

The future of fossil fuels: How to steer fossil fuel use in a transition to a low-carbon energy system

An analysis of fossil fuels trajectories in low-carbon scenarios
prepared by Copenhagen Economics for the Energy
Transitions Commission

January 2017 – Full report

Disclaimer

This working paper has been produced by Copenhagen Economics in support of the work being undertaken by the Energy Transitions Commission (ETC).

The paper has contributed to the ETC's report Better Energy, Greater Prosperity available on the [ETC website](#).

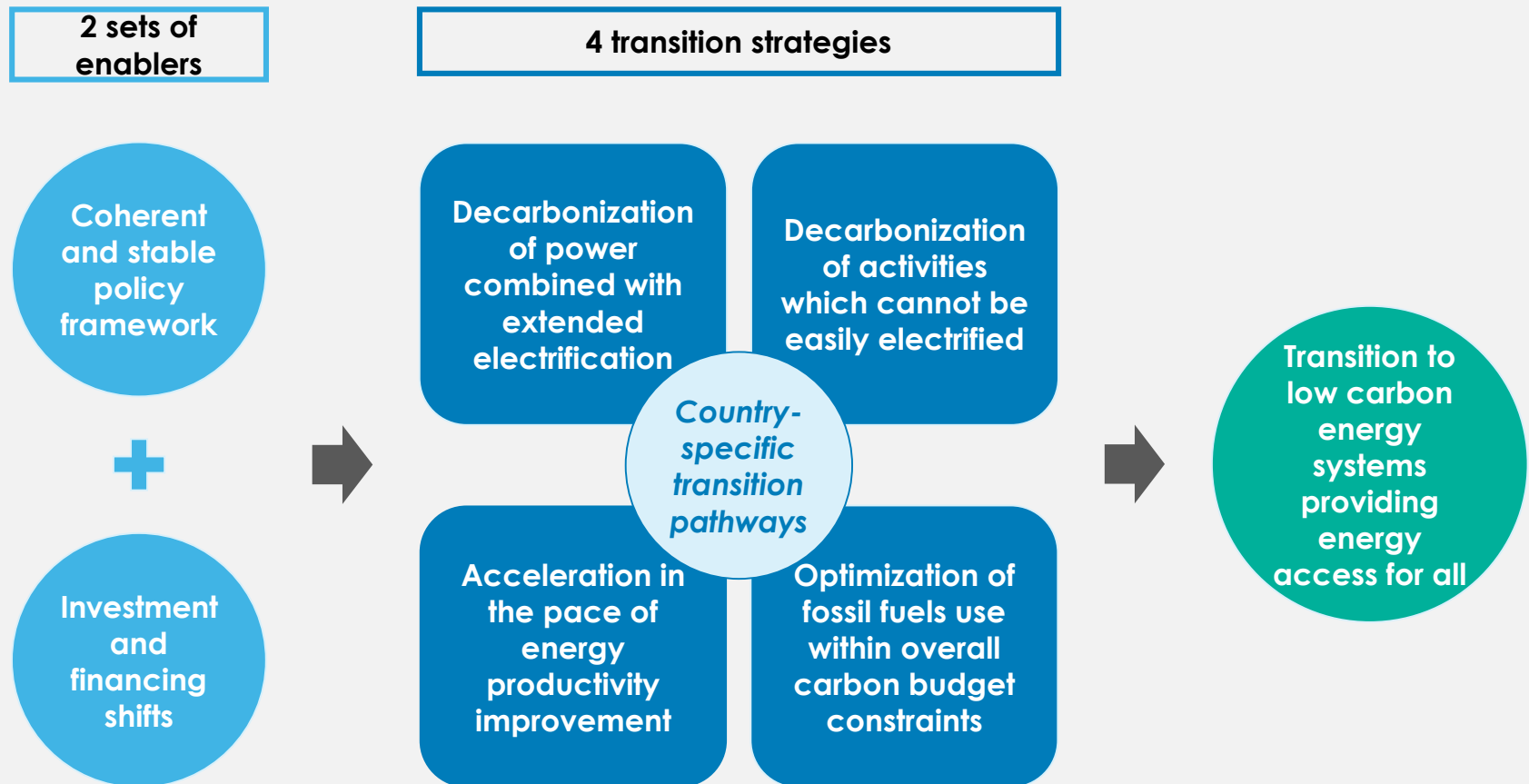
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This research paper supports the work of the ETC by analyzing fossil fuels trajectories in low carbon scenarios

The Energy Transitions Commission believes that accelerating energy transitions to low carbon energy systems providing energy access for all will require rapid but achievable progress along 4 dimensions. This research paper examines the implications of such a transition to a low-carbon energy system for the existing, fossil fuel-based energy system.



THE FUTURE OF FOSSIL FUELS: HOW TO STEER FOSSIL FUEL USE IN A TRANSITION TO A LOW-CARBON ENERGY SYSTEM

Research paper for the Energy Transitions Commission

Full report

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Summary Findings

1. Rapidly growing energy needs set the scene for an energy transition
2. A 2°C objective implies a strict carbon budget
3. Fossil fuel use would fall by one-third by 2040 to meet 2°C objectives
4. The role of fossil fuels changes by 2040 in a 2°C energy system
5. A 2°C energy transition has profound impacts on fossil fuel markets
6. Carbon capture is a key factor in a 2°C energy transition
7. Appendix: scenario methodology

Summary Findings – Energy needs and future emissions

Energy needs will grow by 60-80% over the next 25 years, accompanying economic development and growth. Absent a profound energy transition, CO₂ emissions would also increase by two-thirds or more.

- **Without an energy transition, emissions could grow by two-thirds**, to ~60 billion tonnes CO₂ per year. An energy transition must achieve rapid improvements in both energy and carbon intensity to prevent this growth, and even more to reduce emissions levels.
- **Population and GDP are likely to grow by ~20% and ~90%**, respectively, albeit with large uncertainty for economic growth in particular. Accompanying trends of urbanisation, industrialisation, infrastructure build-out, and a growing global middle class jointly lead to a large demand for energy services, from mobility to industrial production.
- **Energy intensity will continue to improve**, and by 2040 we might be able to generate 75% more income globally per unit of energy used. This depends on ongoing structural shifts to less energy-intensive economic activity as well as improving technology.
- **Even so, energy demand will increase by 50%** if developments follow the trends seen in the past. There is large uncertainty, with plausible range for future energy demand increasing anywhere between 30% to 60%.
- **The current energy system is highly carbon intensive**, with coal, oil, and natural gas providing 85% of all energy. Each tonne of “oil equivalent” (a unit of energy) used results in 2.7 tonnes of CO₂, and total emissions from energy and industry are 36 billion tonnes. Meeting future energy needs with this level of carbon intensity will see rapidly growing emissions.

Summary Findings – Carbon budgets

Limiting climate change depends on restricting *cumulative* emissions. The “carbon budget” to limit warming to 2°C amounts to ~900 billion tonnes of carbon-dioxide (Gt CO₂) from now until 2100. Achieving this requires that current emissions of 36 Gt CO₂ per year are halved by around 2040, and then rapidly brought to net zero levels.

- **The remaining carbon budget for a 2°C target is less than 900 Gt CO₂**, for all emissions from fossil fuels and industry to 2100 for a probability of two-thirds that warming will not exceed 2°C. This quantity of emissions is similar to the amount that was emitted between 1980 and 2015.
- **Keeping within the budget requires a transition to net zero emissions** before cumulative emissions exceed the budget. “Peaking” emissions levels per year is insufficient. Likewise, higher emissions today leave less room for emissions tomorrow.
- **Most 2°C scenarios see emissions halved by 2040.** This leaves room for an average of just ~4 Gt CO₂ per year, 2040-2100, or one-tenth of current emissions for a much larger economy. Technologies to remove CO₂ from the atmosphere (“negative emissions”) may be a prerequisite to achieve this, or to handle earlier “overshoot” of emissions.
- **A more stringent target rapidly reduces the budget.** The “well below 2°C” objective adopted in the Paris Accord implies a smaller budget. A 1.5°C target reduces the budget by almost 80%, to 200 Gt CO₂.
- **Fossil fuel reserves exceed the budget by a factor 3-6.** Coal reserves alone would create emissions more than twice its size (~2,000 Gt). Hydrocarbon reserves are more uncertain, with oil around 600 Gt and conventional gas 400 Gt (and unconventional reserves potentially much larger).
- **Substantial emissions already are locked in.** For example, one-third (~300 Gt) of the remaining 2°C carbon budget would be claimed if current power plants operated for their technical life. Addressing such “locked-in” emissions is thus a key aspect of an energy transition.

Summary Findings – Fossil fuel trajectories for a 2°C outcome

In a successful transition scenario, fossil fuels could represent 60% of primary energy by 2040 – compared to 85% today. This reduction is required even if very large volumes of carbon capture are feasible, and has profound consequences for patterns of energy use and energy markets.

- **A 2°C pathway requires a 30-50% reduction in fossil fuel use by 2040.** Even with high levels of carbon capture (~10 Gt CO₂ per year or more after 2040), consumption would need to be one-third lower in 2040 than today.
- **This implies a very rapid energy transition.** Meeting energy needs with fossil fuels would require an increase by 60% to meet energy needs. Achieving a reduction by 30+% therefore implies the need both to sharply reduce energy demand growth (through increased energy efficiency/productivity), and to scale up zero-carbon energy very rapidly.
- **The impact differs across fuels:**
 - A sharp and immediate decline in coal consumption by two-thirds. As key industrial uses of coal are difficult to replace, the decline in coal used for power production needs to be steeper still.
 - A peak in oil consumption in the 2020s, and then a fall by one-third by 2040, primarily by finding alternatives across a wide range of transportation uses.
 - A limited rise in natural gas consumption, with 2040 use at roughly current levels and concentrated in uses where alternatives are hard to scale (some power generation, industry, and heating).
- **Carbon capture is important in most such scenarios**, but does not avoid the need to reduce fossil fuel use. These consumption levels depend on carbon capture of 7+ Gt CO₂ by 2040, rising further thereafter to more than 10 Gt per year. Without carbon capture, consumption would have to fall still faster: to half of current levels already by 2040, and then rapidly to zero.

Summary Findings – The role of fossil fuels by 2040 in a 2°C scenario

Fossil fuels continue to provide the majority of energy in 2040 even in a 2°C scenario. However, the pattern of use will change significantly: away from coal and towards gas, and increasingly concentrated in industry, where alternatives are more difficult to find.

- **Coal would be increasingly concentrated in steelmaking and industry.** This includes as feedstock for steelmaking but also for high-temperature applications (notably, metals and minerals). By 2040, most of thermal coal use in the power sector would be phased out, even if carbon capture and storage/utilisation (CCS/U) could be mobilised. Coal consumption therefore would be increasingly concentrated in metallurgical coal, and in a small amount of residual coal-fired power that has not yet been phased out, or fitted with carbon capture.
- **Oil would be concentrated in transport use and as feedstock for chemicals production.** A significant share of future passenger transport needs would need to be served through electrification, modal shifts, and increased efficiency. In other transport, much depends on the availability and desirability of using biofuels at scale. Applications where replacing oil is particularly difficult include heavy-duty road transport, aviation, and shipping. By 2040, some 25% of oil may be used as feedstock for chemicals (compared to 10% today).
- **Natural gas would continue to be used across the energy system.** In power, it has half the emissions intensity of coal and therefore can persist longer. However, by 2040, its global share in the power sector must decline to 10-15%, even with substantial CCS/U volumes. In buildings, natural gas use for heating and hot water is replaced to a significant extent by electrification and increased efficiency, while industrial use may increase, as natural gas provides a cleaner alternative to coal for high-temperature heat.

Summary Findings – Fossil fuel markets and investment

A 2°C energy transition would have profound implications for fossil fuel markets. The primary impact is on the rate of growth and resulting lower prices. However, even in a rapid energy transition, continued investment in hydrocarbon production capacity would be required, as most of supply in 2040 would come from new fields.

- **Fossil fuel prices would be lower in a 2°C scenario**, reflecting less need to mobilise high-cost reserves to meet demand. The uncertainty about resulting technology and market dynamics is large, but a range of assessment suggest significant change.
 - For oil, prices may fall from USD 90-120/bbl in a reference case, to 60-80/bbl. Consumers would save ~USD 1 trillion per year, even at the lower demand levels.
 - For natural gas, prices vary regionally, but on average may fall from USD 10 to 6/MMBTU. The regional impact differs significantly depending on transmission infrastructure.
- **Continued investment will be necessary**: the majority of 2040 hydrocarbon supply would come from new developments even in a 2°C scenario.
 - Production from existing fields declines at 4-6% per year, faster than demand declines even in a stringent 2°C scenario.
 - Some 60% of oil demand and 75% of natural gas demand in 2040 will be met by fields that are yet to be developed.
- **Some 70% of investment in oil and gas extraction will therefore still be required in a 2°C scenario compared to a reference case**. Cumulative investment in upstream oil production falls from approx. USD 14 trillion in a baseline scenario to USD 10 trillion (-25%), while natural gas investment falls from USD 6.7 to 4.4 trillion (-35%). Investment rates start to fall off from the 2030s.

Summary Findings – Carbon capture in a 2°C energy transition

Carbon capture plays a major role in pathways to limit warming to 2°C, with many analyses predicated on volumes of 10 or even 20 Gt CO₂ of CCS/U per year. However, CCS/U faces large barriers, and there may be other solutions: process change, bioenergy, and hydrogen in industry; renewable energy in power; and different forms of “negative emissions” technologies.

- **Very large volumes of carbon capture feature in nearly all 2°C scenarios.** Volumes reach close to 10 Gt by 2040, and then 20 Gt (or even 40 Gt) per year.
- **We define three CCS/U scenarios** based on existing pathways, to analyse the impact on fossil fuels.
 - No CCS/U: carbon capture is not available. Only a handful of scenarios find it is possible to meet future energy needs under these conditions.
 - Central CCS/U: carbon capture reaches 8 Gt, of which 3 Gt on fossil fuels. This level of CCS/U requires 2040 fossil fuel use to fall by one-third on current levels.
 - High CCS/U: carbon capture reaches 18 Gt/year after 2040. Although the majority of available pathways assume such volumes, the feasibility is highly speculative.
- **Reaching even the central CCS/U scenario faces large challenges of scale, infrastructure, and cost:**
 - Scale: There are fewer than 30 carbon capture plants in the world. Volumes of 7-8 Gt by 2040 would require more than two installations each week 2020-2040.
 - Infrastructure: carbon capture of 7-8 Gt per year would require capture, transport, and storage of a volume of CO₂ similar to current total oil and natural gas production.
 - Cost: carbon capture is unusually dependent on a strong and predictable carbon price, and unlike other mitigation options have few other benefits or drivers.
- **CCS/U may be particularly important in industry.** More than half of remaining fossil fuel use may be in industry by 2040, making carbon capture key to a continued energy transition towards net zero emissions. Other options include process changes, bioenergy, and hydrogen.
- **Negative emissions are a feature of nearly all analyses that meet a 2°C objective** while meeting energy needs. Most analyses rely on bioenergy and CCS/U, which is currently unproven at scale.

