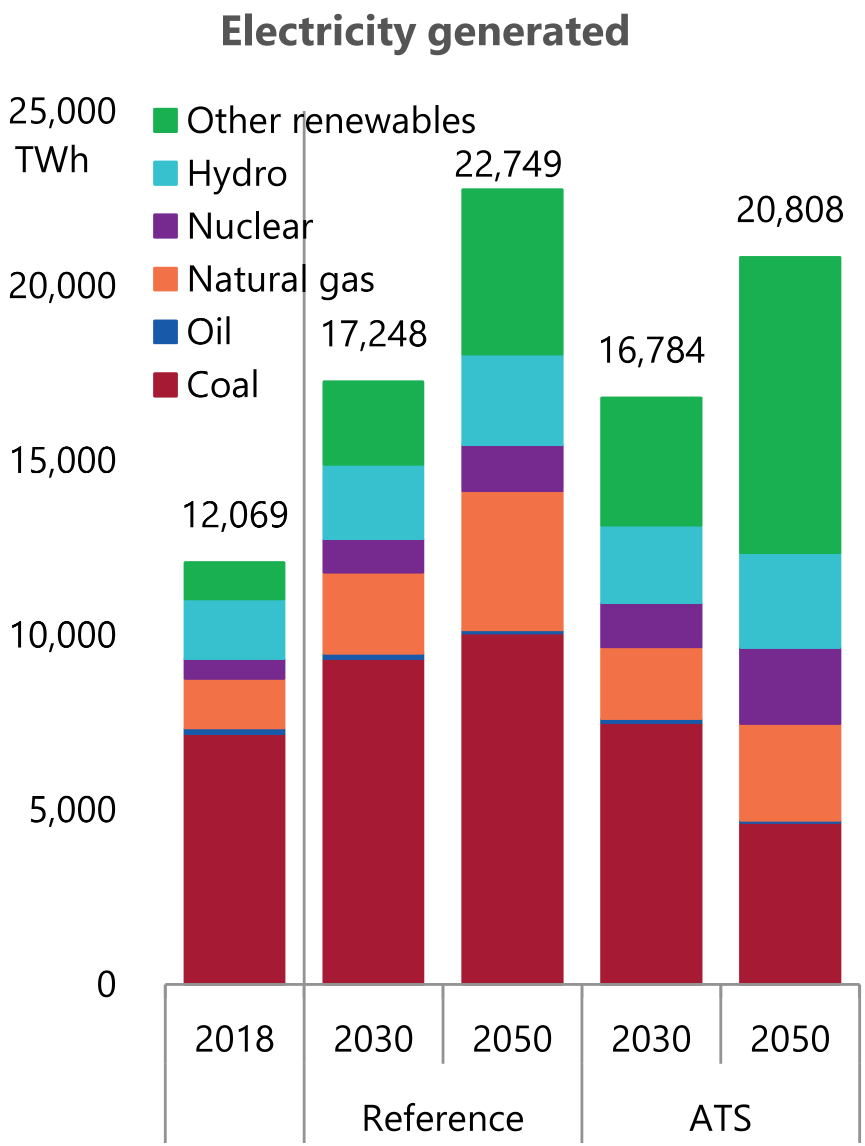


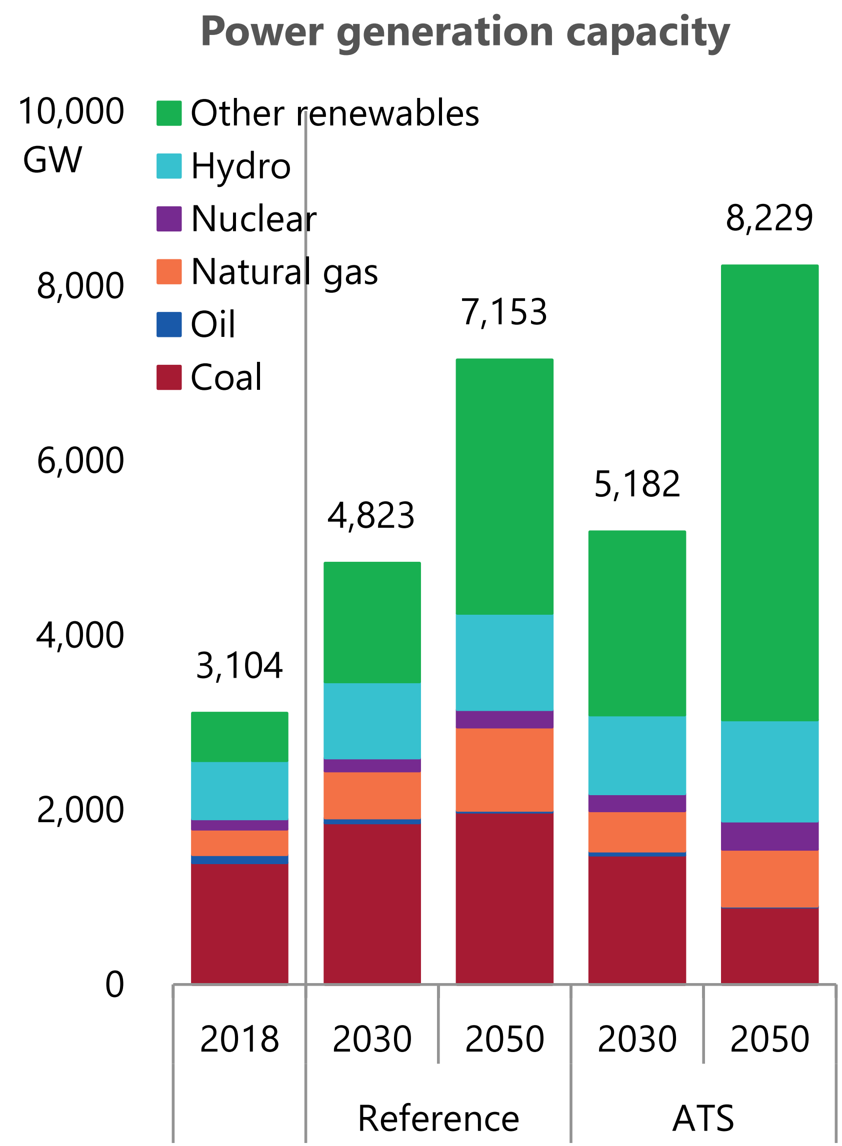
Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.



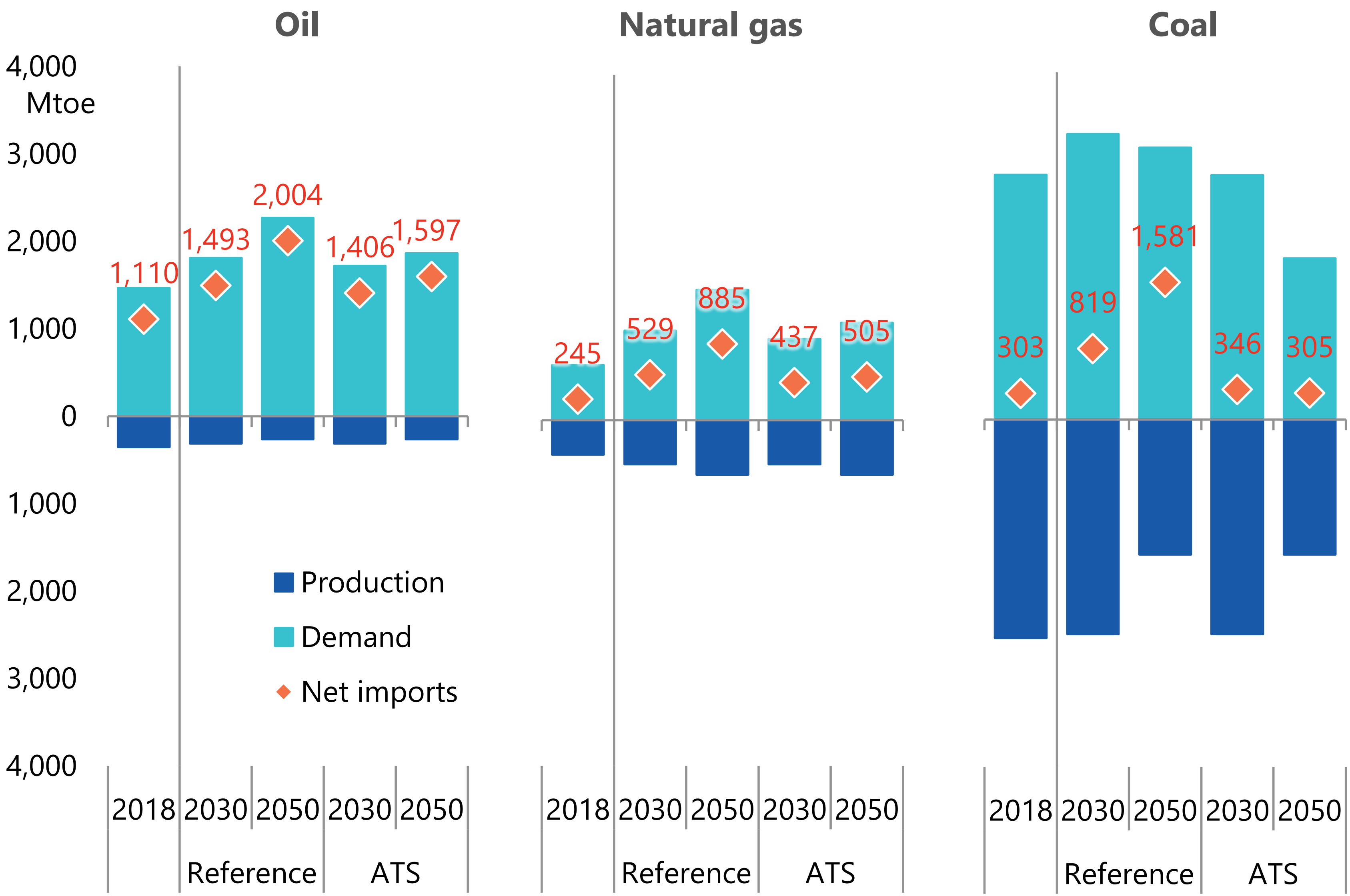
Note: Solid lines stand for Advanced Technologies Scenario and dotted lines stand for Reference Scenario.