Summary Findings

1. Rapidly growing energy needs set the scene for an energy transition

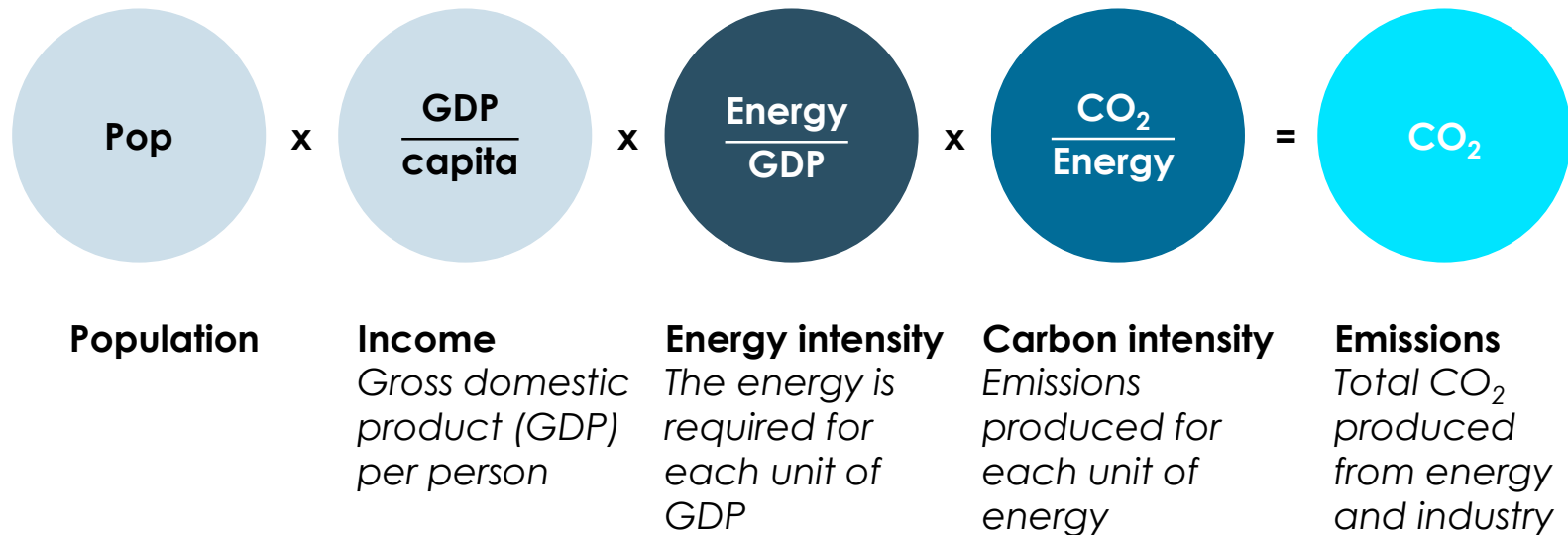
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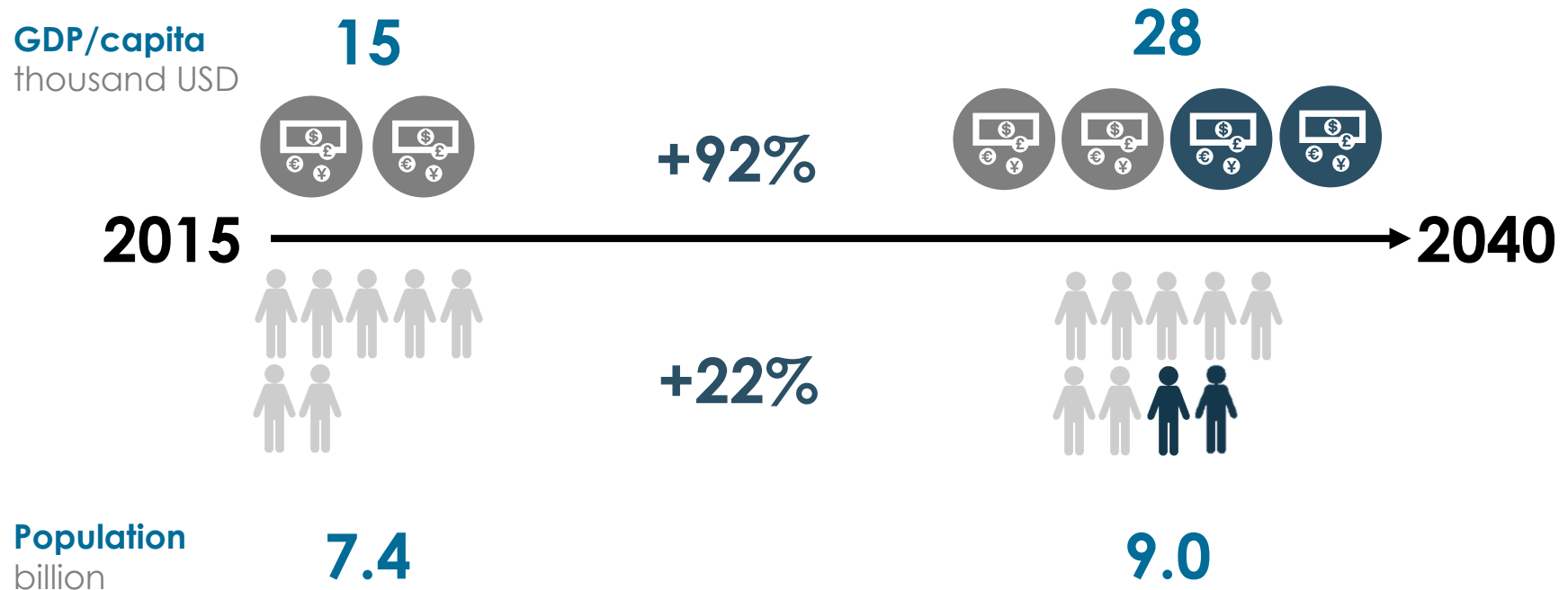
Future emissions depend on economic growth, the energy needed to drive it, and how polluting the energy will be



We draw on a range of scenarios to characterise an illustrative “reference” case for energy use and CO₂ emissions in the absence of an energy transition:

- The AR5 database: a collection of 30+ “baseline” scenarios from a range of research groups, collated for the work of the Intergovernmental Panel on Climate Change
- International Energy Agency projections in the Energy Technology Perspectives
- OECD long-term scenarios for GDP and economic development

Increased population and higher incomes underpin a rapid increase in future demand for energy



Note: GDP in terms of PPP (2005 USD). GDP projection up to 2040 from OECD Long-term baseline projections.

Source: Historical data from UNPD (population), OECD (2014) Dataset: Economic Outlook No 95 - May 2014 - Long-term baseline projections (GDP)

Transport needs are expected to grow by ~80% with increasing wealth, trade, and urbanisation

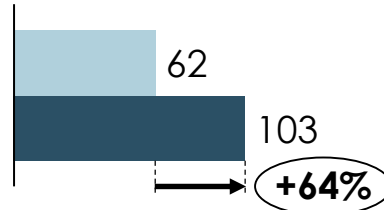
2015
2040

EXAMPLES

Baseline development of key energy services

Passenger travel

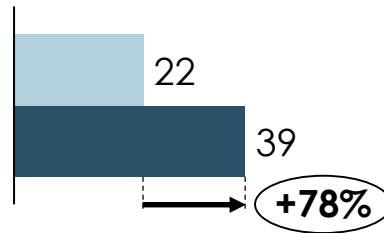
Trillion passenger kilometres



- Passenger travel grows, primarily in cities, which may hold 63% of world population by 2040 vs. just over 50% today

Domestic freight

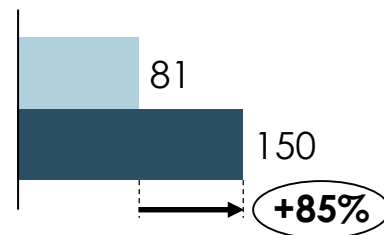
1,000 billion tonne-km



- Domestic freight volumes grow on the back of increasing industrialisation and urbanisation

International freight

1,000 billion tonne-km



- Growth in international freight accompanies increasing trade volumes

Source: Copenhagen Economics analysis based on IEA Energy Technologies Perspectives 2016, baseline scenarios in IPCC AR5 database and the Global Calculator.

Building energy services are expected to grow 50-70% with large increases in the built area

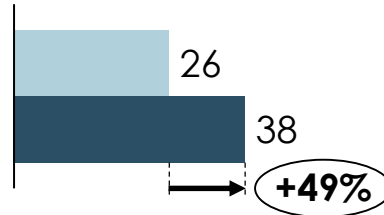
2015 2040

EXAMPLES

Development of key energy services

Built area

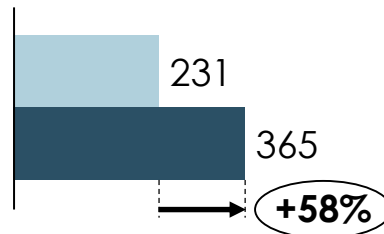
Million hectares



- Growing cities host both new dwellings and commercial buildings, resulting in a ~50% increase in the built area by 2040

Cooling demand

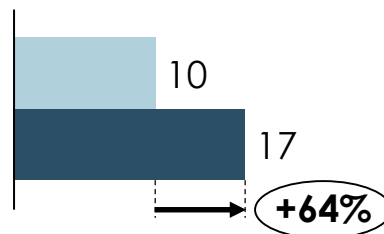
Degree days



- Space heating, cooling, and lighting grow with larger built area and increasing wealth

Appliance ownership

Appliances per household



- Increased incomes also enable higher appliance ownership and hot water use, as well as increased equipment use in commercial activities

Heavy industrial production is expected to increase by 20-80% through increased consumption and build-out of infrastructure

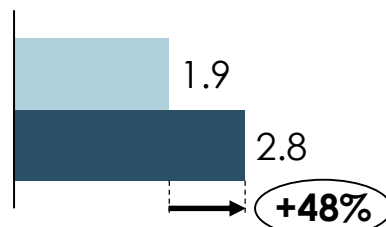
EXAMPLES

Scenarios for development of key energy services

2015
2040

Steel

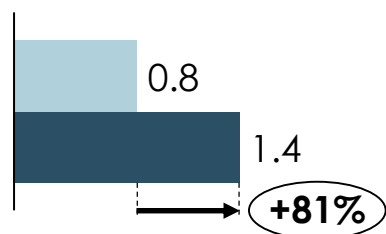
Billion tonnes



- Steel demand grows with continued build-out of infrastructure and increased consumption of various goods, such as vehicles and appliances

Chemicals

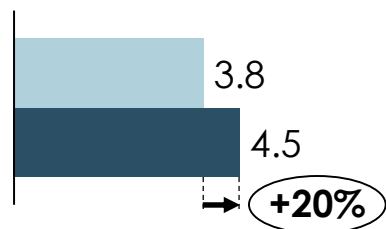
Billion tonnes



- Chemicals demand has historically been strongly correlated with GDP, driven by growth in consumption

Cement

Billion tonnes



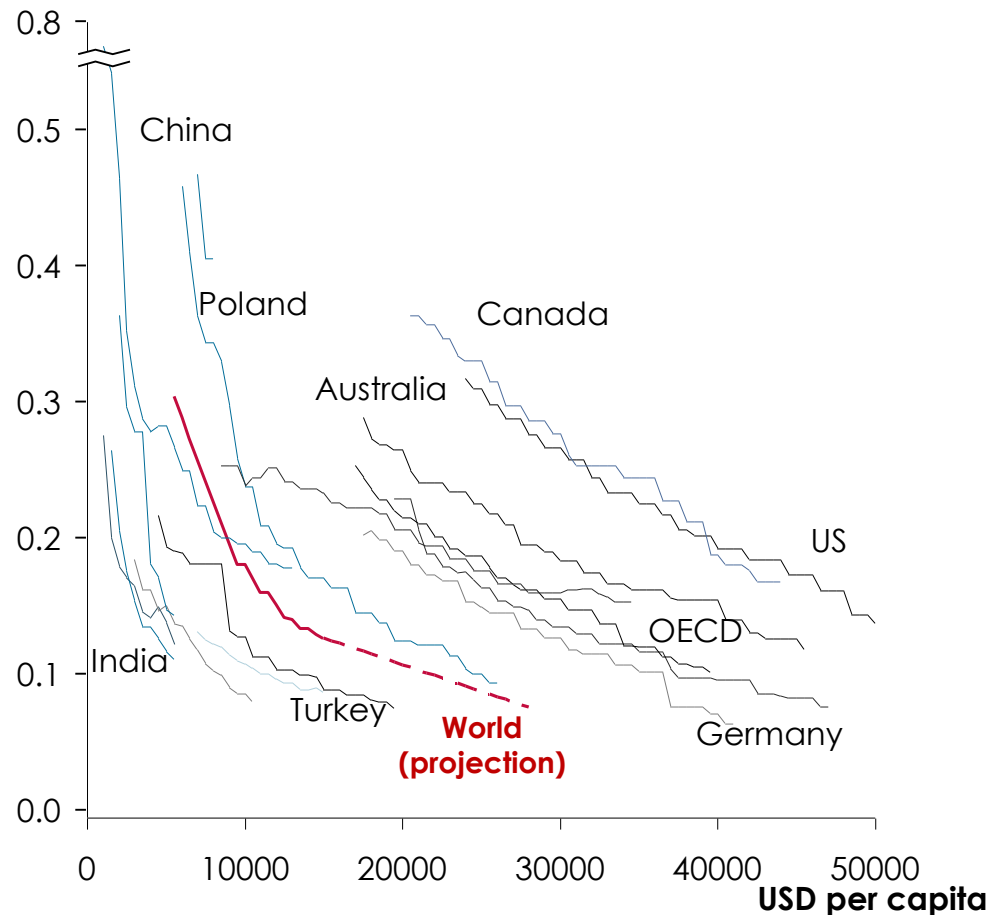
- Cement growth depends on new construction; despite high growth in other geographies, growth may slow as Chinese demand falls off from very high levels, for a net increase of 20% by 2040

Source: Copenhagen Economics analysis based on IEA Energy Technologies Perspectives 2016, baseline scenarios in IPCC AR5 database and the Global Calculator.

World energy intensity is likely to decrease as countries develop, but very different outcomes are possible

Energy intensity at different income levels, 1971-2013

Tonnes of oil equivalent per million USD; USD per capita

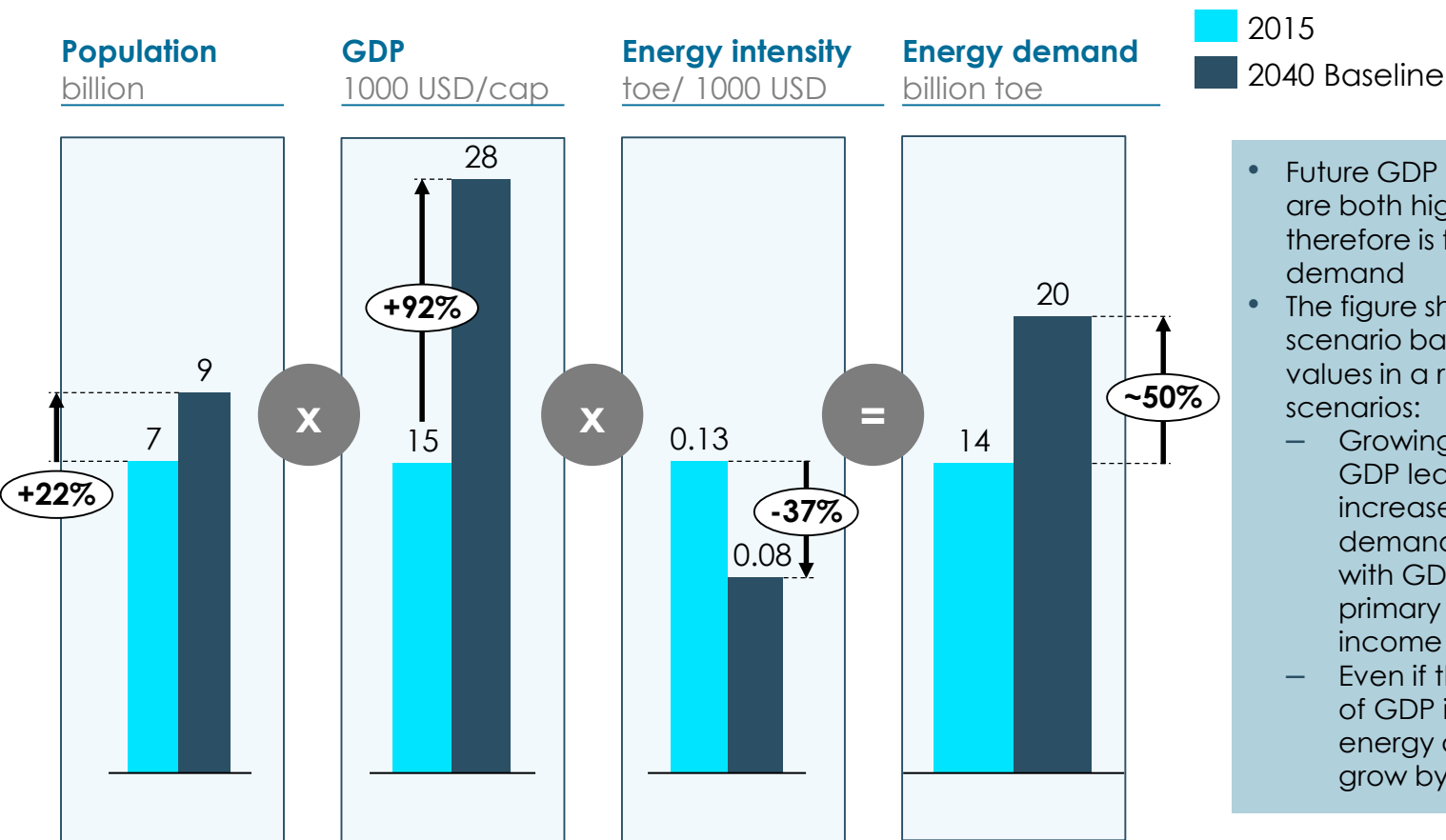


- **Energy intensity** is the amount of energy (e.g., one tonne of oil equivalent, toe) required to produce one unit of economic value (e.g., one million USD of GDP)
- **Energy intensity decreases as countries grow richer**, reflecting two mechanisms:
 - Changing economic structure, from energy-intensive manufacturing to less energy-intensive services
 - Increased efficiency of a range of energy processes, through improved technology, as well as improving capital markets and investment capacity
- **Global energy intensity therefore is expected to continue to fall**, on historical trend by ~20% by 2040
 - Current energy intensity is 0.13 toe/M dollars (PPP), down from 0.26 in the early 1970s
 - Baseline projections are around 0.08 toe per million dollars (PPP) in 2040
- **A key objective of an energy transition is to reduce energy intensity further**

Note: GDP in terms of PPP (current international dollars). The figure shows historical GDP per capita and energy intensity

Source: World Bank Development Indicators; Projections for global GDP from OECD; Projected energy intensity for Australia, Brazil, China, Germany, India, Indonesia, Mexico, Nigeria, Philippines, Poland, Rep. of Korea, Russia, Turkey, United Kingdom, Ukraine, United States and Vietnam and the World as a whole.

Assuming energy intensity improvements in line with historical trends, energy demand increases by ~50% by 2040



- Future GDP and energy intensity are both highly uncertain, as therefore is future energy demand
- The figure shows a “what if” scenario based on median of values in a range of 30 baseline scenarios:
 - Growing population and GDP lead to a strong increase in the underlying demand for energy services, with GDP growth the primary driver as lower-income countries catch up
 - Even if the energy intensity of GDP is reduced by 37%, energy demand would grow by half.

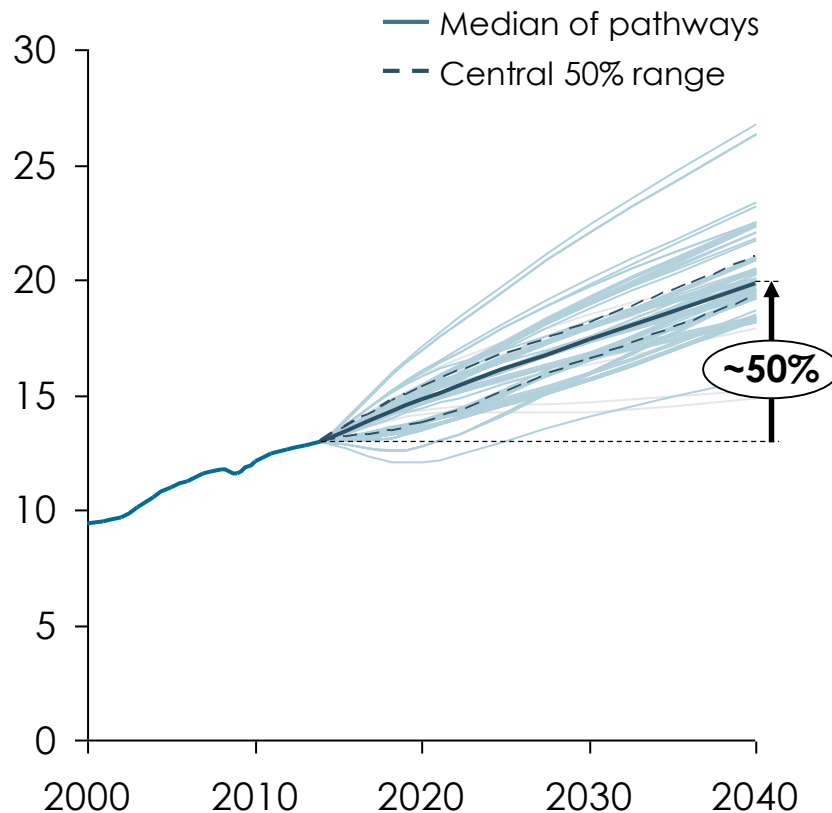
Note: GDP in terms of PPP (2005 USD). The median primary energy demand in the IPCC database differs somewhat from the energy demand calculated here, as the population and GDP figures are based on different sources. The assumptions used in the IPCC scenarios are not available.

Source: Data from UNPD (population) and OECD (GDP) and historical data from IEA World indicators, available at iea.org/statistics (Energy intensity). Projections for 2040 are median baseline scenarios in the IPCC AR5 Database (energy intensity)

Increased living standards for a growing population will require ~50% more energy by 2040

Primary Energy Demand

Billion tonnes of oil equivalent per year



- Half the baseline scenarios included in IPCC cluster around an increase of 45-60%
- However, the uncertainty span is large, with key factors including:
 - The extent of development and growth in economic activity: will GDP growth be closer to 4% or 2% per year? The difference leads to a 160% difference in the size of the economy by 2040.
 - The composition of growth: which countries will grow the most, and will they in turn be based primarily around energy intensive activities and sectors?
 - The extent of “leapfrogging”: will countries now industrialising have access to increasingly efficient technology that enable lower energy use?

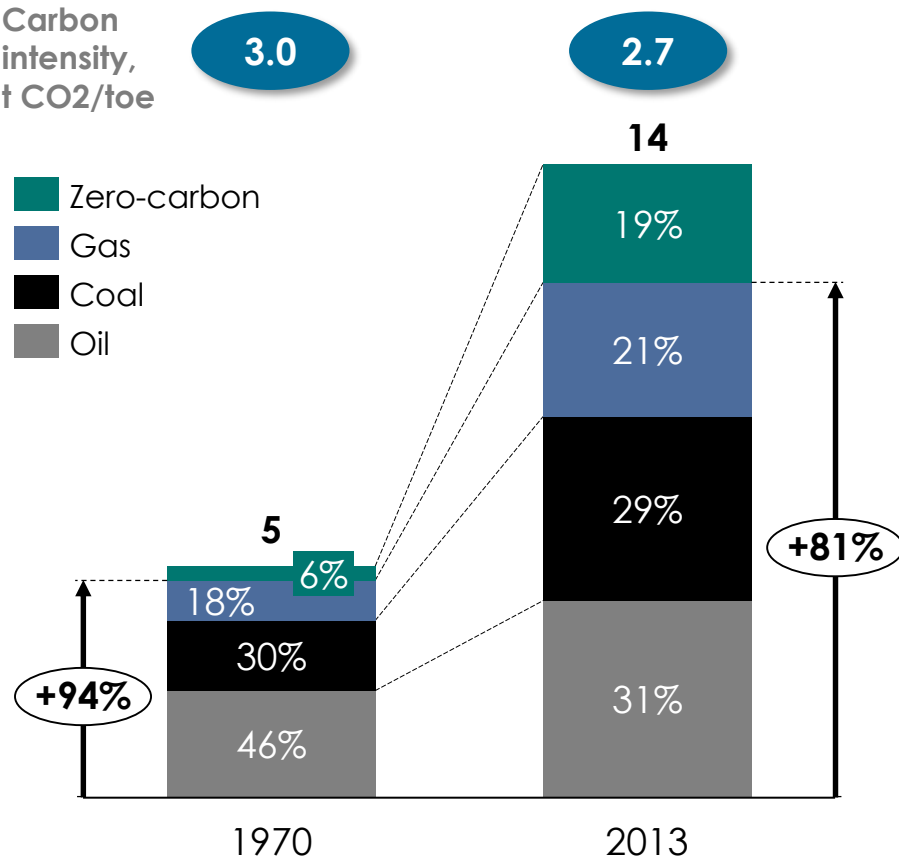
Source: Historical data from BP, Projections for 2040 are baseline scenarios in IPCC AR5 Database, IEA WEO 2015 CPS, IEA ETP 2016 6DS, BP Energy Outlook 2035 Baseline scenario (February 2015), and EIA IEO 2016 Baseline.

The carbon intensity of energy has remained at similar levels since the 1970s

Global energy supply and carbon intensity

Billion tonnes of oil equivalent, % of total; tCO₂/toe

Carbon
intensity,
t CO₂/toe



- Carbon intensity refers to the amount of CO₂ emissions produced per unit energy
- Fuels differ: coal emits more than oil and coal and oil emits more than natural gas per unit of energy
- Zero-carbon sources, such as nuclear or hydropower, produce energy without emitting CO₂
- Overall, today's energy system produces 3 tonnes of CO₂ for each tonne of oil equivalent of primary energy used
- Despite the changes wrought by the oil shocks and the entry of nuclear power in the 1970s, the carbon intensity has, however, changed little, falling from 3 to 2.7 tCO₂ per toe
- A key objective of an energy transition is to reduce carbon intensity by replacing fossil fuels with zero-carbon energy; by preventing the release of CO₂ emissions to the atmosphere; or by shifting from more to less carbon intensive fossil fuel uses

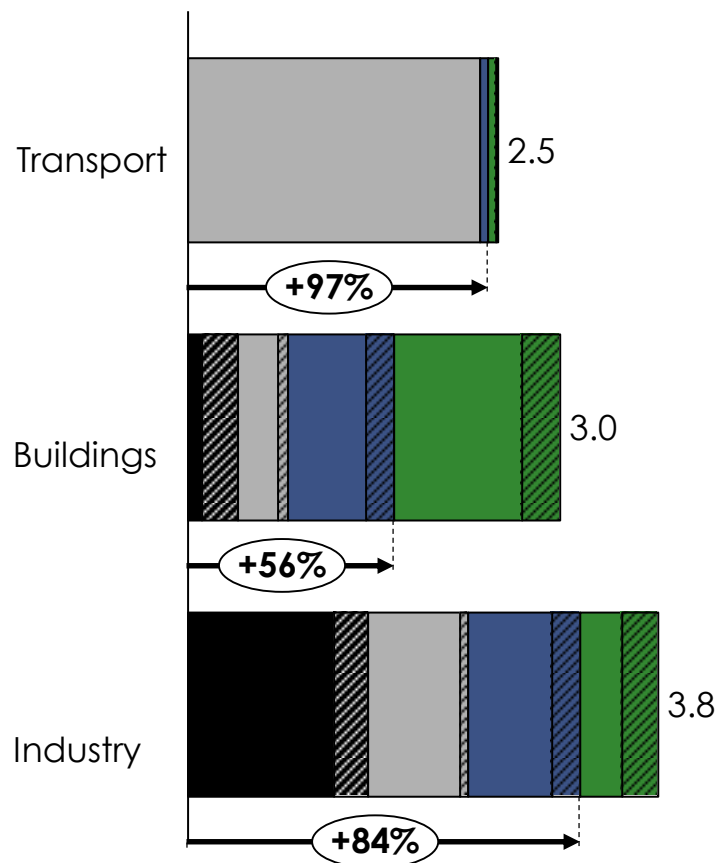
Note: Fossil fuels for electricity production are attributed on a simple pro-rated basis corresponding to the share of each sector in global electricity demand. Carbon intensity includes emissions from fossil fuel combustion in power and industry, and from cement industry.

Source: Copenhagen Economics analysis based on BP energy statistics 2013, IEA World Energy Outlook 2013

Fossil fuels meet 80% of energy requirements today, with a substantial share across all end-use sectors

Energy use by end-use sector and fuel (including fuels used for electricity production)

Billion tonnes of oil equivalent



- Transportation is overwhelmingly powered by oil, across both types (passenger and freight) and different modes (light and heavy-duty road, sea, air).
- Electric rail, compressed natural gas, and bio-based fuels remain small in comparison
- Buildings account for a significant share of electricity demand for lighting, appliances, and space cooling
- Direct use of gas, coal, and (to a lesser extent) oil power space heating, hot water, and cooking
- Traditional bioenergy is used for cooking by households without access to modern energy, while zero-carbon sources also are used for power generation
- Coal is used primarily for steelmaking and high-temperature applications; oil and gas as feedstock for chemicals; a mix of fossil fuels for steam raising and heat; and electricity to power manufacturing and motors across a range of applications

Note: *Fossil fuels for electricity production are attributed on a simple pro-rated basis corresponding to the share of each sector in global electricity demand.

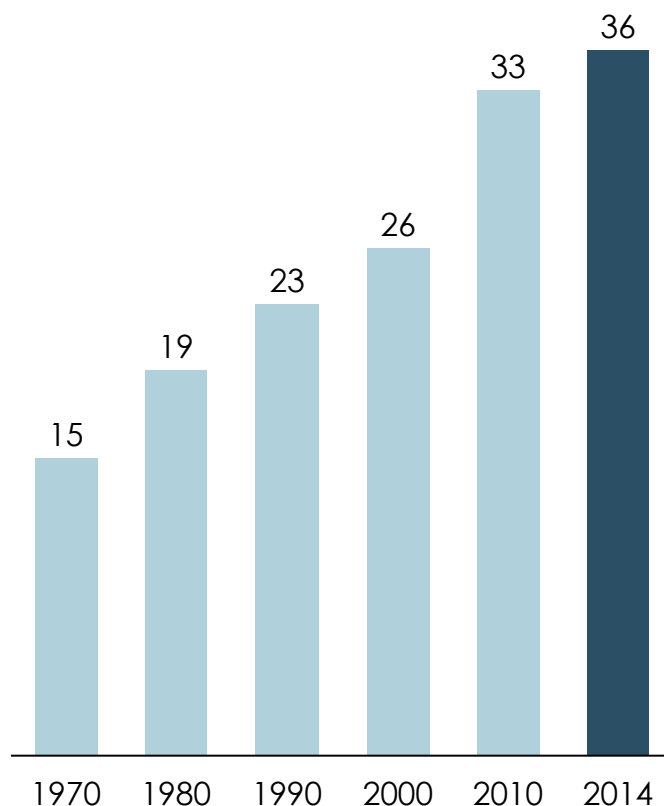
Source: Copenhagen Economics analysis based on IEA Energy Technologies Perspectives 2016.

Today's energy system is based on fossil fuels and is therefore carbon intensive, producing 36 Gt CO₂ per year

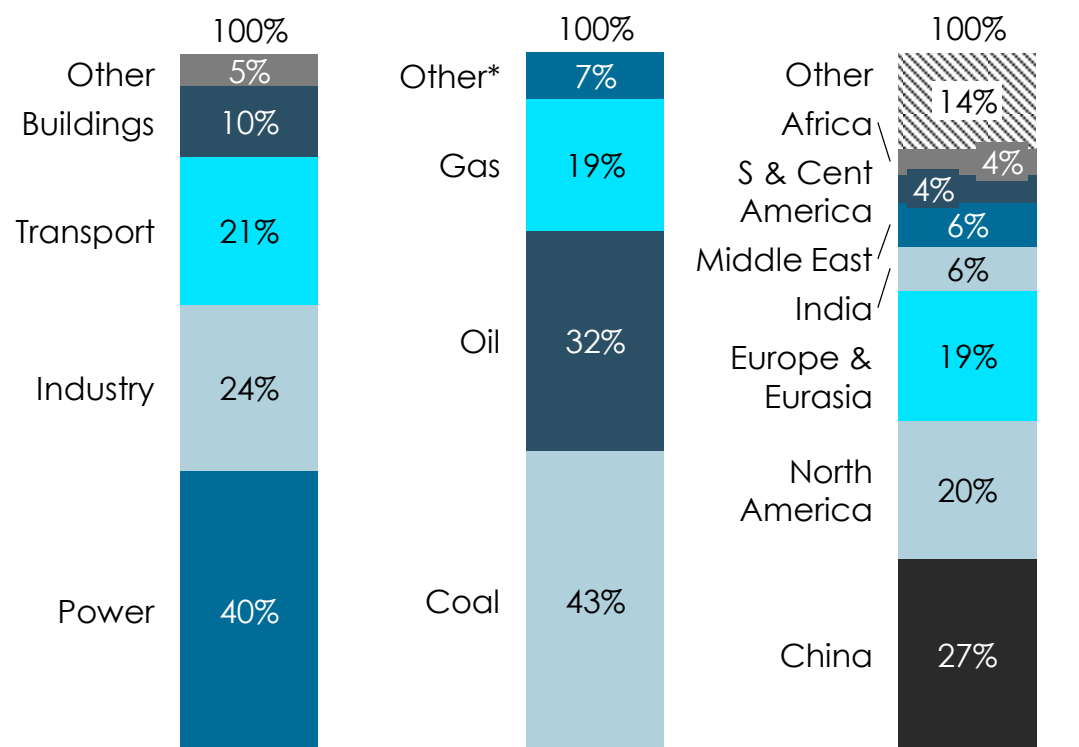
CO₂ emissions from fossil fuel combustion and industrial processes

Billion tonnes per year; % of total

1970-2014



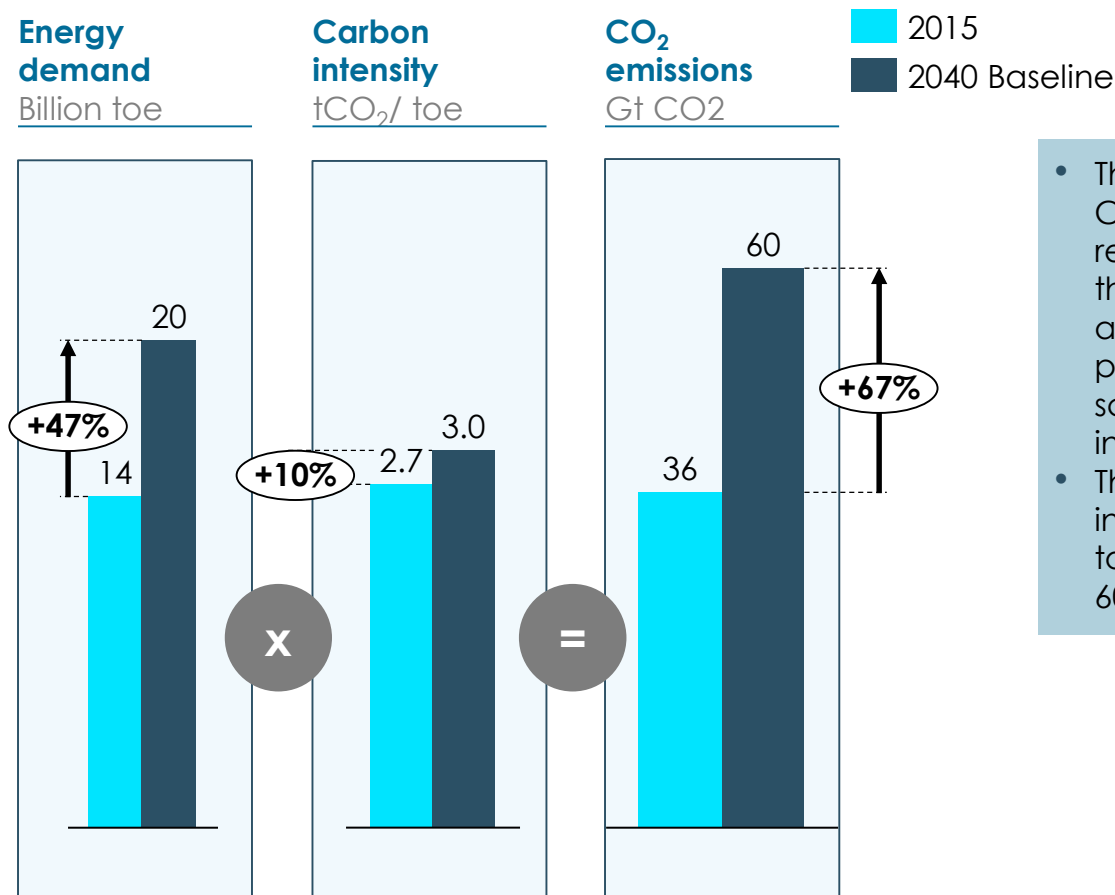
2014



Note: Sectoral shares from 2013. *) Emissions other than from combustion of coal, oil and gas, including cement, steel, and chemical process emissions.