Power generation mix



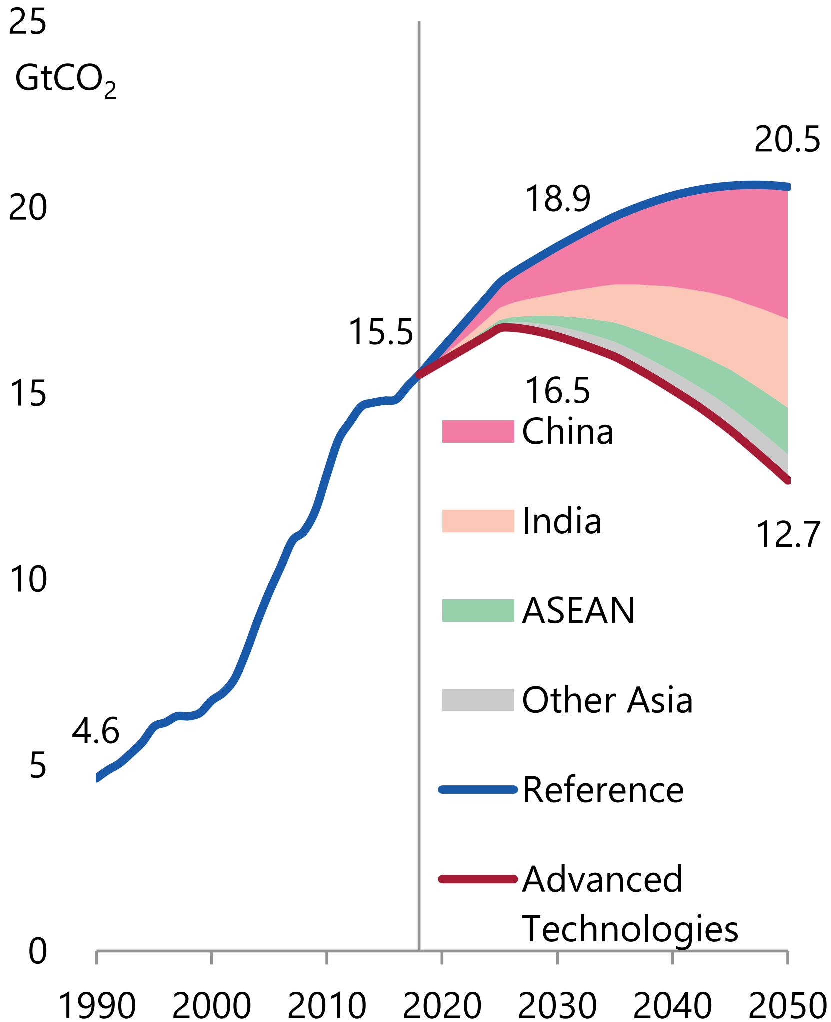


Supply and demand balance of fossil fuels

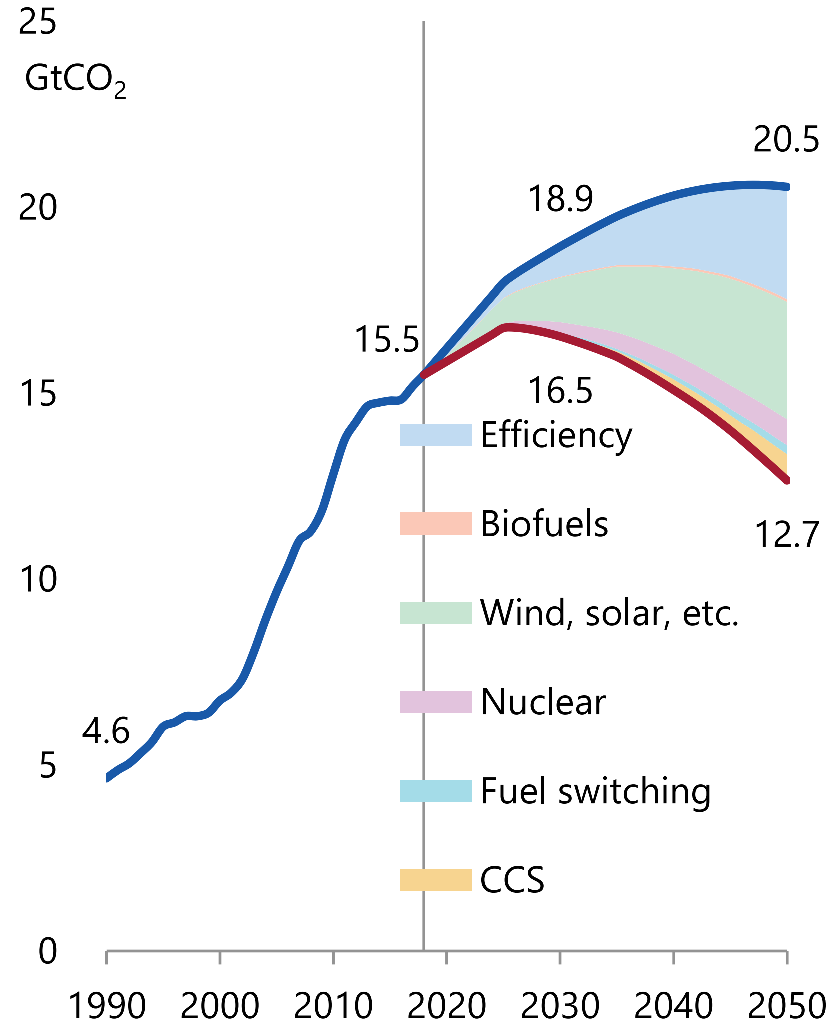


Energy-related CO_2 emissions

By region



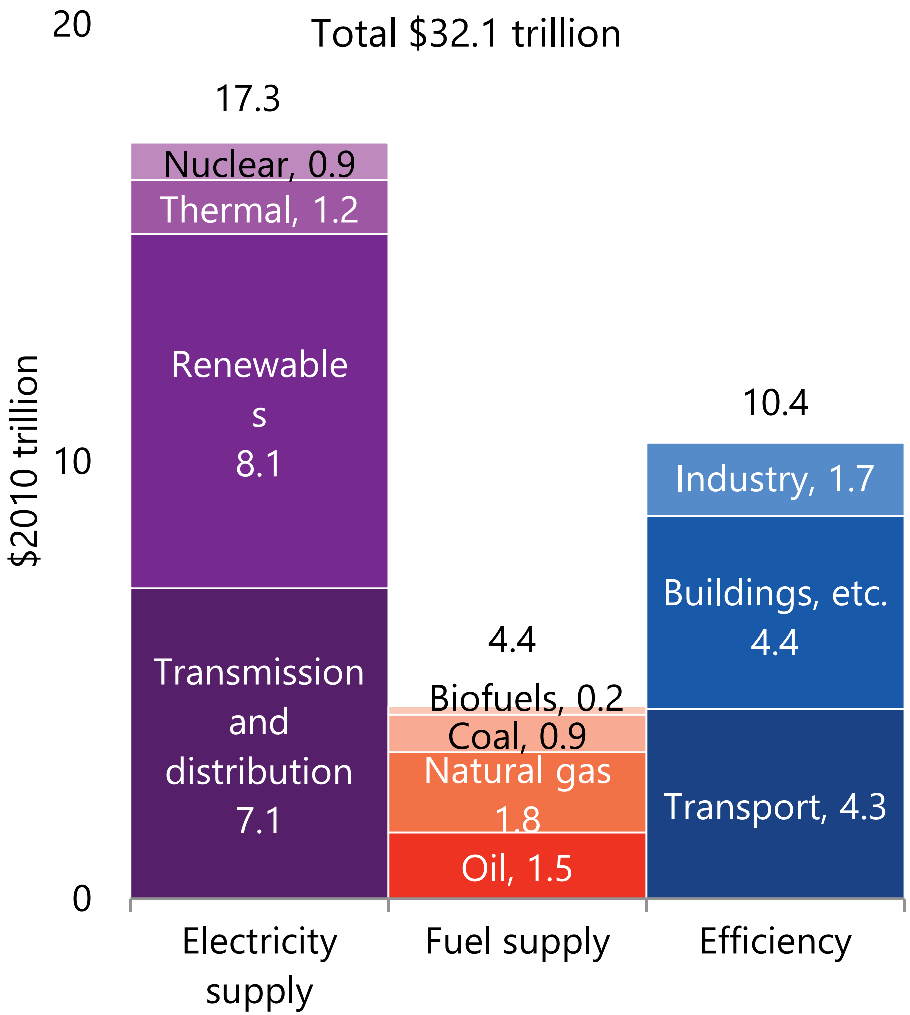
By technology



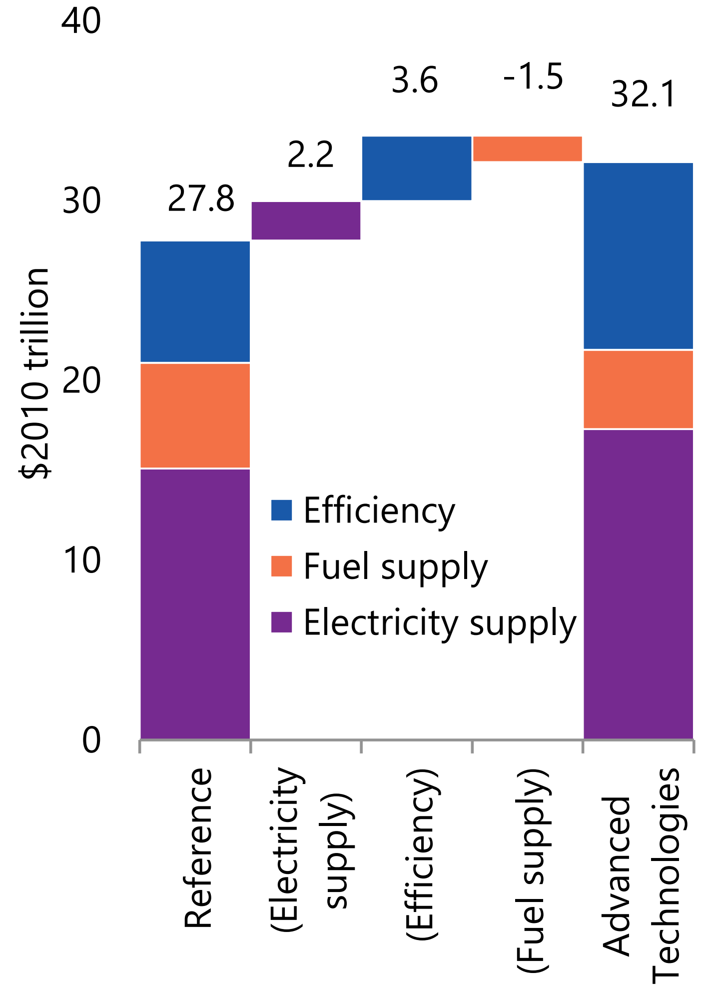
Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.