Source: Historical emissions data from BP (2015) Statistical Review of World Energy. Sectoral shares from IEA (2016) ETP, fuel shares from IEA (2016) CO₂ emissions from fuel combustion. Highlights 2016, regional shares from BP (2015) BP Statistical Review of World Energy. 2014 emissions data from PBL (2015), Trends in global CO₂ emissions: 2015 report.

Without an energy transition, CO₂ emissions could grow by two-thirds by 2040



- The figure illustrates the total CO₂ emissions that would result in such a scenario given the 2040 energy use discussed above of around 20 billion toe per year (the median of 30+ scenarios) at today's carbon intensity
- The resulting increase is an increase by two-thirds, from today's level of 36 Gt CO₂, to 60 Gt CO₂ per year.

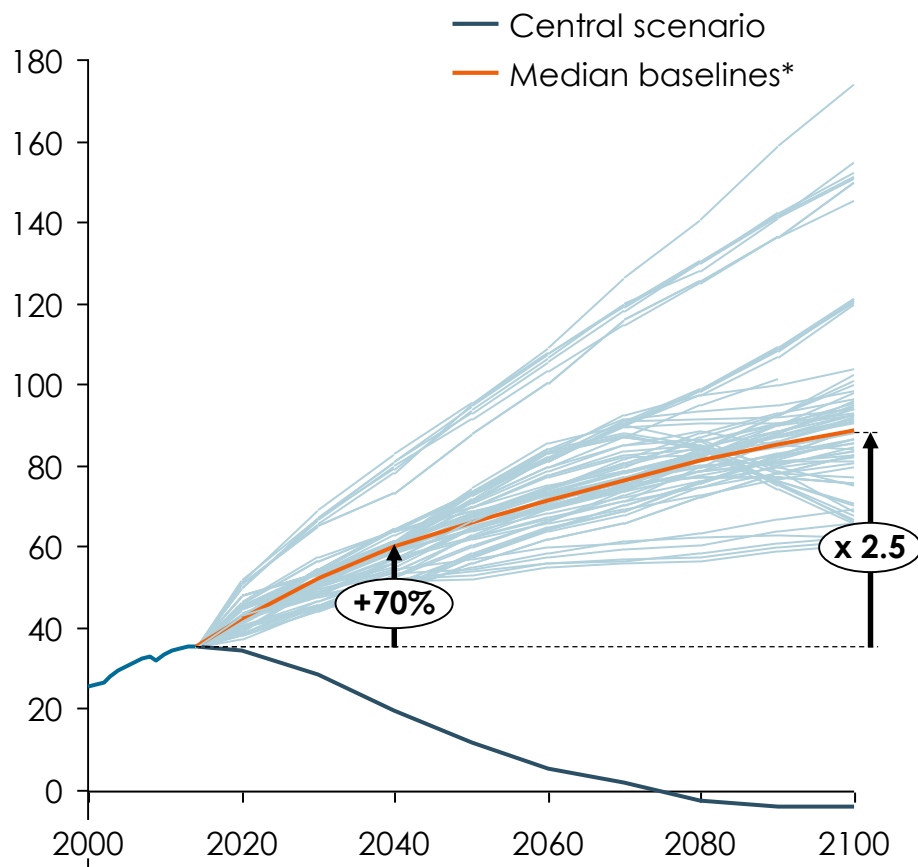
Note: Carbon intensity includes emissions from fossil fuel combustion in power and industry, and from cement industry.

Source: Data from UNPD (population) and OECD (GDP) and historical data from IEA World indicators, available at iea.org/statistics (Energy intensity and carbon intensity) and PBL Netherlands Environmental Assessment Agency, Trends in global CO₂ emissions: 2015 Report (CO₂ emissions). Projections for 2040 are median baseline scenarios in the IPCC AR5 Database (energy intensity, carbon intensity and CO₂ emissions).

Without an energy transition, CO₂ emissions could eventually rise to 2-3 times current levels

Carbon dioxide emissions, baseline scenarios

Billion tonnes CO₂ per year



- “Baseline” scenarios illustrate a future with an energy system broadly similar to today’s – i.e., absent an energy transition, based on fossil fuels, and with a similar carbon intensity
- Resulting emissions in 2040 are in the range 45-65 Gt CO₂ for most scenarios, but with outliers up to 80 Gt. The large range reflects uncertainty about economic growth, resulting energy demand levels, and the mix of energy sources used to meet energy needs
- Moreover, emissions could continue to grow beyond 2040, to perhaps ~80 Gt by 2100, as available fossil fuel reserves are unlikely to prevent such levels
- Current trends may already be breaking such trends towards such scenarios; for example, global CO₂ emissions have been largely flat for three years, 2013-16
- Nonetheless, they illustrate the extent of transformation required to achieve a significant absolute reduction in emissions levels, as required to meet climate objectives

Note: * Based on the median value for 2100.

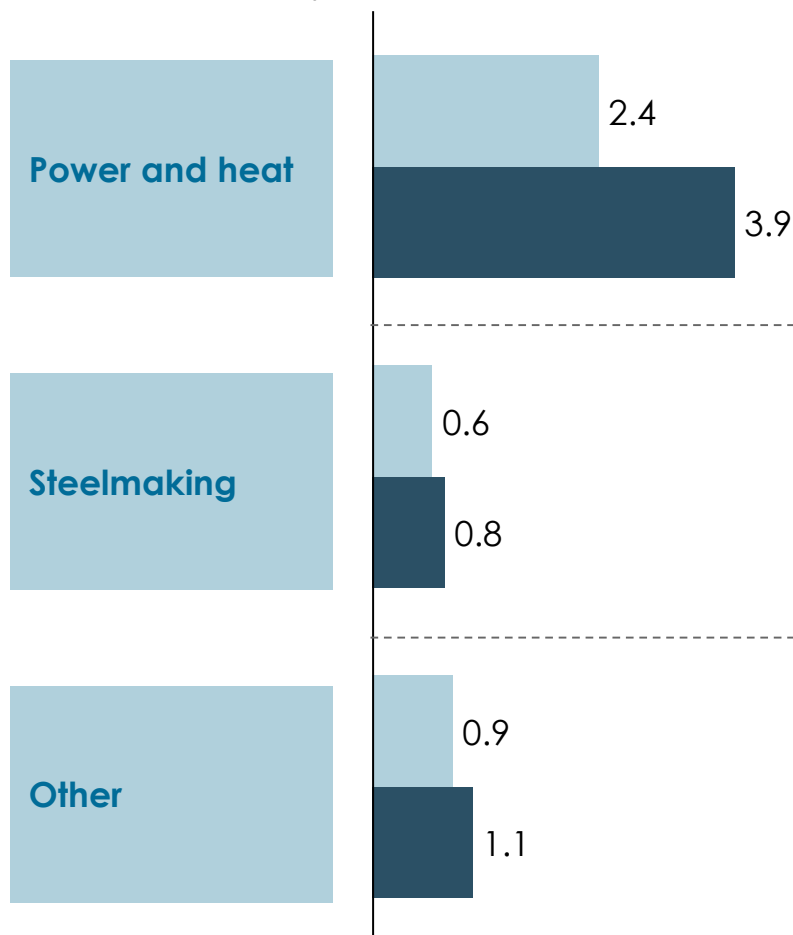
Source: Historical data from BP, Projections for 2040 are baseline scenarios in AR5 Database

Growth in coal use depends primarily on how new power demand is met in rapidly growing Asian economies

Coal consumption, baseline scenario

Billion tonnes of oil equivalent

2015 2040



- Coal use in power and heat generation could increase by 60%, unless rapidly growing countries rapidly switch to other sources to meet new power demand
- Development in recent years may indicate that a shift already is underway (notably through a peak in Chinese coal consumption)

- The use of coal for steelmaking is likely to increase with a continued increase in the total stock of steel in circulation
- However, growth may be lower than growth in steel production, reflecting a trend towards steel processes using natural gas and electricity

- Coal use also persists in high-temperature industrial processes as well as residential and commercial heating, but growth is smaller than for other fuels (notably, natural gas), reflecting concerns about air quality and other factors

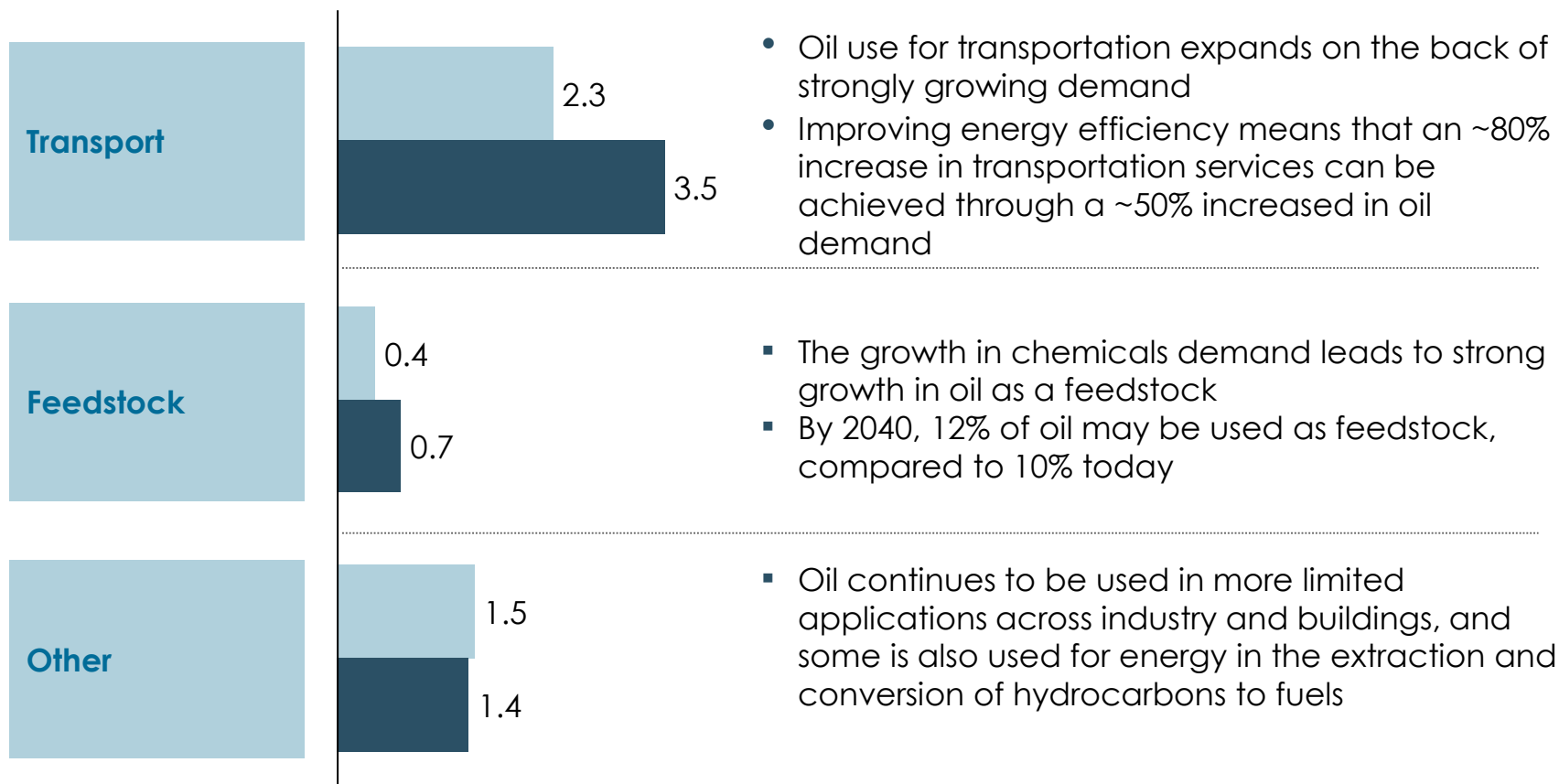
Source: Copenhagen Economics analysis based on IEA Energy Technologies Perspectives 2016.

Oil growth results from increased transportation needs as well as growth in plastics and other high-value chemicals

Oil consumption, baseline scenario

Billion tonnes of oil equivalent

2015 2040

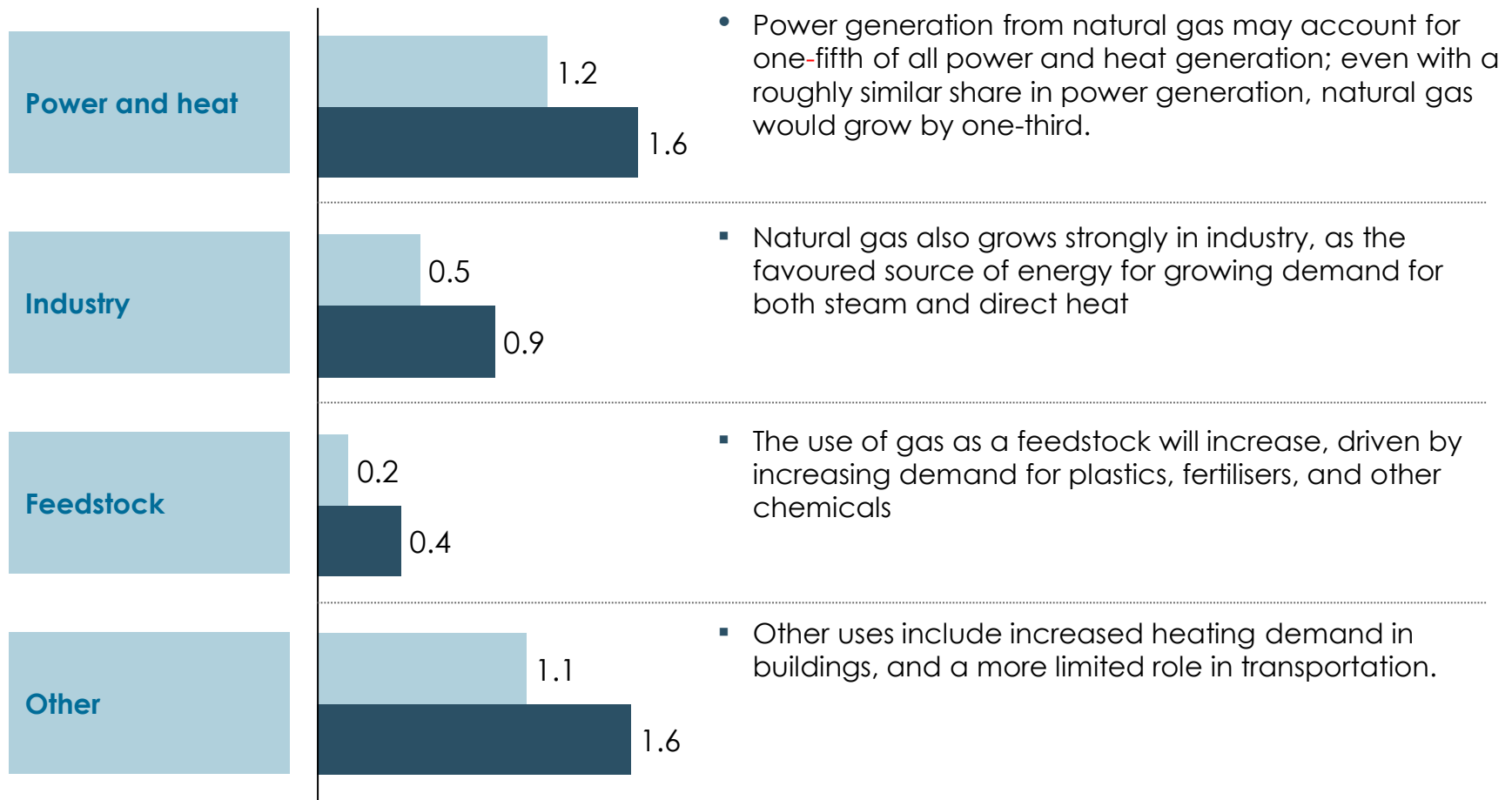


Natural gas has grown strongly across applications, and dominates outside transport and power in coal-rich countries

Natural gas consumption, baseline scenario

Billion tonnes of oil equivalent

2015 2040



Source: Copenhagen Economics analysis based on IEA Energy Technologies Perspectives 2016