Energy-related investments (2019 – 2050)

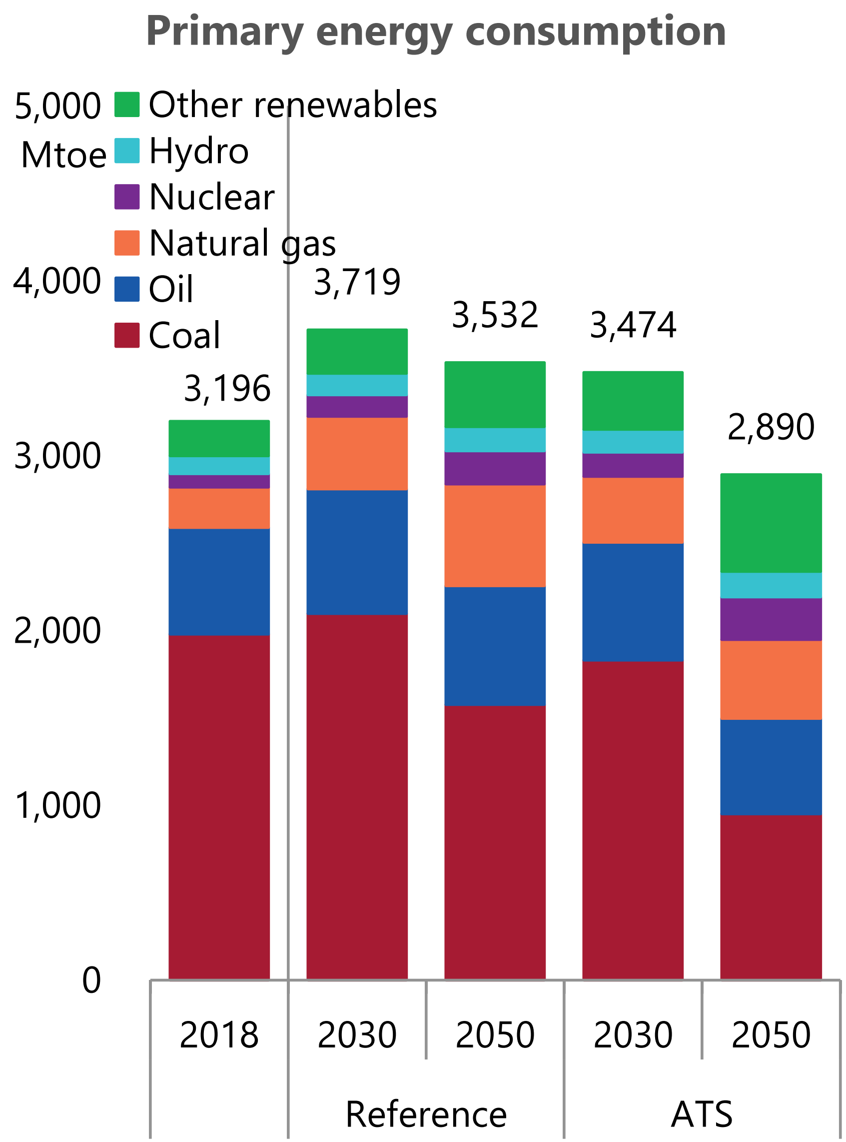
By sector

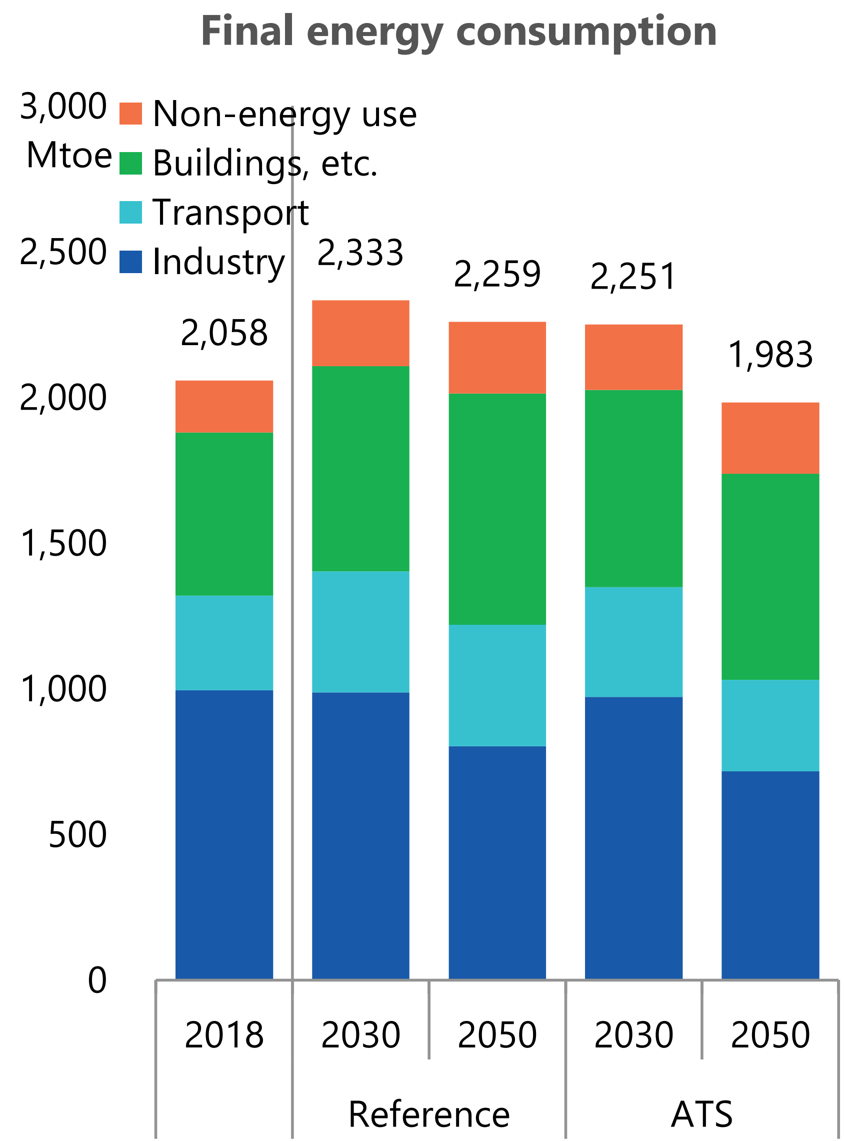


Changes from Reference Scenario

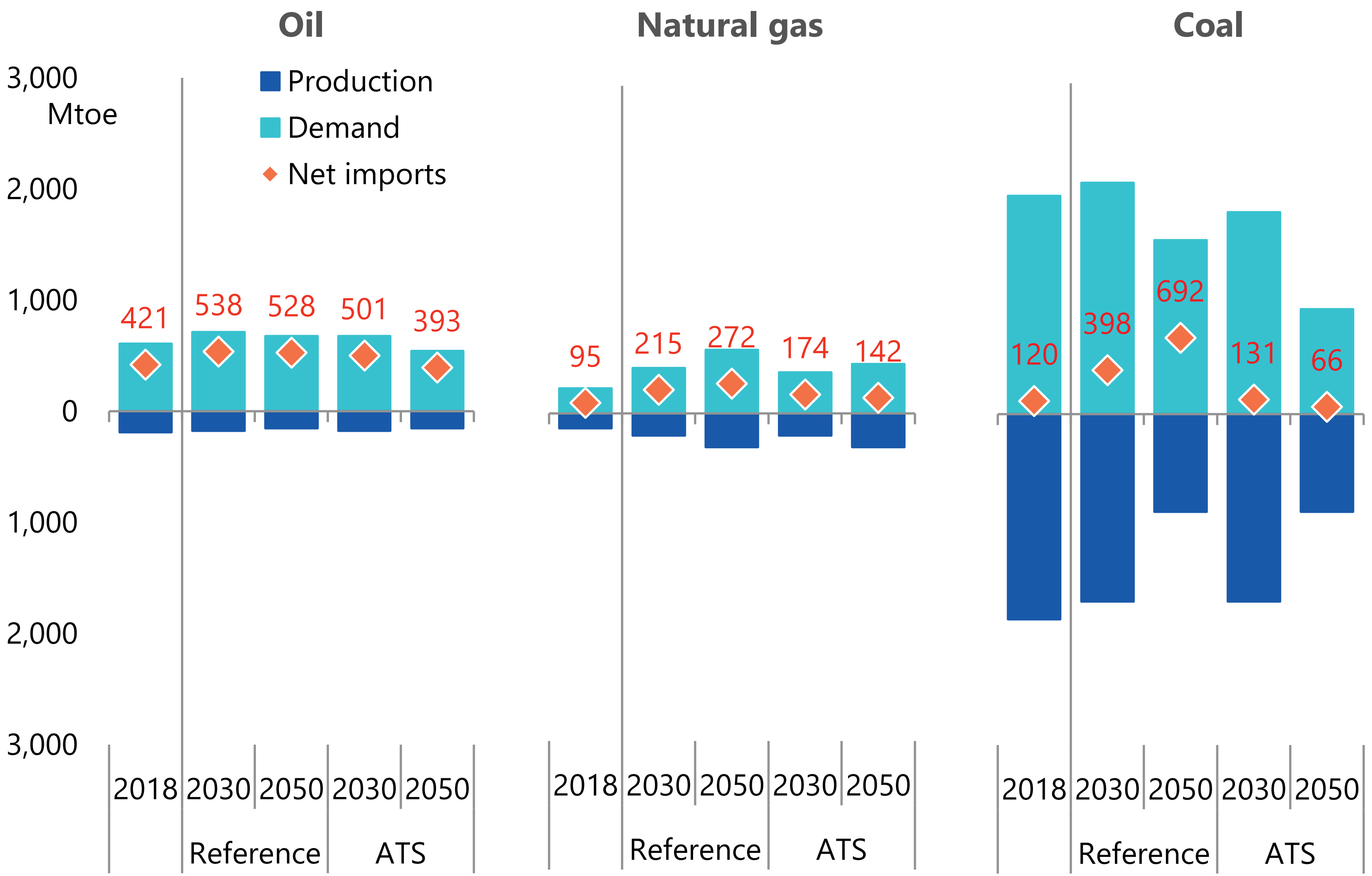


Energy consumption

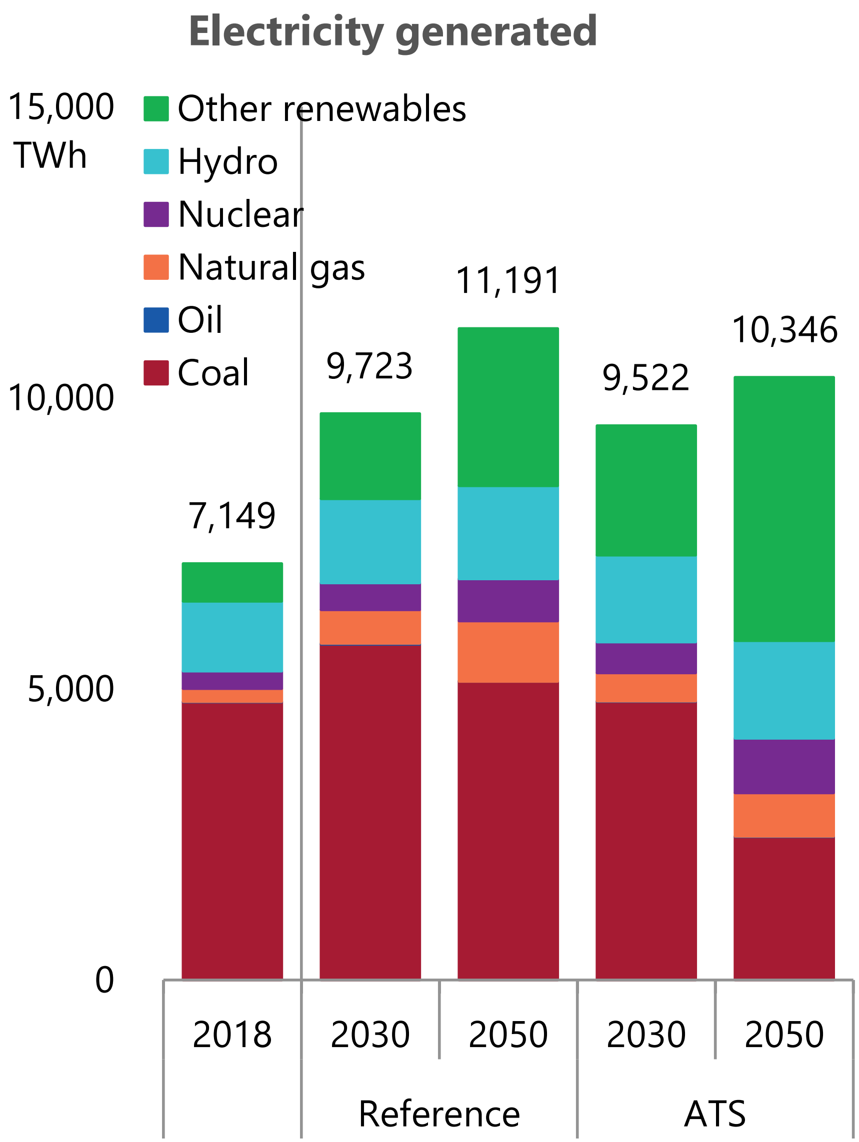


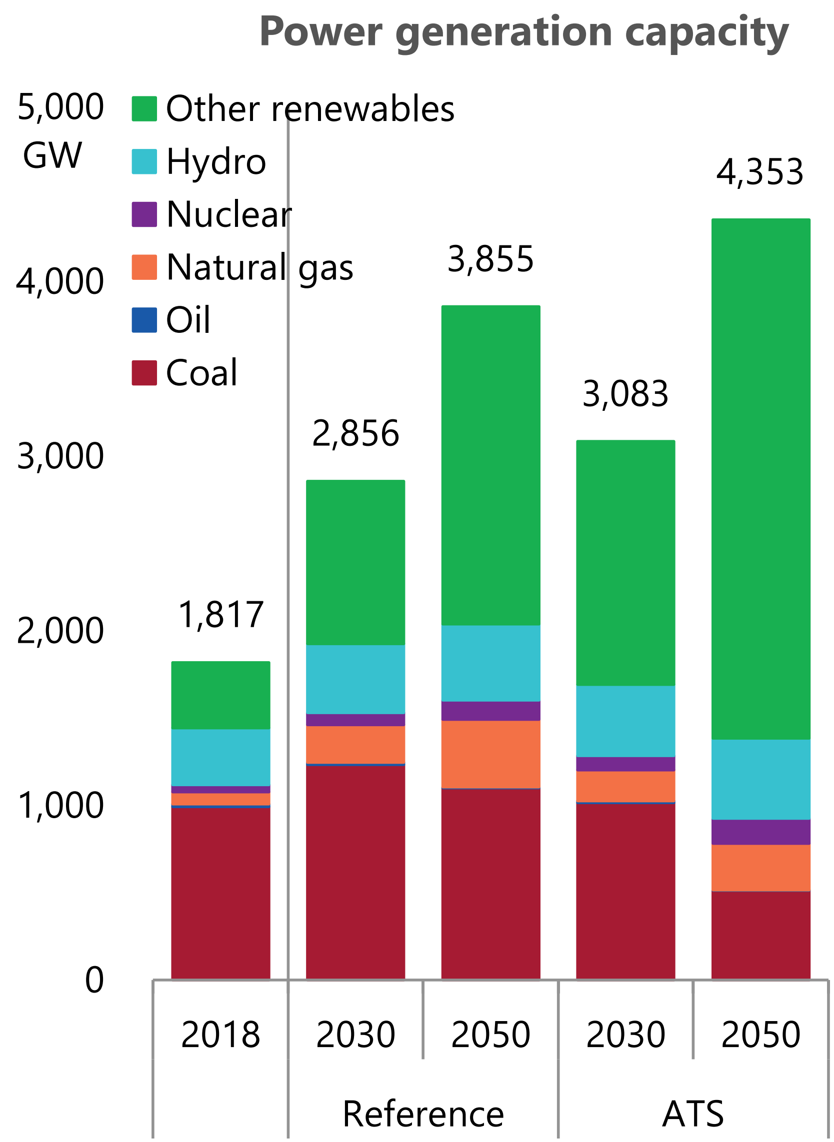


Supply and demand balance of fossil fuels

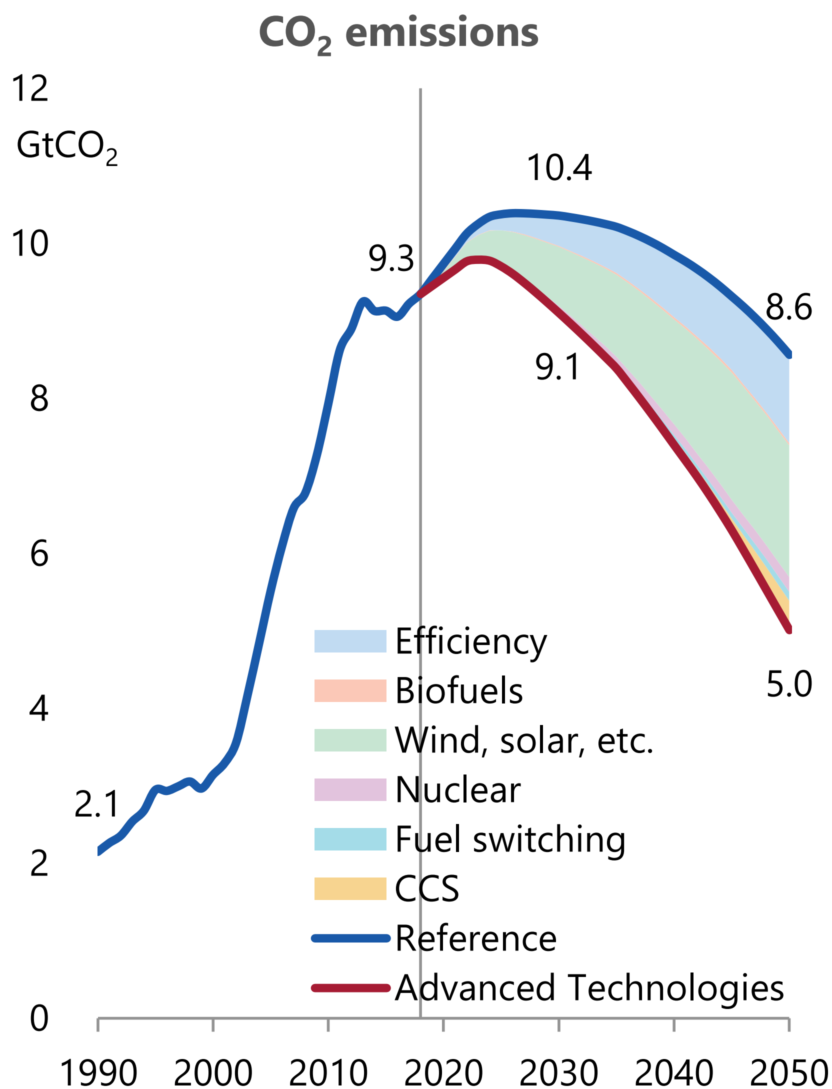


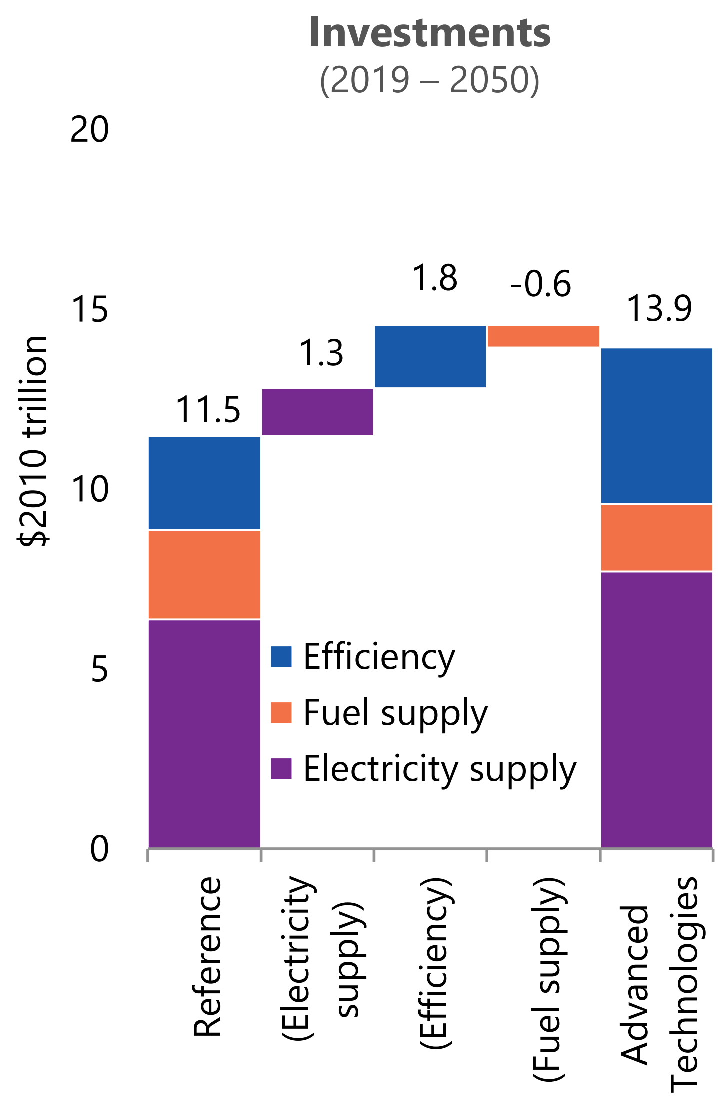
Power generation mix