Summary Findings

1. Rapidly growing energy needs set the scene for an energy transition

2. A 2°C objective implies a strict carbon budget

3. Fossil fuel use would fall by one-third by 2040 to meet 2°C objectives

4. The role of fossil fuels changes by 2040 in a 2°C energy system

5. A 2°C energy transition has profound impacts on fossil fuel markets

6. Carbon capture is a key factor in a 2°C energy transition

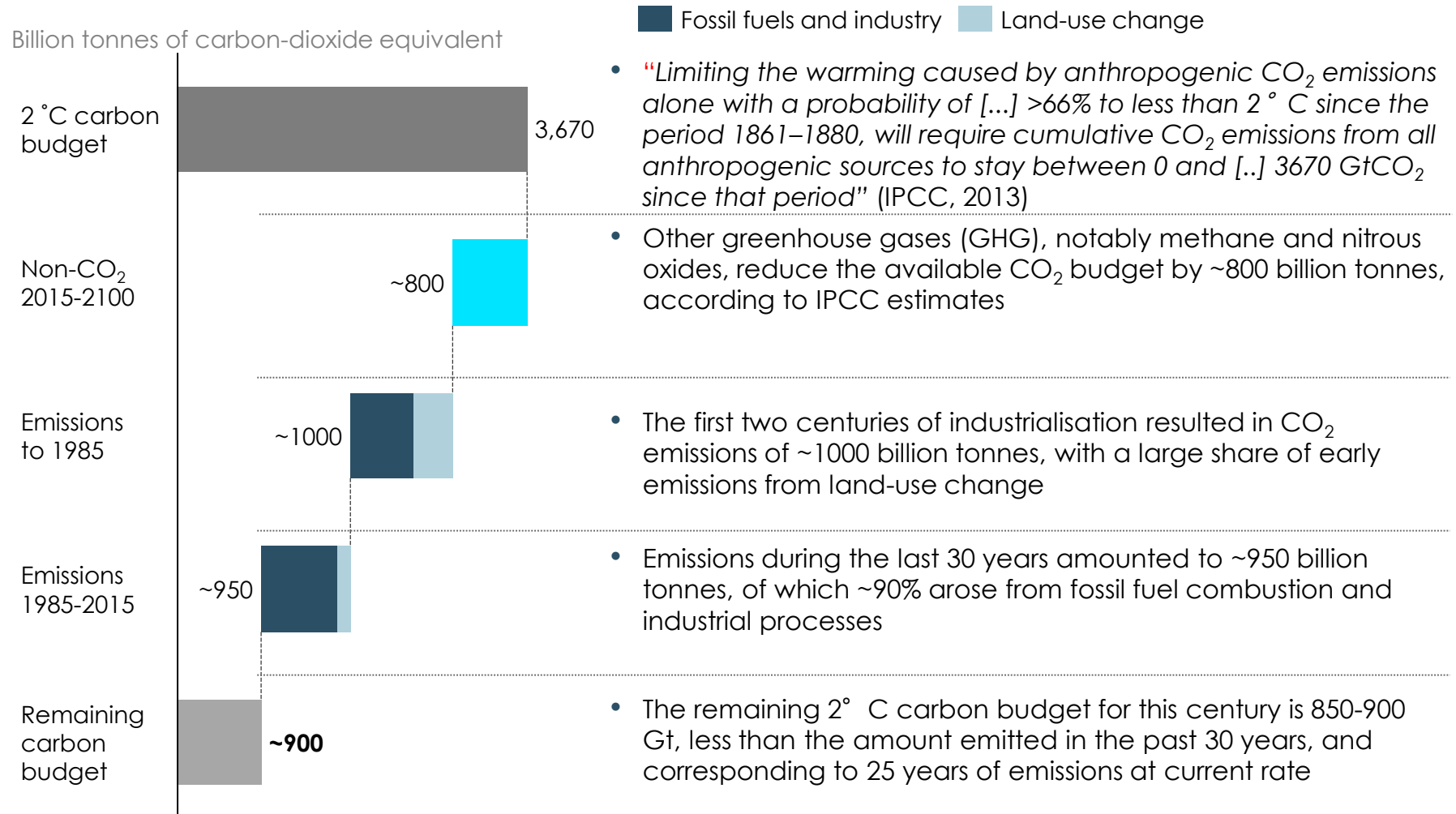
7. Appendix: scenario methodology

Summary Findings – Carbon budgets

Limiting climate change depends on restricting *cumulative* emissions. The “carbon budget” to limit warming to 2°C amounts to ~900 billion tonnes of carbon-dioxide (Gt CO₂) from now until 2100. Achieving this requires that current emissions of 36 Gt CO₂ per year are halved by around 2040, and then rapidly brought to net zero levels.

- **The remaining carbon budget for a 2°C target is less than 900 Gt CO₂**, for all emissions from fossil fuels and industry to 2100 for a probability of two-thirds that warming will not exceed 2°C. This quantity of emissions is similar to the amount that was emitted between 1980 and 2015.
- **Keeping within the budget requires a transition to net zero emissions** before cumulative emissions exceed the budget. “Peaking” emissions levels per year is insufficient. Likewise, higher emissions today leave less room for emissions tomorrow.
- **Most 2°C scenarios see emissions halved by 2040.** This leaves room for an average of just ~4 Gt CO₂ per year, 2040-2100, or one-tenth of current emissions for a much larger economy. Technologies to remove CO₂ from the atmosphere (“negative emissions”) may be a prerequisite to achieve this, or to handle earlier “overshoot” of emissions.
- **A more stringent target rapidly reduces the budget.** The “well below 2°C” objective adopted in the Paris Accord implies a smaller budget. A 1.5°C target reduces the budget by almost 80%, to 200 Gt CO₂.
- **Fossil fuel reserves exceed the budget by a factor 3-6.** Coal reserves alone would create emissions more than twice its size (~2,000 Gt). Hydrocarbon reserves are more uncertain, with oil around 600 Gt and conventional gas 400 Gt (and unconventional reserves potentially much larger).
- **Substantial emissions already are locked in.** For example, one third (~300 Gt) of the remaining 2°C carbon budget would be claimed if current power plants operated for their technical life. Addressing such “locked-in” emissions is thus a key aspect of an energy transition.

The remaining carbon budget for 2°C warming is less than 900 Gt CO₂, similar to emissions in the past three decades

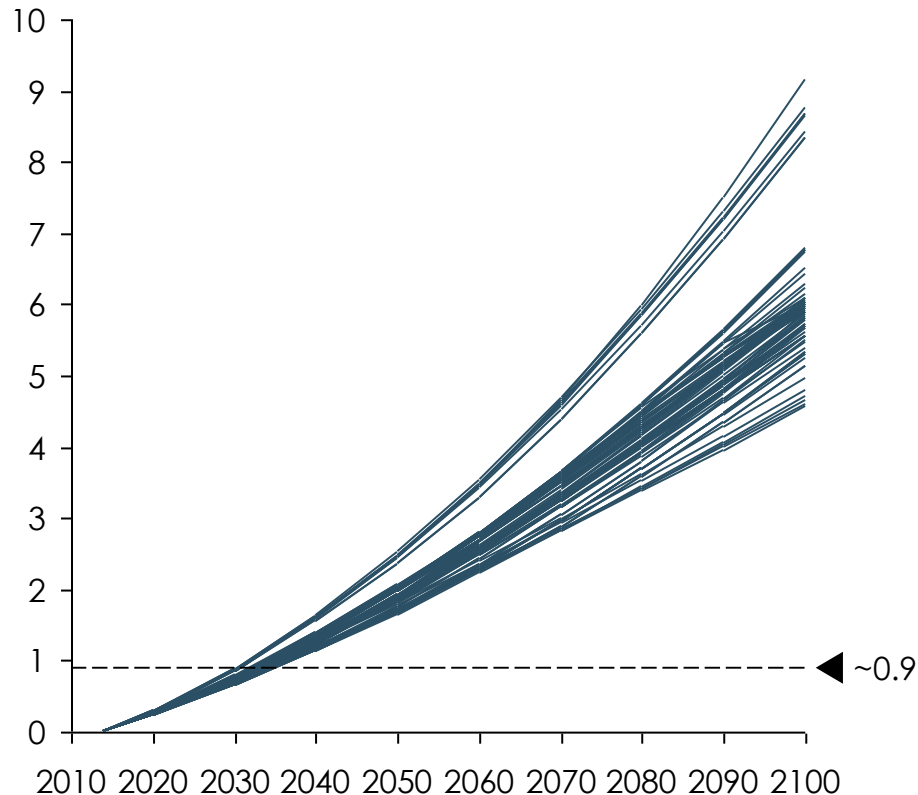


Source: Copenhagen Economics analysis based on IPCC (2013) WGI Summary for Policy Makers (quote from p. 27 of Summary); La Quéré (2014) Global carbon budget 2014

Scenarios without an energy transition imply cumulative emissions 5-10 times larger than the carbon budget for 2°C

Cumulative emissions 2014-2100

1000 billion tonnes carbon dioxide



- CO₂ is a stock pollutant: it is the total level ("stock") of CO₂ in the atmosphere that affects the climate, not the flow of emissions
 - As of 2015, the atmospheric stock of CO₂ is ~3 trillion tonnes, or just over 400 parts per million (ppm)
 - The majority of emitted CO₂ remains in the atmosphere for over three decades before being absorbed by natural processes.
- The stock of CO₂ would increase by 4-9 trillion tonnes of CO₂ by 2100 absent a deep energy transition, 5-10 times the remaining 2°C carbon budget.
- Net zero emissions are required to prevent further increases in the stock of CO₂
 - Even if the flow (annual emissions) reaches a peak or is reduced, any addition to the stock of emissions continues to add to the effect on the climate
 - Only when the flow reaches net zero – so any additions are cancelled out by removals of CO₂ – is there no additional contribution to global warming

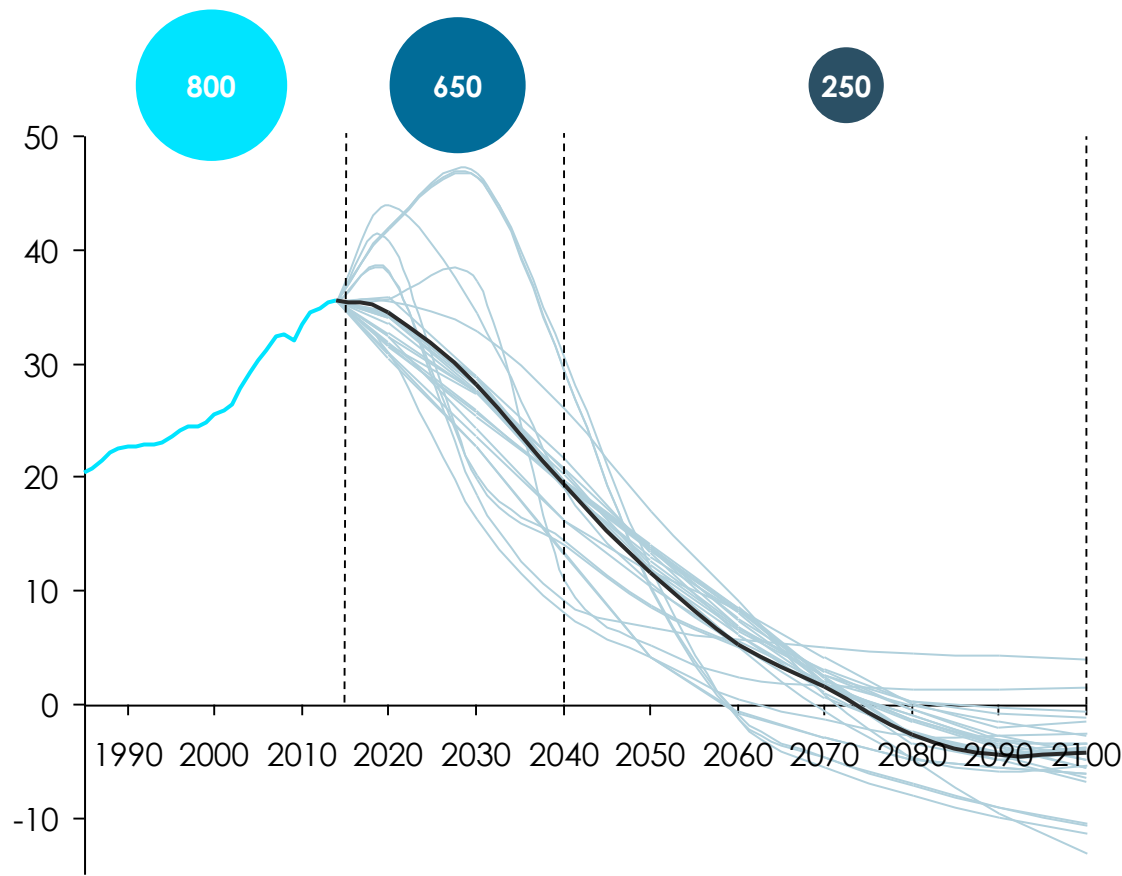
Note: The CO₂ concentration is approximated by a sum of exponentially decaying impulse response functions specified in the Bern model. Using the same parameters as the IPCC implies a half-life of CO₂ in the atmosphere of ~30 years. After 100 years, 36% of a pulse of CO₂ emissions still remains in the atmosphere. After 1,000 years, 22% of a pulse of CO₂ remains in the atmosphere.

Sources: Copenhagen Economics analysis based on IPCC (2007), WGI: The Physical Science Basis; IPCC(2013) WGI Summary for Policy Makers; La Quéré (2014) Global carbon budget 2014

Even in a 2°C scenario, 650 Gt CO₂ could be emitted up to 2040, ~75% of the CO₂ budget until 2100

Emissions pathways for scenarios limiting warming to 2°C*

Billion tonnes CO₂



— Central scenario
(median)



Cumulative
emissions during
period

- We derive a “Central” 2° C scenario from a large body of existing scenario analysis of how energy needs can be met while limiting emissions.
- Large-scale transformation across the energy system would see emissions fall by half by 2040, even as energy needs increase by ~50%
- This leads to cumulative emissions of ~650 Gt of CO₂ 2016-2040, corresponding to ~75% of the total remaining carbon budget
- The remaining ~250 Gt CO₂ available to 2100 imply annual average emissions of 4 Gt CO₂ per year, one-tenth of current levels
- Keeping emissions to these levels may require emissions to become “net negative” through technologies that remove CO₂ from the atmosphere – a theoretical concept unproven at scale

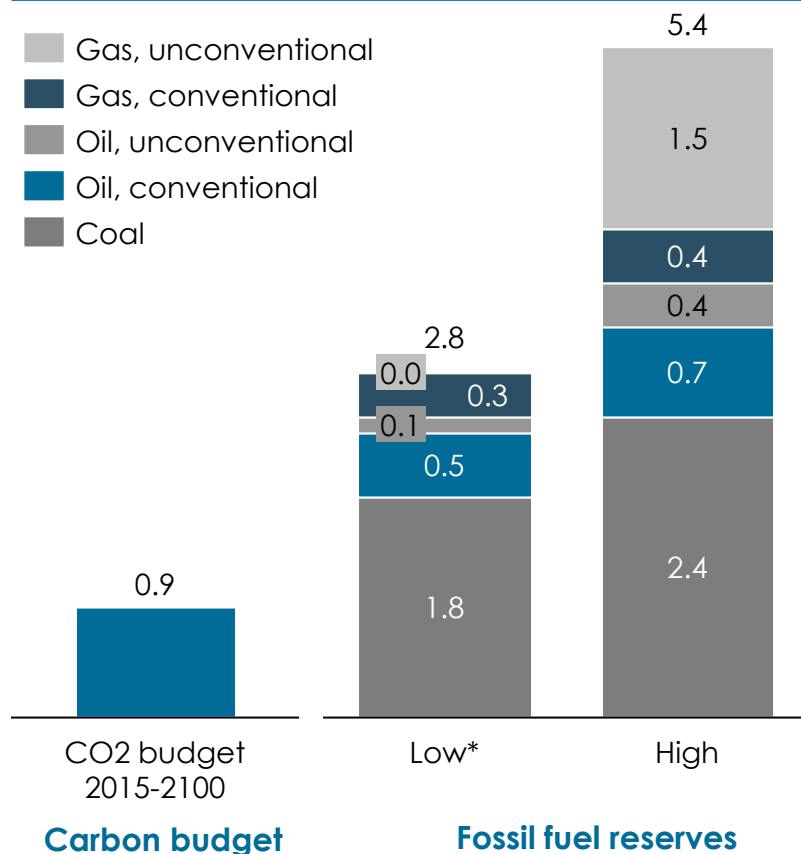
Note: * The figure shows 28 pathways consistent with limiting warming to 2°C, as well as other criteria.

Source: Copenhagen Economics analysis of data from AR5 database

The carbon content of current fossil fuel reserves exceeds the remaining carbon budget by a factor 3-6

Carbon budget and emissions implied by fossil fuel reserves

1000 billion tonnes of CO₂-eq.



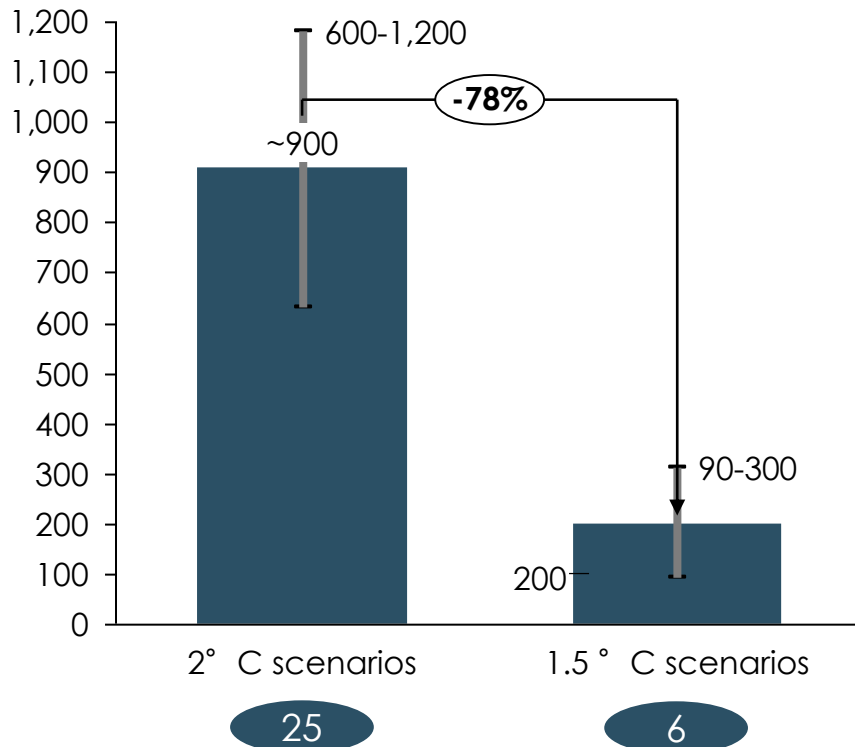
- The figure shows that CO₂ emissions that would result from using current conventional and likely unconventional fossil fuel reserves exceed the 2°C carbon budget by a factor 3-6
 - Overall, estimates vary between 2.8 and 5.4 1000 Gt CO₂, (where sum of lowest) and 5.4 (such of highest) with the lower value
- The implication is that fossil fuel availability will not on its own limit emissions to reach a 2°C objective; in addition, some of current reserves must be left unexploited to meet climate objectives
- “Reserves” are an economic concept, referring to fossil fuel resources that could be economically mobilised
 - Resource estimates are much greater (30,000-40,000 Gt for coal, 2,000-5,000 Gt for gas, and 1,000-1,500 Gt for oil).
 - Estimates for unconventional gas are highly uncertain, with little agreement on what resources are appropriately classified as reserves.