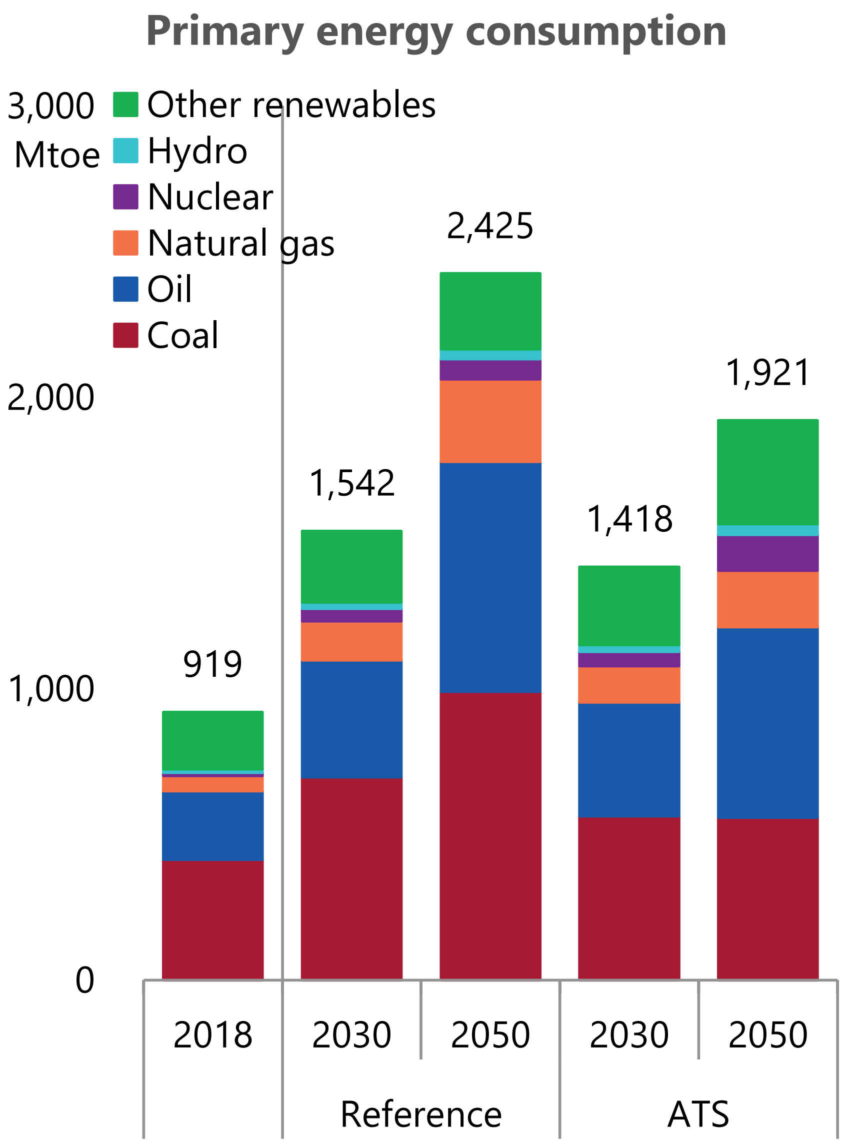
Energy-related CO_2 emissions and investments

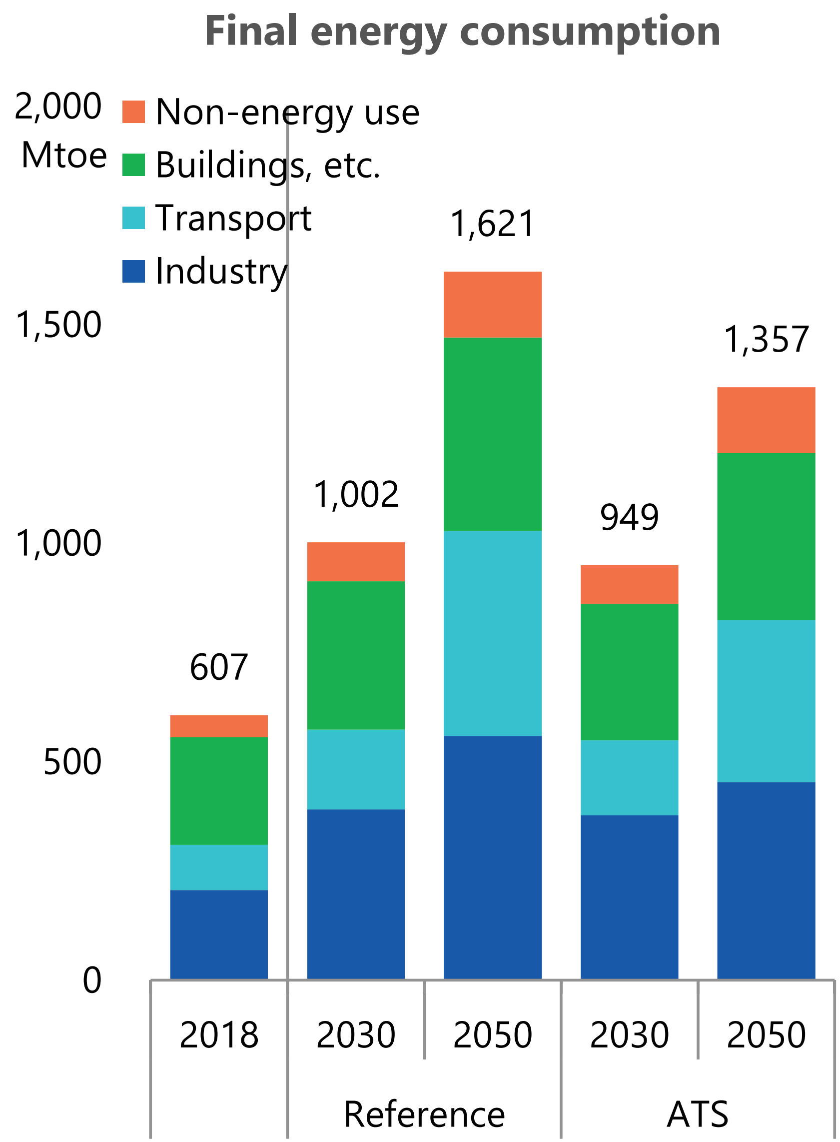




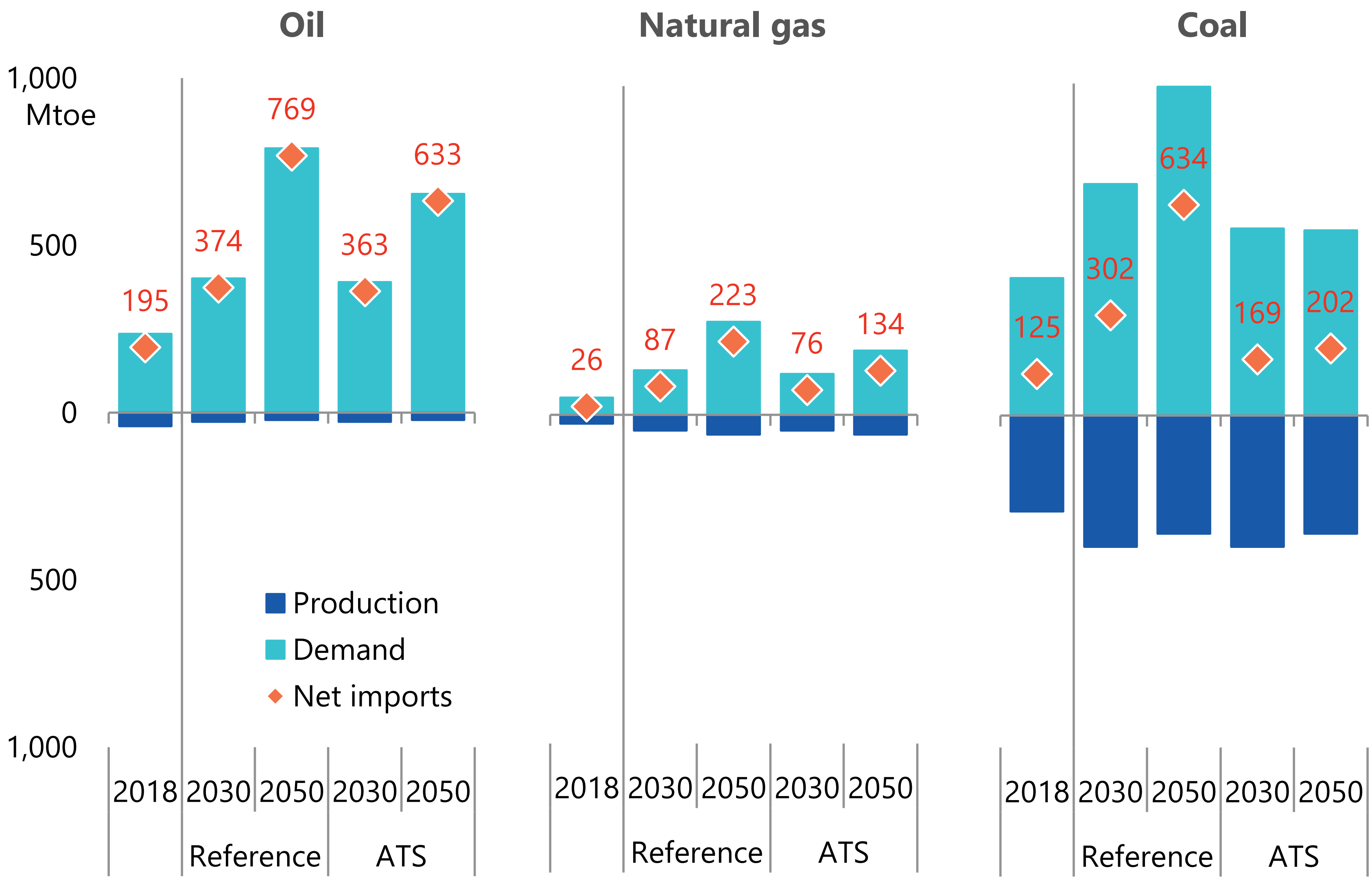
Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.

Energy consumption

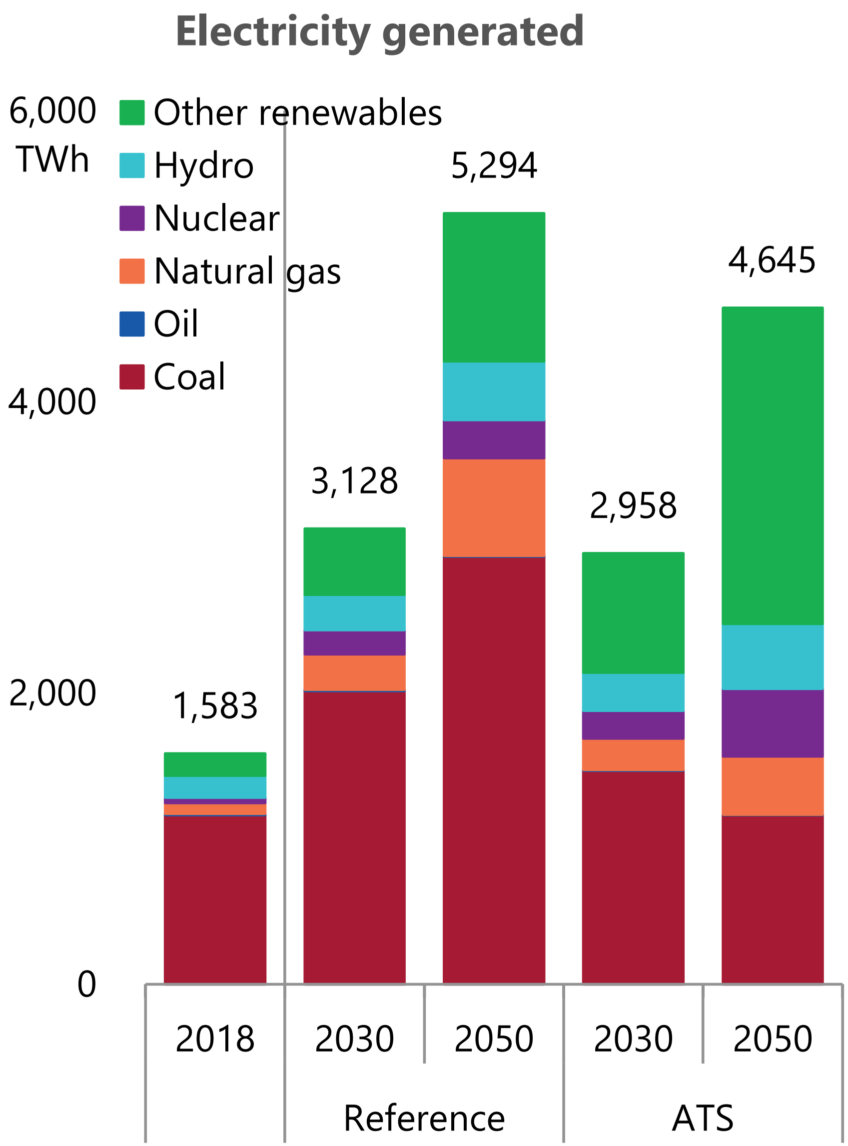


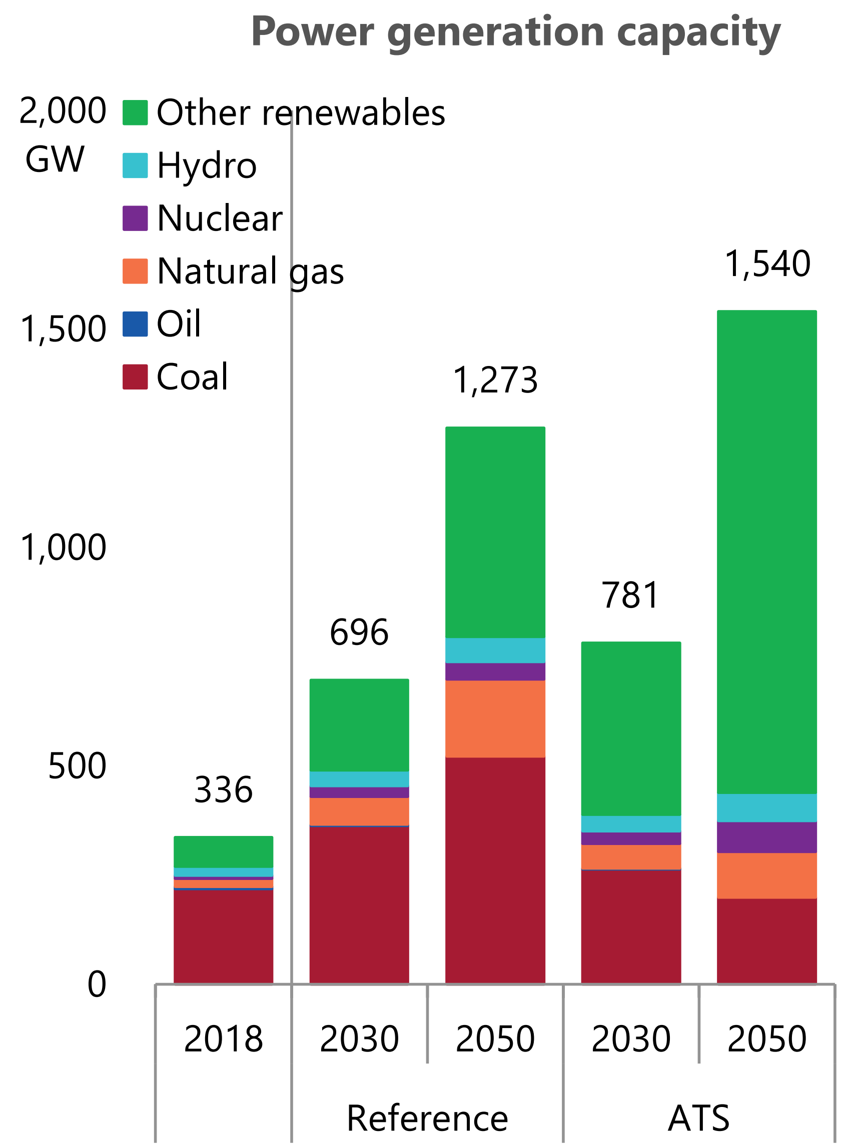


Supply and demand balance of fossil fuels

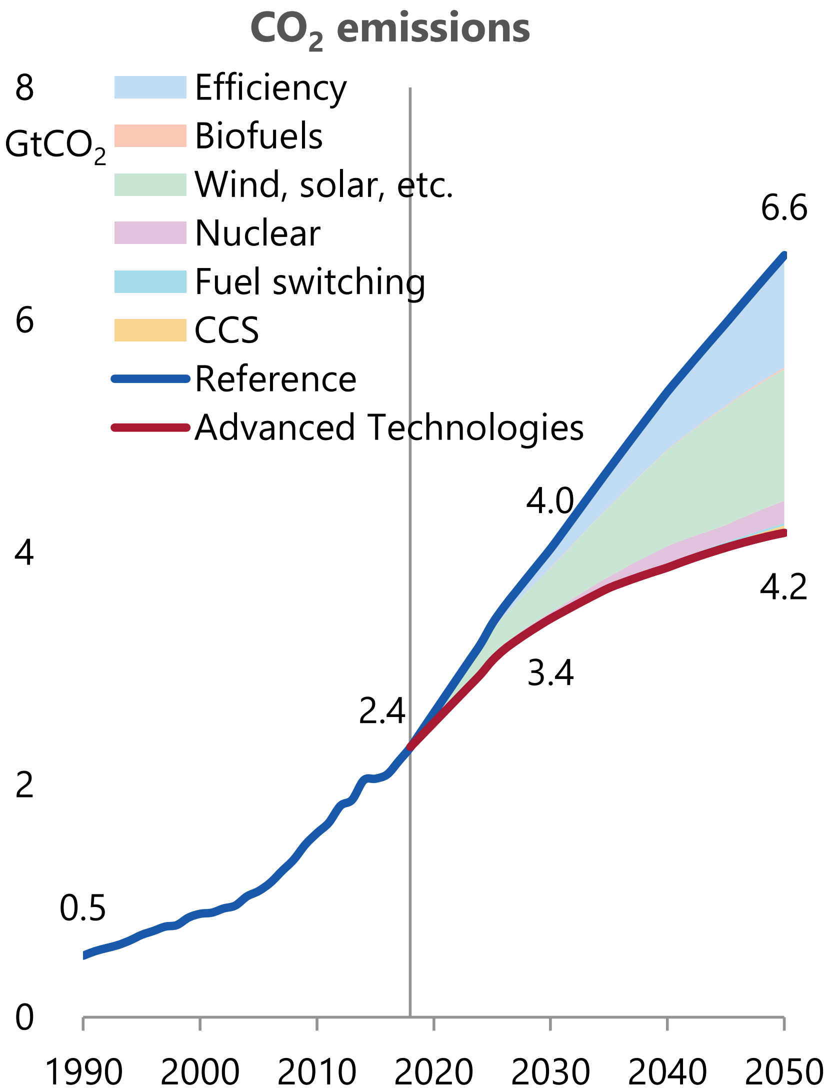


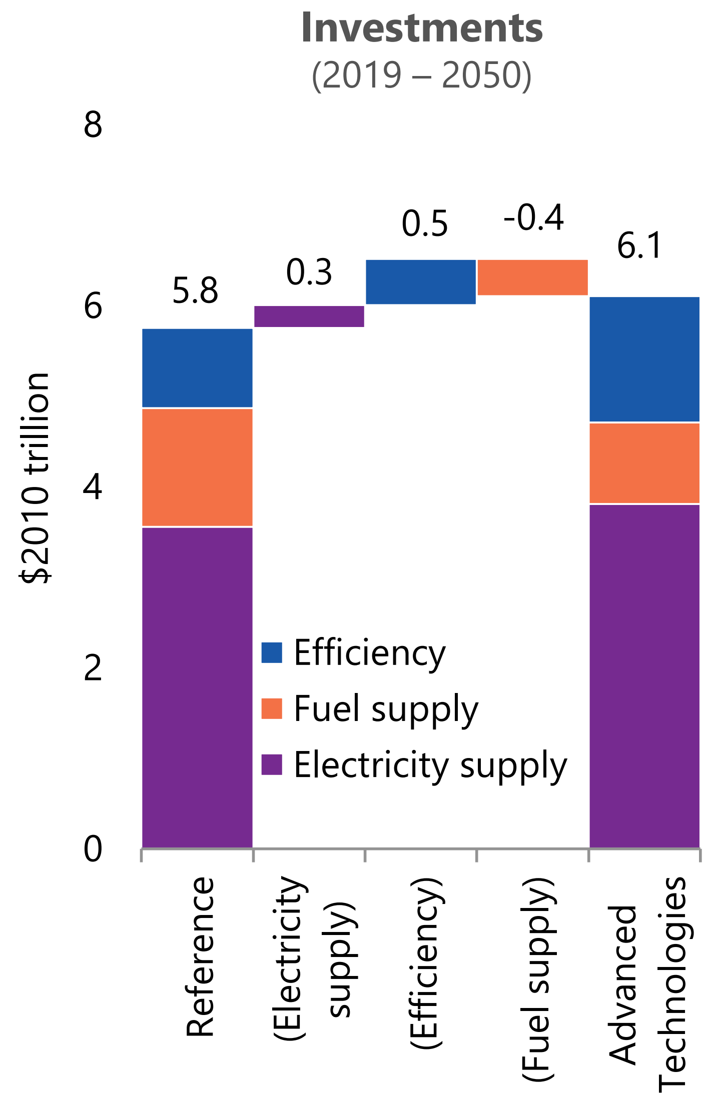