Sources: For carbon budgets: IPCC (2013); La Quéré et al (2014); Fossil fuel reserves shown are ranges for mid-point estimates of a range of different sources, including BGR (2013); GEA (2012); WEC (2013); BP (2013); BP (2016); Copenhagen Economics analysis

“Well-below” 2°C is challenging: a target of 1.5°C reduces the carbon budget from ~900 to ~200 Gt CO₂

Cumulative emissions to 2100

Billion tonnes CO₂



X

Remaining years of CO₂ emissions at current rate

- The Paris Agreement set out the ambitions of holding global average temperature increase to “well below 2°C above pre-industrial levels” and “pursuing efforts to limit the temperature increase to 1.5°C”.
- Currently available analyses are limited, but indicate that 1.5°C is significantly more exacting than a 2°C objective:
 - The carbon budget is almost 80% smaller
 - Emissions in 1.5°C pathways become net negative by mid-century, two decades earlier than in 2°C pathways
 - Large volumes of CO₂ need to be removed from the atmosphere after 2050 (more than is added)
 - Decarbonisation of energy supply must happen faster
 - Energy use must be limited through still greater energy efficiency improvements

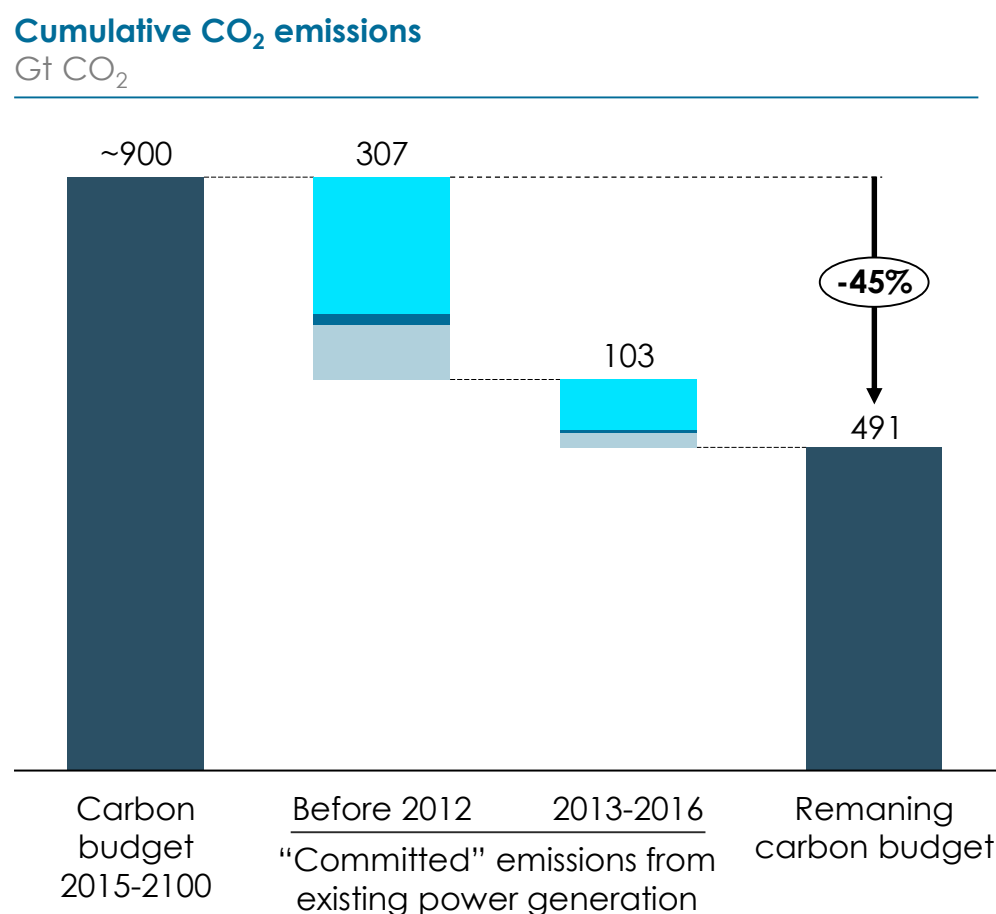
Note: Error bars show 10-90% percentile of estimates across studies. No overshoot assumed. 2°C scenarios are 430-480 ppm scenarios in which it is likely that temperature increases are limited to 2°C. 1.5°C scenarios are the handful of scenarios reviewed by IPCC assuming <430ppm GHG concentrations as reported in Rogelj et al. (2015). Annual industry emissions for 2014 of 35.7 Gt CO₂ are for emissions from fossil fuel combustion and industrial processes taken from Olivier et al. (2015), “Trends in Global CO₂ emissions: 2015 report”

Sources: Clark et al. (2014), Rogelj et al. (2015), Olivier et al. (2015); UNFCC (2016), Decision 1/CP.21 Adoption of the Paris Agreement.

“Lock-in” rapidly eats into the carbon budget

Example: existing and planned power generation to 2050

Cumulative CO₂ emissions
Gt CO₂



- The figure shows “committed” emissions: the emissions that would result if all fossil fuel plants already in existence were operated for their remaining technical lifetime
- The resulting emissions would exceed >400 Gt CO₂, or 45% of the remaining carbon budget
- Coal plants account for more than two-thirds of these “committed” emissions
- Since 2013, 70-90 GW per year of new coal generating capacity have been added, or 17-22 billion tonnes of life-time emissions per year
- This shows the importance of “lock-in”: that current decisions have very long-term consequences for future emissions
- Also, it may be necessary to close existing fossil fuel-based infrastructure early (and at a cost)

Notes: Remaining committed emissions (as of 2012) from power infrastructure assuming 40 year lifetime of generators. All fossil fuel-fired electricity generating units that were built globally between 1950 and 2015 are included as well including projection for 2016.

Source: Davis and Socolow (2014). Data on capacity for 2013-2016 from Platts and Bloomberg New Energy Finance. Projections from Bloomberg New Energy Finance.

Summary Findings

1. Rapidly growing energy needs set the scene for an energy transition
2. A 2°C objective implies a strict carbon budget
- 3. Fossil fuel use would fall by one-third by 2040 to meet 2°C objectives**
4. The role of fossil fuels changes by 2040 in a 2°C energy system
5. A 2°C energy transition has profound impacts on fossil fuel markets
6. Carbon capture is a key factor in a 2°C energy transition
7. Appendix: scenario methodology

Summary Findings – Fossil fuel trajectories for a 2°C outcome

In a successful transition scenario, fossil fuels could represent 60% of primary energy by 2040 – compared to 85% today. This reduction is required even if very large volumes of carbon capture and sequestration* (CCS) are feasible, and has profound consequences for patterns of energy use and energy markets.

- **A 2°C pathway requires a 30-50% reduction in fossil fuel use by 2040.** Even with high levels of CCS (~10 Gt CO₂ per year or more after 2040), consumption would need to be one-third lower in 2040 than today.
- **This implies a very rapid energy transition.** Meeting energy needs with fossil fuels would require an increase by 60% to meet energy needs. Achieving a reduction by 30+% therefore implies the need both to sharply reduce energy demand growth (through increased energy efficiency/productivity), and to scale up zero-carbon energy very rapidly.
- **The impact differs across fuels:**
 - A sharp and immediate decline in coal consumption by two-thirds. As key industrial uses of coal are difficult to replace, the decline in coal used for power production needs to be steeper still.
 - A peak in oil consumption in the 2020s, and then a fall by one-third by 2040, primarily by finding alternatives across a wide range of transportation uses.
 - A limited rise in natural gas consumption, with 2040 use at roughly current levels and concentrated in uses where alternatives are hard to scale (some power generation, industry, and heating).
- **Carbon capture is important in most such scenarios**, but does not avoid the need to reduce fossil fuel use. These consumption levels depend on carbon capture of 7+ Gt CO₂ by 2040, rising further thereafter to more than 10 Gt per year. Without CCS, consumption would have to fall still faster: to half of current levels already by 2040, and then rapidly to zero.

Our approach: we use existing analyses to characterise the level of feasible fossil fuel consumption in a 2°C scenario

Represent joint development and climate objectives

We use analyses that explicitly account both for the need to meet future energy needs for development, and model the ability to service these needs while reducing emissions.

Capture the full set of analyses

We avoid reliance on single scenarios or models by analysing the implications of the full set of 1000+ pre-existing pathways scenarios.

Use a small set of objective criteria

We limit the analysis to scenarios that a) meet ambitious climate ambition targets, b) are not outdated, and c) are fully global but otherwise avoid restricting the set of pathways used.

Limit the extent of carbon capture

We additionally limit the extent of carbon capture, using cut-off thresholds of 40 Gt CO₂ (similar to current total global CO₂ emissions) and 15 Gt CO₂ (larger than current emissions from the global power sector). See Appendix for more detail.

Accept uncertainty and ensure variation

We ensure that the resulting selection of pathways reflects a range of model representations, research teams, scenario assumptions, policy parameters, etc.

Summarise results through central values

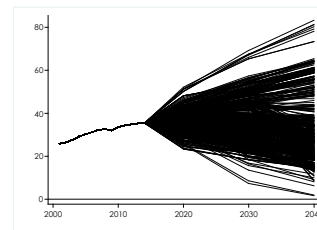
Where we show single values, we use the median value as a reasonable summary of the underlying variation.

We limit our analysis to scenarios that meet climate objectives and avoid aggressive levels of carbon capture

1

Draw on the full set of available analyses

- 1000+ pathways described in the database underpinning the IPCC's Fifth Assessment Report

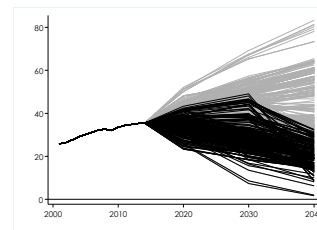


1000+
candidate
pathways

2

Retain pathways that don't meet climate criteria, or which are outdated or incomplete

- Two-thirds probability of 2°C
- Fully global analyses undertaken since 2010

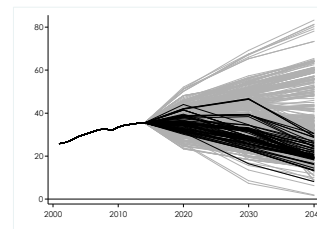


241 pathways
Not used

3

Avoid extreme assumptions for CCS* and for near-term emissions

- CCS less than 40 Gt CO₂ in any one year
- 2020 emissions 30 Gt CO₂/ year or more

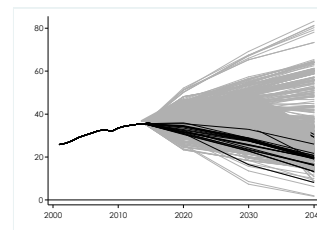


84 Pathways
Used for a "High
CCS" scenario

4

Restrict CCS while retaining a diversity of models and research groups

- CCS less than 15 Gt CO₂ in any one year (For comparison, current global power sector emissions are 13 Gt CO₂ per year)



28 Pathways
Used for Central"
and "No CCS"
scenarios

Source: Copenhagen Economics analysis of data from AR5 database.

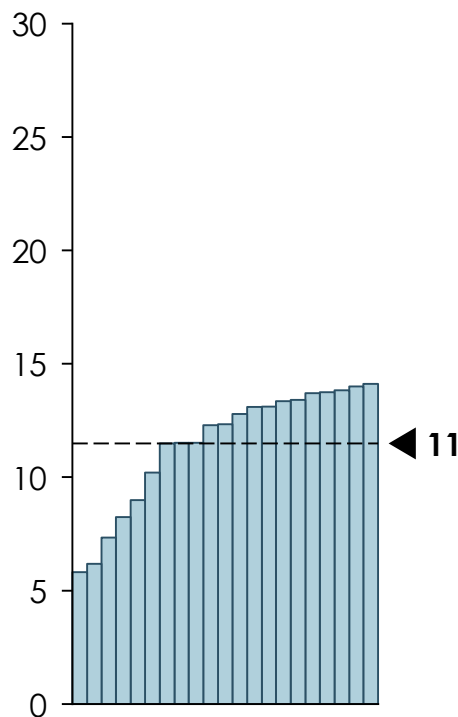
Notes: *Analyses of carbon capture in the scenarios used here refer to CCS – carbon capture and storage – and we therefore follow this nomenclature. It is in principle possible also to sequester carbon removed from the atmosphere through various forms of carbon utilisation.

We define three scenarios for fossil fuel use based on the maximum level of CO₂ capture and sequestration used

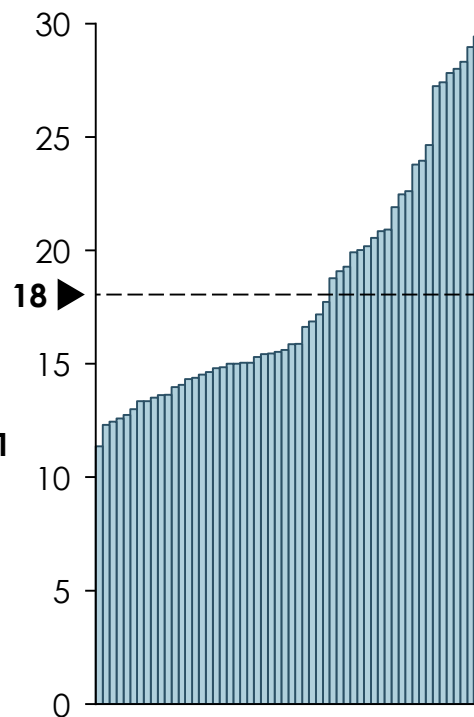
Average CO₂ capture from CCS on fossil fuels and bioenergy
2040-2100 in 2°C pathways

Gt CO₂ per year

Central CCS scenario



High CCS scenario



To derive scenarios, we split pathways into three groups depending on the maximum level of annual carbon capture:

- **No CCS:** no or marginal carbon capture at any point. Only seven pathways meet 2°C objectives without the use of CCS
- **Central CCS:** 28 scenarios where CCS never exceeds 15 Gt CO₂. Most see high CCS deployment, with an average across pathways of 11 Gt CO₂ per year, 2040-2100
- **High CCS:** 56 scenarios where CCS eventually reaches levels between 15-40 Gt CO₂ per year, with an average value of 18 Gt CO₂ per year, 2040-2100.

The future FF use trajectories are based on the central CCS scenarios.

Note: We restrict analyses to scenarios with no more than 40 Gt CO₂ per year in any year. 84 of 241 considered scenarios meet this criteria (cf. Appendix). Central scenario/High CCS consists of scenarios with no more than 15/40 Gt CO₂ captured through CCS in any given year

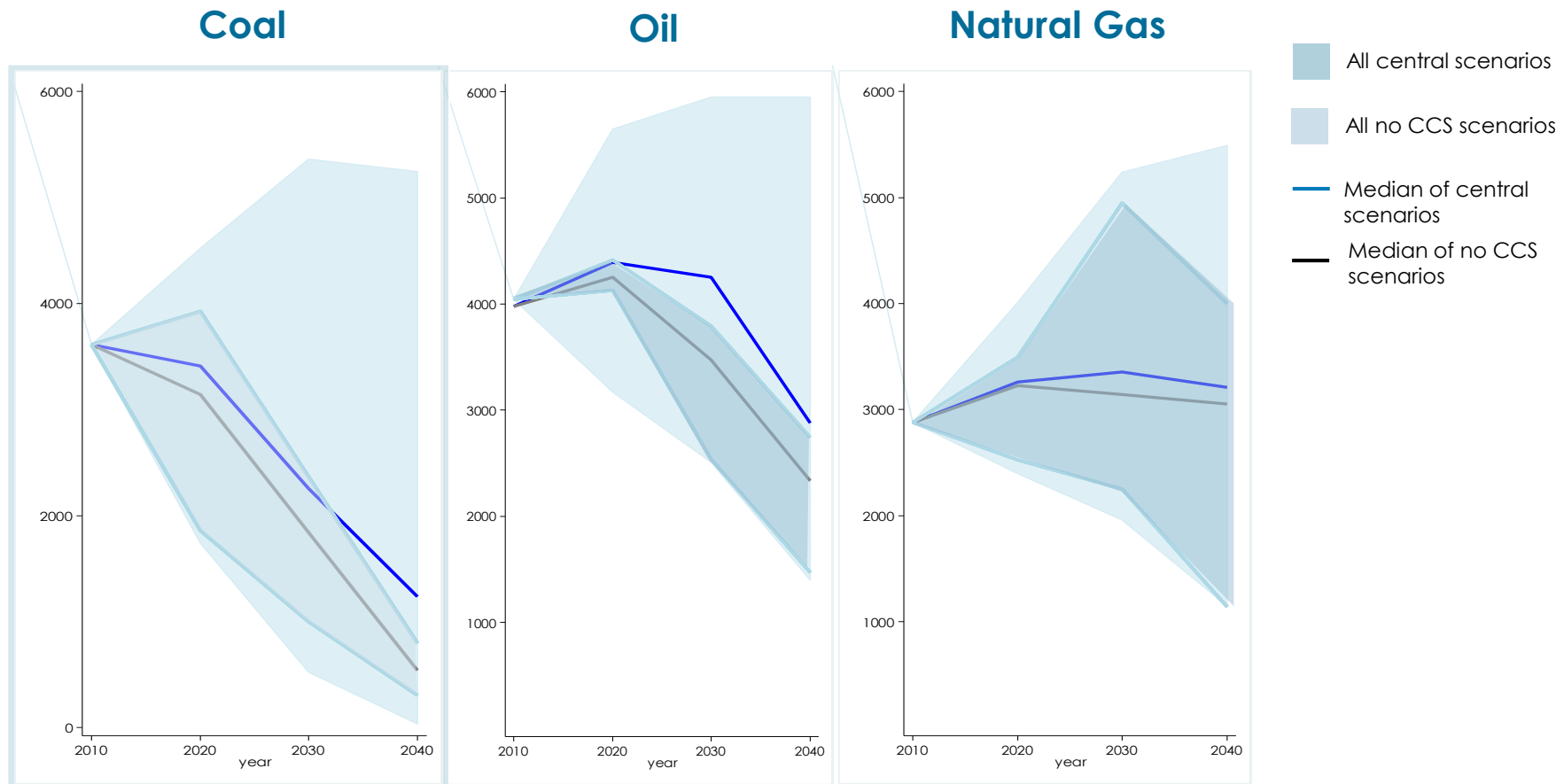
Source: Copenhagen Economics analysis of data from AR5 database.