Power generation mix





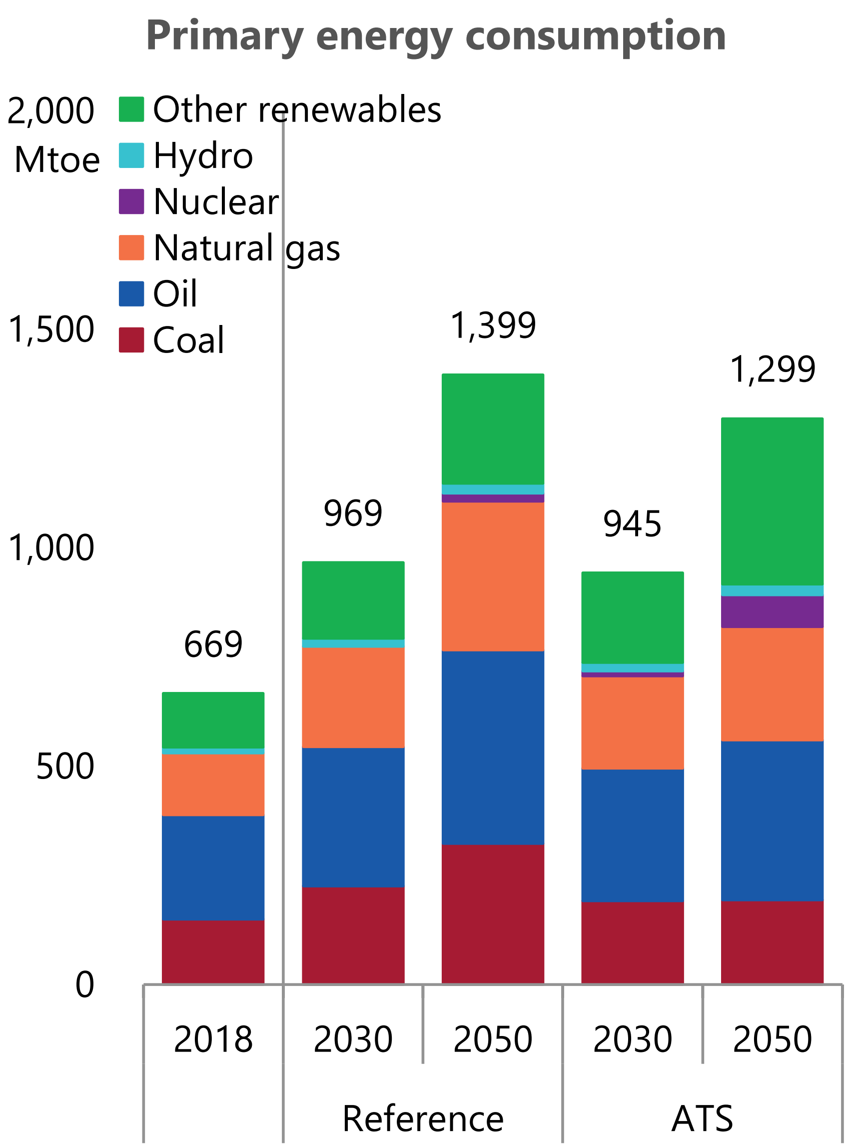
Energy-related CO_2 emissions and investments

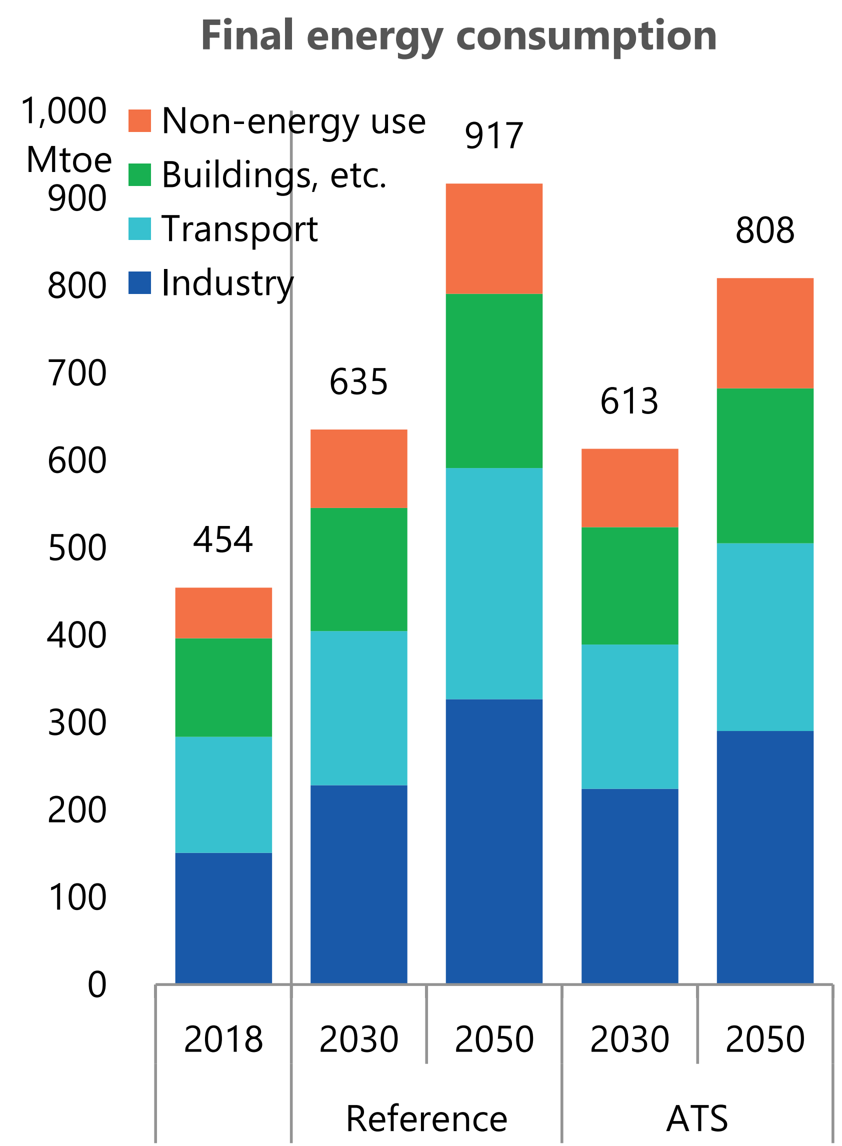




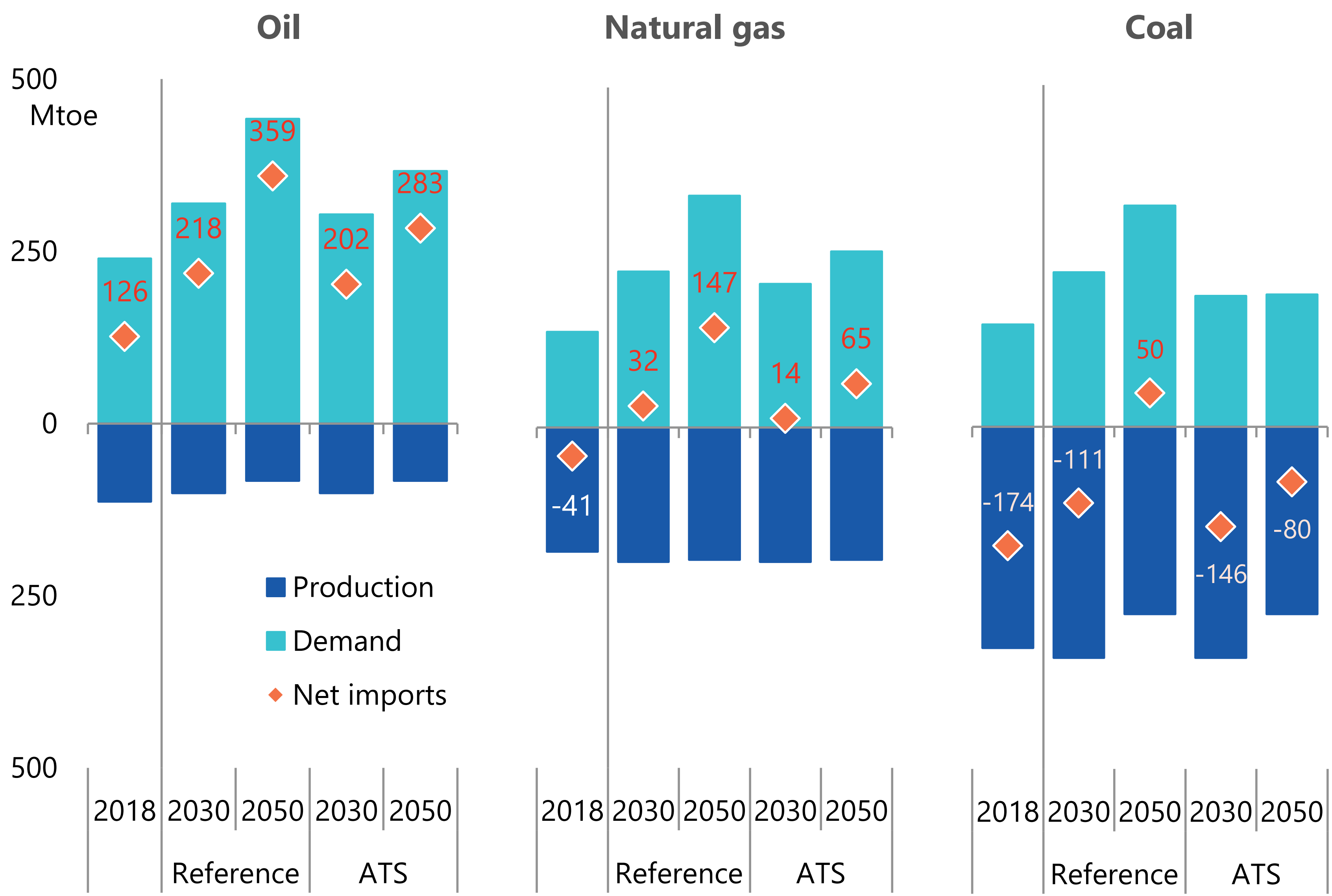
Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.