3. FOSSIL FUEL USE WOULD FALL BY ONE-THIRD BY 2040 TO MEET 2°C OBJECTIVES

The median values for each fossil fuel within each group represent the demand pathway for that fuel

Fossil fuel consumption 2010-2040

Million tonnes of oil equivalent



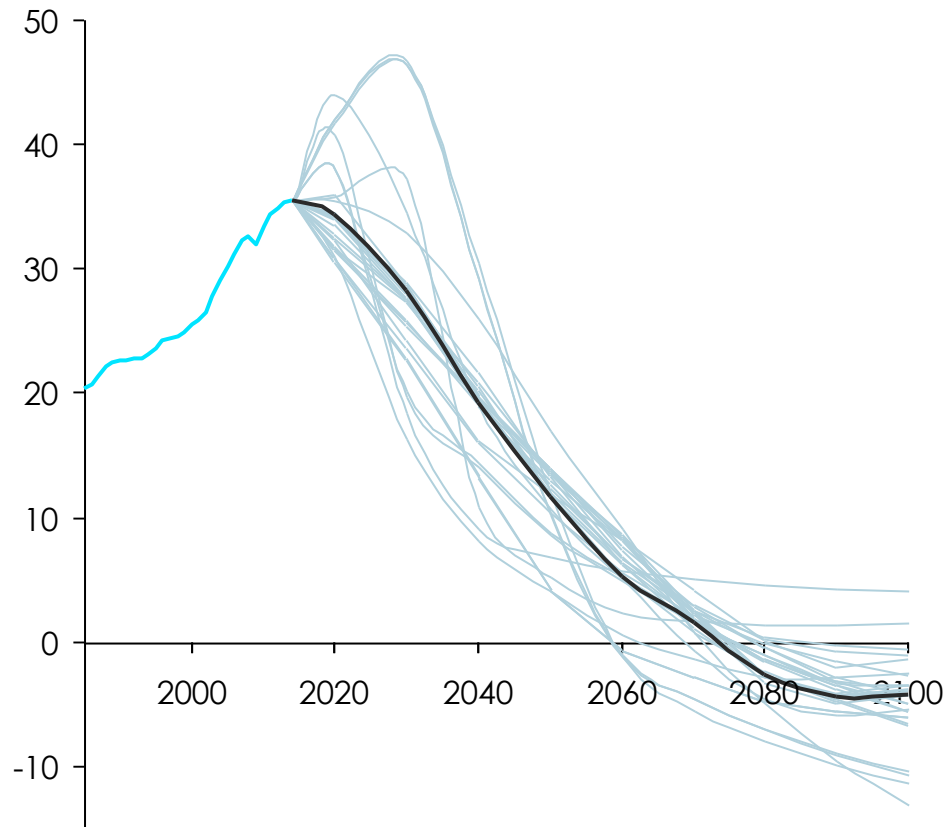
Note: Central scenarios limit the risk of a global temperature rise of more than 2 degrees to less than one third, with 2020 emissions of at least 30 GtCO₂, and with no more than 15 GtCO₂ removal from CCS in any given year.

Source: AR5 database

Emissions in a given year can vary significantly across 2°C pathways, reflecting significant underlying uncertainty

Development in 28 2°C emissions pathways

Billion tonnes CO₂



— Central scenario

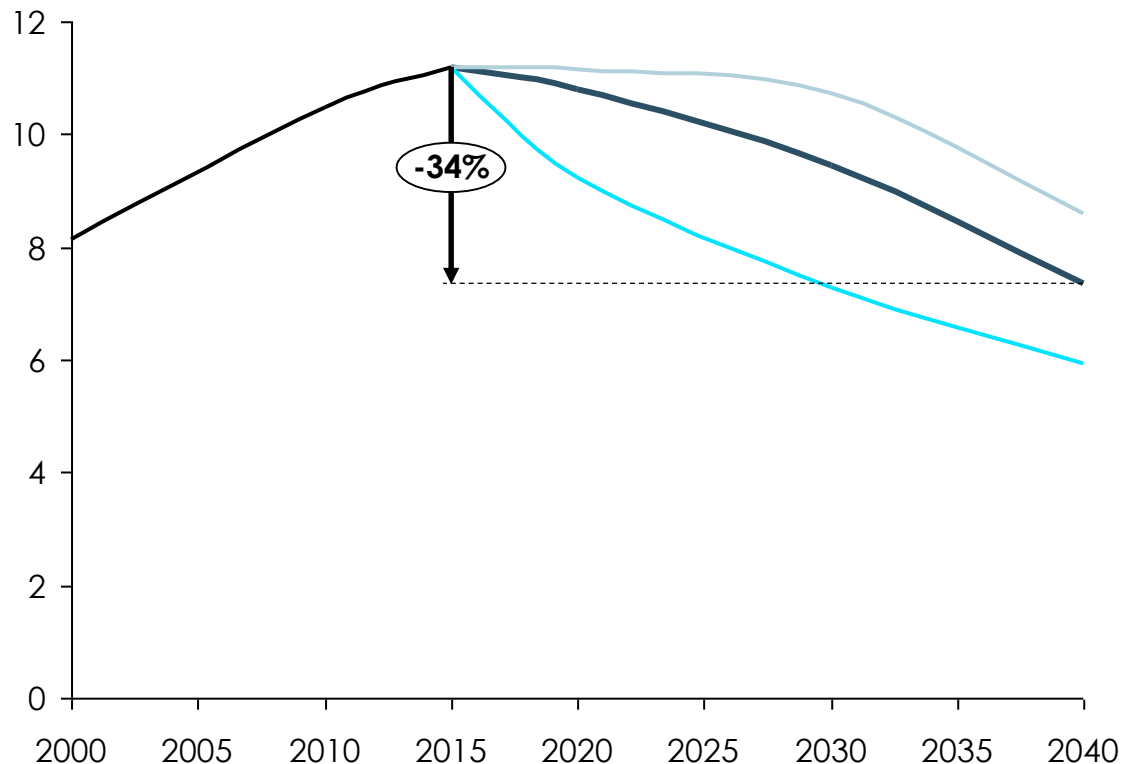
- **Pathways differ along a range of dimensions**
 - Baseline assumptions: economic growth, structure of output, etc.
 - Model structure: model principles, economic relationships, trade, interdependencies, etc.
 - Resource availability: e.g., availability of biomass, oil, etc.
 - Technology development: costs, characteristics, rate of deployment,
 - Assumptions about future technology availability (e.g., “negative emissions”)
 - Policy and scenario characteristics: global scope, delay in mitigation, “optimal” vs. “likely” developments, etc.
 - Fossil fuel prices
 - Etc.
- **The 28 pathways used here retain variation across models, research teams, policy assumptions, etc.**

Note: * The figure shows 28 pathways consistent with limiting warming to 2°C, as well as other criteria.
Source: AR5 database

To meet 2°C objectives, fossil fuel consumption would need to fall by one third by 2040, even with large volumes of CCS

Fossil fuel consumption

1000 million tonnes of oil equivalent per year



Average annual total CO₂ capture, 2040 and 2040-2100

Billion tonnes CO₂ per year

	2040	2040-2100*
High CCS	8	18
Central CCS	8	11
No CCS	Nil	Nil

- "Central CCS" implies large future capture volumes, similar to the emissions from current global power production (13 Gt CO₂)
- "No CCS" requires 2040 fossil fuel use to fall to half of current levels

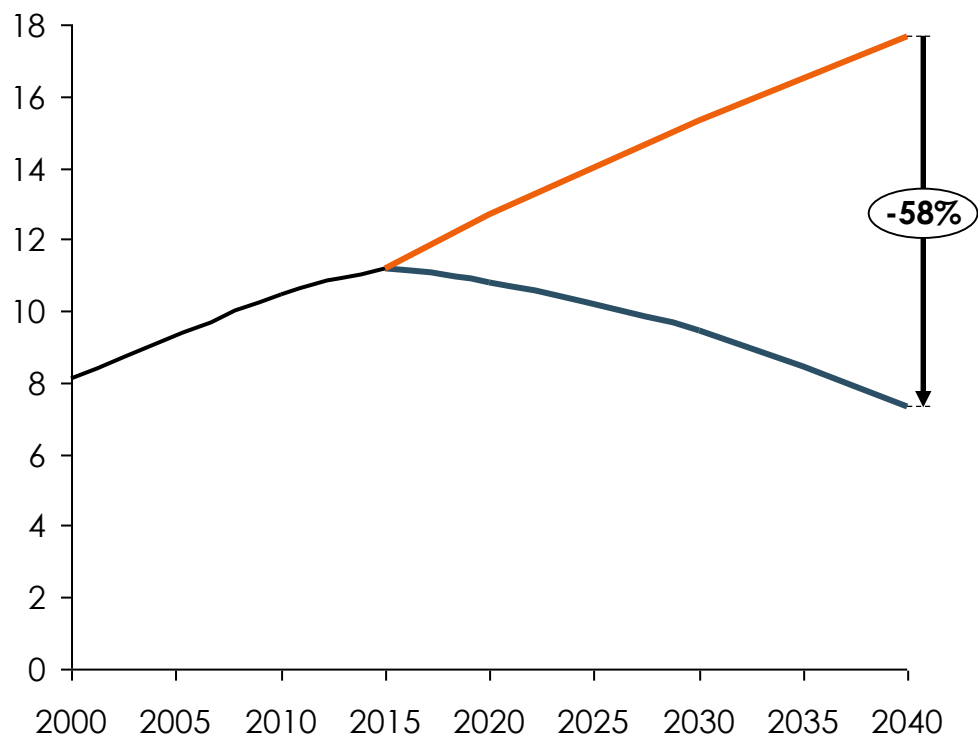
Notes: *In the central and high CCS scenarios, CO₂ removal needs increases significantly beyond 2040 to remain within 2°C . The "Central CCS" scenario is based on scenarios limiting the risk of a global temperature rise of more than 2 degrees to less than one third, with 2020 emissions of at least 30 GtCO₂ and with no more than 15 GtCO₂ removal from CCS in any given year. The "No CCS" scenario fulfils the same criteria as the Central scenario but has no CO₂ removal through CCS. "High CCS" is the median of scenarios with CCS capture rates reaching between 15 and 40 Gt in any given year.

Source: Historic data from BP. Projections are Copenhagen Economics calculations on median values from scenarios in the AR5 database

For comparison, fossil fuel use absent an energy transition would be more than twice as large as in the Central scenario

Fossil fuel consumption

Billion tonnes of oil equivalent per year



— Central scenario — Baseline

- Fossil fuel supply of ~18 billion tonnes of oil equivalent would be required to serve energy needs by 2040 if supply were broadly similar to today's energy system
- Keeping fossil fuel use below 8 billion tonnes of oil equivalent therefore implies that more than half of the underlying energy needs must be met through other means
- Both increased energy productivity and zero-carbon energy will be required to fill this gap: the first by reducing the amount of energy needed to meet needs, the second to avoid CO₂ emissions from energy supply

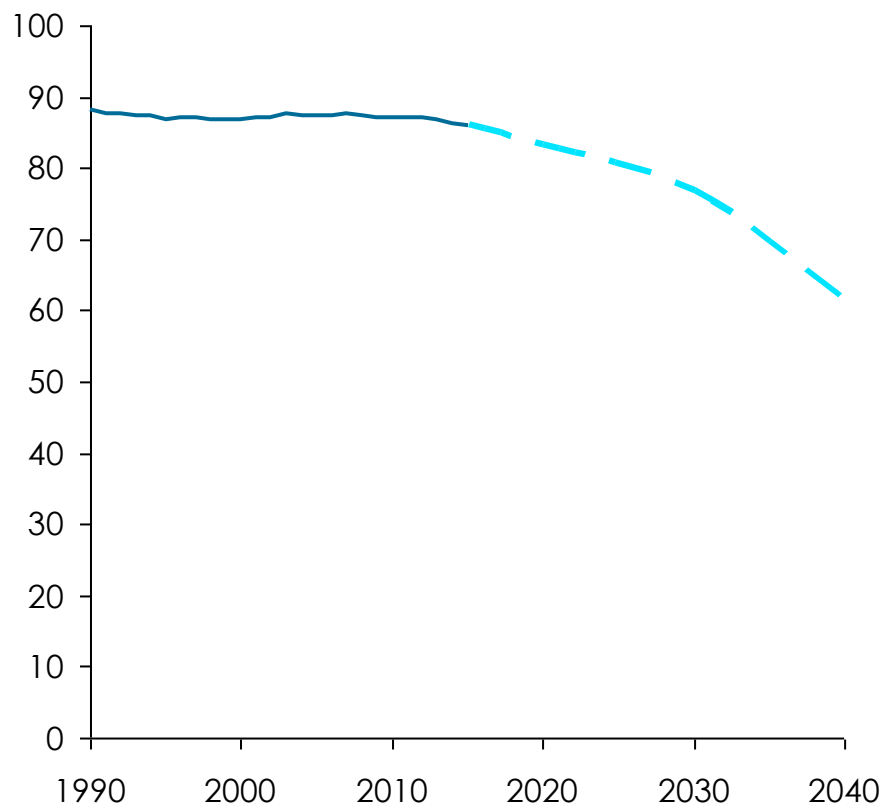
Note: Central scenario is based on scenarios limiting the risk of a global temperature rise of more than 2 degrees to less than one third, with 2020 emissions of at least 30 GtCO₂ and with no more than 15 GtCO₂ removal from CCS in any given year. No CCS scenario fulfils the same criteria as the Central scenario and in addition requires 0 GtCO₂ removal from CCS in any given year. High CCS allows for CCS capture rates of between 15 and 40 Gt in any given year

Source: Historic data from BP. Projections are Copenhagen Economics calculations on median values from scenarios in the AR5 database

Fossil fuels would still provide the majority of world energy supply in 2040, but non-fossil energy provides the vast majority of new supply

Fossil fuel share of total primary energy demand

Per cent



— Median of Central scenario

- Fossil fuels provide >60% of total energy in 2040, even in a 2°C scenario
 - Half of scenarios see fossil fuels make up 60-65% of total primary energy demand in 2040
- Fossil fuel shares have been nearly constant in the past 25 years, falling only marginally from 88% in 1990 to 86% today
- In order to reach 60%, non-fossil energy must provide the majority of new supply
- In the longer-term, continued fossil fuel use depends on CCS. Even with large volumes of CCS, by the late 21st century fossil fuels make up no more than ~12% of total energy

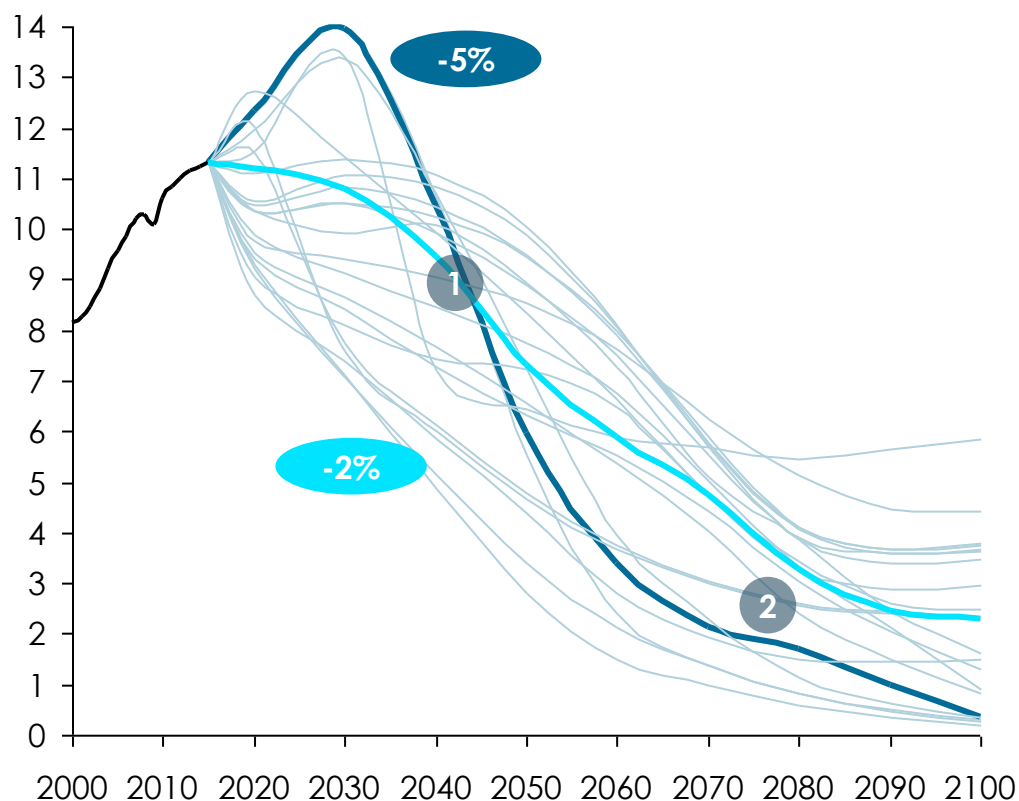
Note: Data based on the 21 pathways in the Central CCS scenario.