Energy consumption

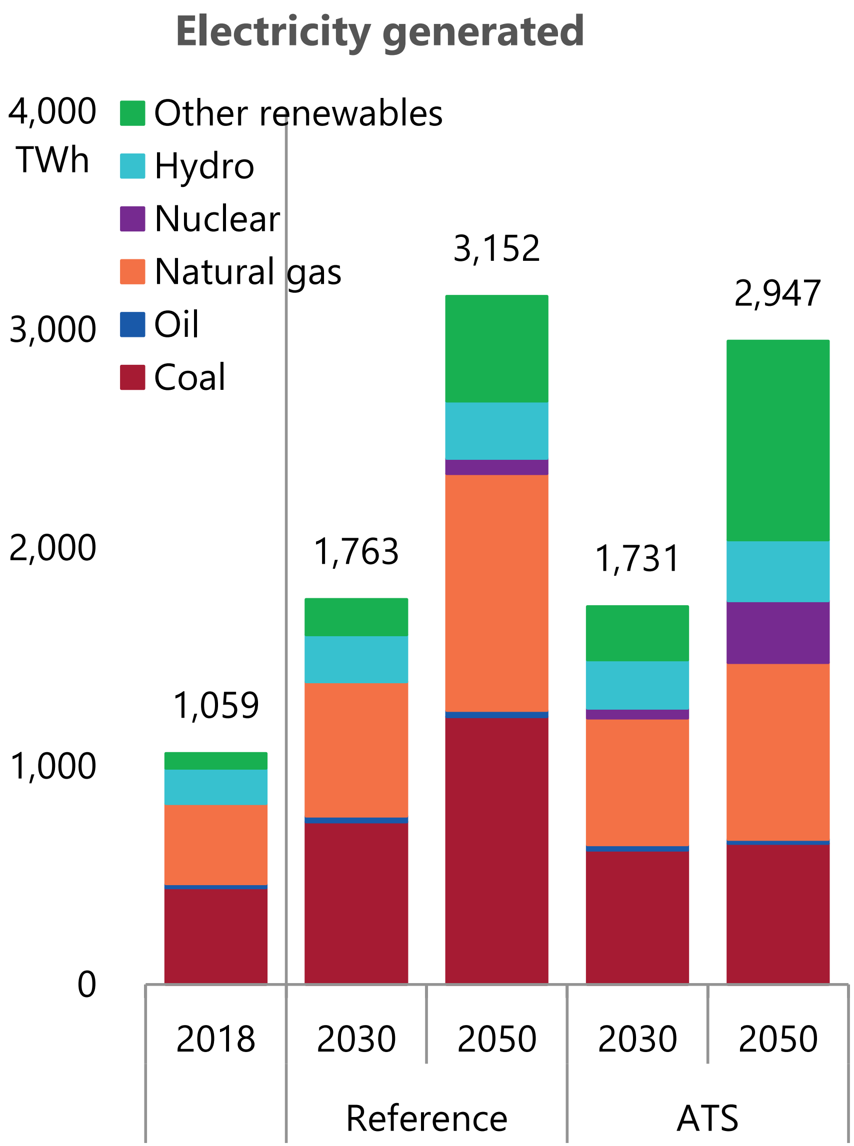


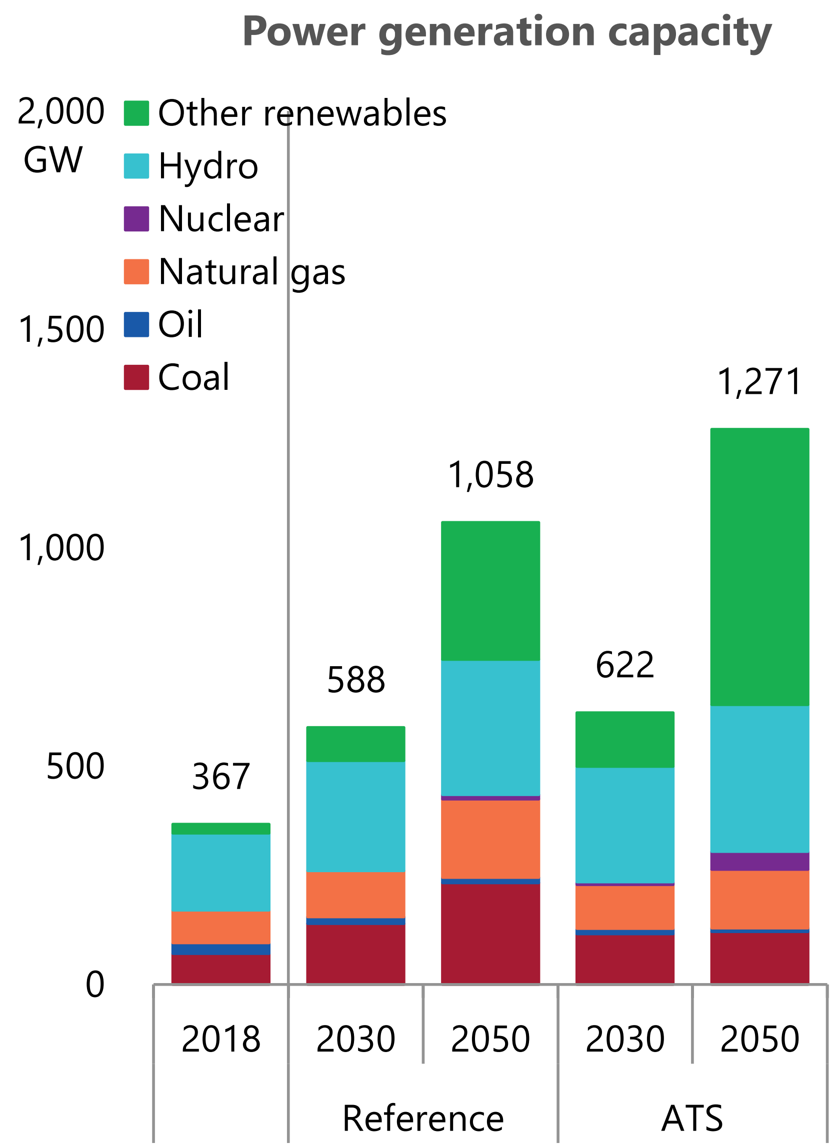


Supply and demand balance of fossil fuels

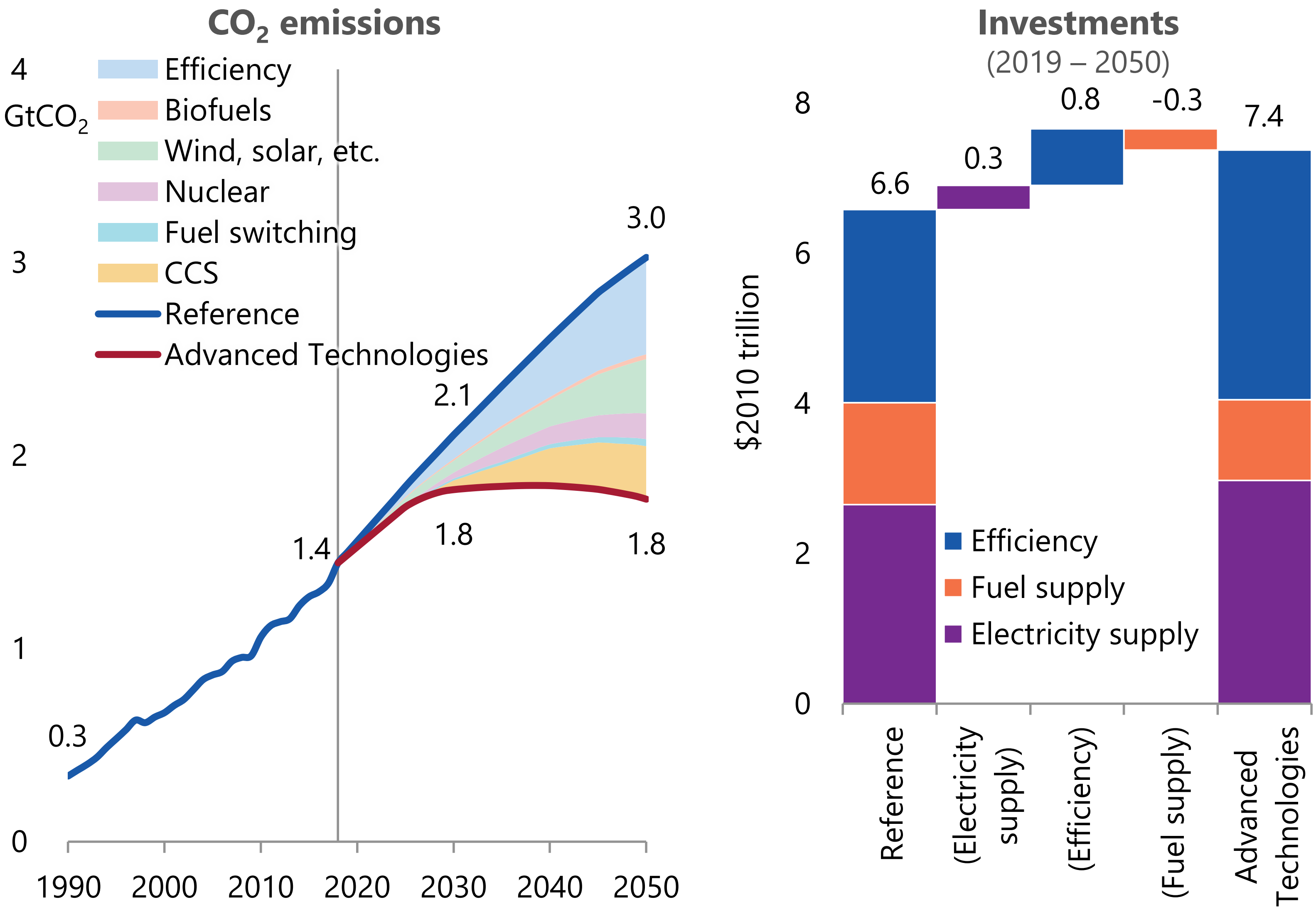


Power generation mix





Energy-related CO_2 emissions and investments



Note: See Figure 6-1 in Chapter 6 for the short-term impact of COVID-19.

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