Source: Historic data from BP. Projections are Copenhagen Economics calculations on median values from scenarios in the IPCC AR5 database

Higher near-term fossil fuel use implies sharp subsequent reductions with high costs and uncertain feasibility

Fossil fuel consumption

Billion tonnes of oil equivalent



X%

Change (CAGR),
2030s-2060

Growing near-term fossil fuel in a 2°C scenario only with strong (and costly) later adjustments

- 1 Cost and asset stranding: Very rapid reductions are required after a 2030 peak, implying large-scale stranding of fossil-fuel based infrastructure. This is a major source of the significantly higher total costs in such scenarios.
- 2 Feasibility of negative emissions: Even with very rapid reductions in the 2030s-50s, large “negative emissions” are required to avoid exceeding the carbon budget (see section 6)

Note: Bright blue line is Central scenario. Dark blue line is a representative pathway chosen for illustrative purposes.

Sources: Copenhagen Economics analysis based on AR5 database

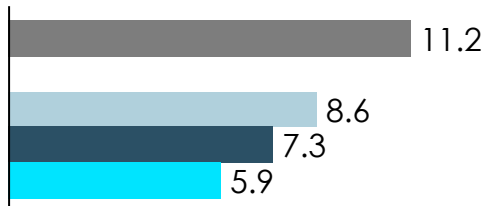
The level of fossil fuel use compatible with a 2°C scenario depends strongly on the level of feasible CCS* assumed

Fossil fuel consumption in 2040, total and by fuel

2015
2040, Central CCS
2040, High CCS
2040, No CCS

Total fossil fuels

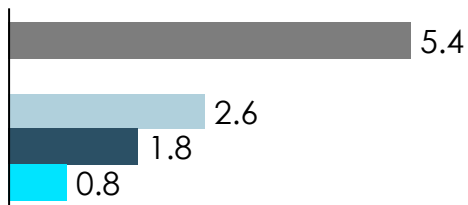
Billion tonnes
oil eq. per year



- Even with very large CCS volumes, total fossil fuel use falls in absolute terms from 2015 to 2040.
- While larger volumes of CCS enables greater continued volumes of fossil fuel use, the increase is small compared to the reduction required from 2015 levels.

Coal

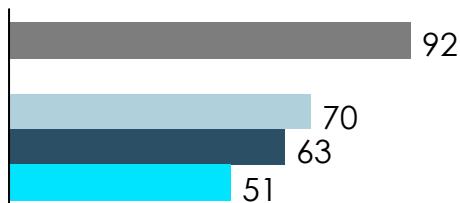
Billion tonnes
coal eq. per year



- Coal use falls by two-thirds by 2040 in pathways where CCS is up to 15 Gt CO₂ per year.
- Even in scenarios where CCS eventually is allowed to grow very large (greater 15 Gt CO₂ per year), coal use falls by 50%.

Oil

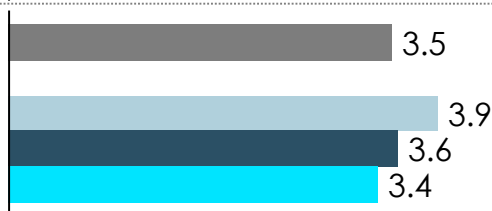
Million barrels
per day



- CCS is not applied on oil, but the level of oil use nonetheless differs with the level of CCS.
- This is because CCS volumes on other fuels affect the carbon budget left, and therefore the amount of oil that can continue to be used.

Natural gas

Trillion cubic
metres per year



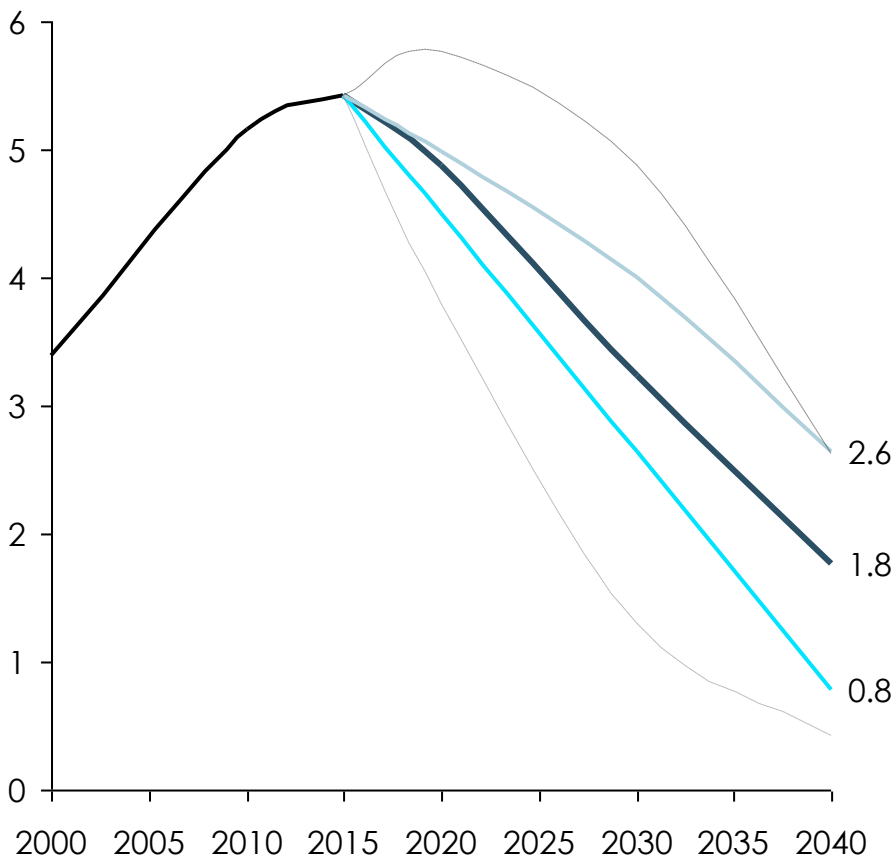
- Natural gas use is not much affected by the level of CCS, but depends more on other factors.
- Effects are greater after 2040, where some pathways see continued natural gas consumption at ~3.5 tcm per year, supported by >10 Gt CCS/year.

Note: The trajectories are the median value of scenarios grouped by the level of maximum carbon capture rates reached.
Source: Copenhagen Economics analysis of data from AR5 database.

Coal consumption declines rapidly, falling by two thirds by 2040; with limited CCS/CCU even steeper declines would be required

Coal consumption, all sectors

Billion tonnes coal equivalent



- All 2°C scenarios see a steep decline in coal, including scenarios when CCS volumes eventually exceed 10 Gt per year
- While there is a wide range of possible outcomes, most analyses see coal substituted ahead of oil or natural gas
- Scenarios with higher levels (>2 Mtce per year) depend on large volumes of coal CCS and on rapid reductions in other sectors – notably oil use in transport
- The variation is closely linked to CCS volumes, reflecting the higher underlying emissions intensity
- Much of the remaining coal use in 2040 is in industry rather than in electricity production, reflecting the limited availability of substitutes for steel production and some high-temperature applications

Note: Percentiles (dashed lines) are 25th and 75th percentile values in analysed set of AR5 database scenarios.

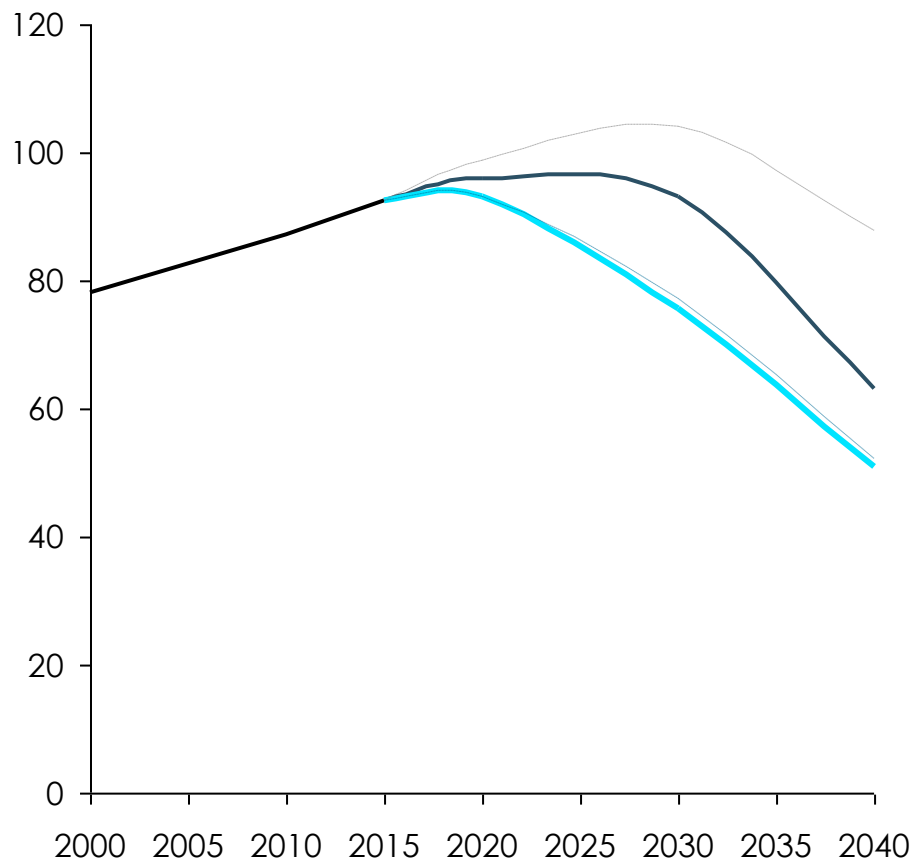
Source: Historic data from BP; future scenarios from Copenhagen Economics analysis of AR5 database as described in appendix

Oil may keep rising into the 2020s before falling by >30% below today's level in 2040; without CCS/CCU, demand must fall by 45%

Oil consumption

Million barrels per day

— Central scenario Central 50% of pathways
— Low CCS scenario



- Peak demand for oil occurs in the 2020s, and by 2040 demand is at two-thirds of current levels
- Many models see a steep decline from approx. 2030. However, the decline rate is typically less than that of output from existing oil fields, implying some continued investment in extraction is required (see below).
- CCS is unlikely to be used on oil, but nonetheless affects feasible volume (as the use of CCS elsewhere “frees up” carbon budget space for oil)
- Scenarios with relatively higher oil use (>70 mbpd) in 2040 depend on steeper reductions of coal and natural gas use in the power sector and industry

Note: Percentiles (dashed lines) are 25th and 75th percentile values in analysed set of AR5 database scenarios.

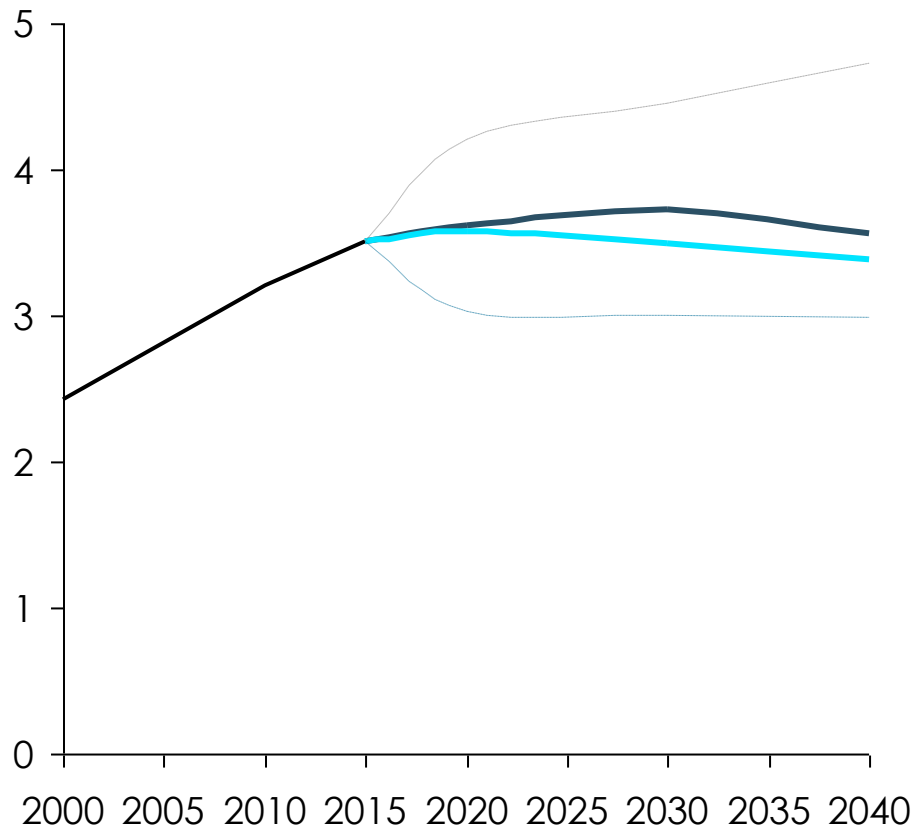
Source: Historic data from BP; future scenarios from Copenhagen Economics analysis of AR5 database as described in appendix

Natural gas consumption stays roughly level up to 2040 and is relatively unaffected by CCS levels

Natural gas consumption

1000 billion cubic metres per year

— Central scenario Central 50% of pathways
— Low CCS scenario



- Natural gas use is less emissions intensive than coal, especially in the power sector
- Consumption therefore typically remains constant for longer than for coal or oil, and in 2040 is roughly at current levels
- Higher natural gas use (> 4 TCM/year) requires a steeper decline in coal or oil use; the rapid phase-in and subsequent phase-out of gas infrastructure, and/or still larger volumes of CCS
- After 2040, gas use falls

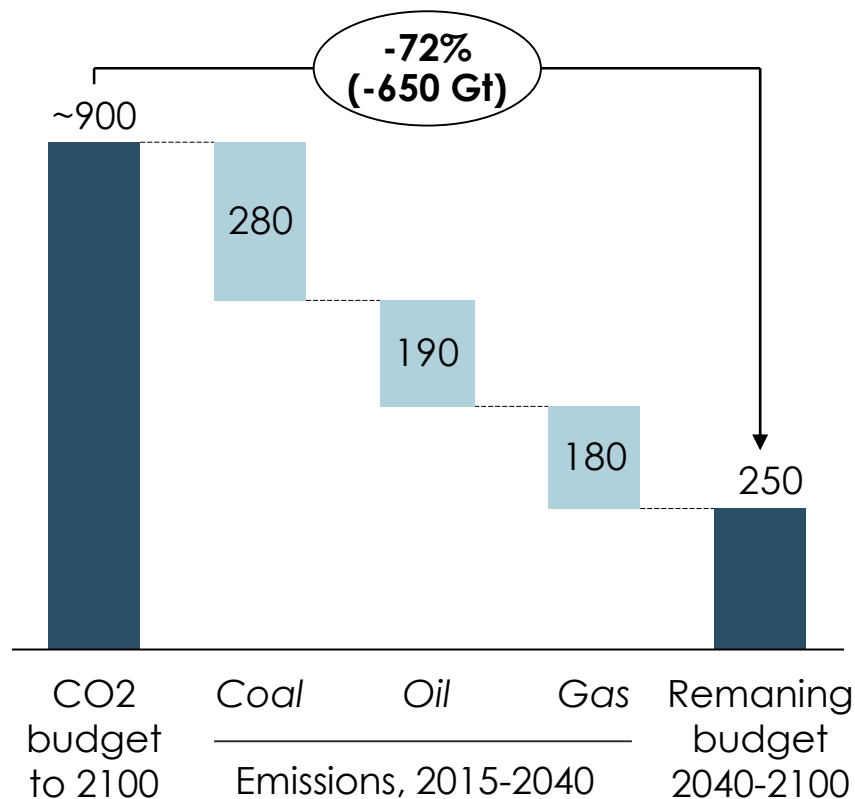
Note: Percentiles (dashed lines) are 25th and 75th percentile values in analysed set of AR5 database scenarios.

Source: Historic data from BP; future scenarios from Copenhagen Economics analysis of AR5 database as described in appendix

In the Central CCS scenario, more than two-thirds of (~650 Gt CO₂) of the remaining carbon budget is used by 2040

Cumulative emissions of CO₂ from fossil fuel consumption, Central CCS scenario

Gt CO₂



- In the “Central CCS” scenarios, ~650 Gt CO₂ are emitted by 2040, with remaining 2040 emissions of ~20 Gt CO₂ per year
- The remaining budget of 250 Gt therefore corresponds to just over a decade of emissions at 2040 rates
- After 2040, net emissions therefore have to fall fast, which in most scenarios require continued rapid reductions in fossil fuel use in combination with “negative emissions” that offset some of the remaining release of CO₂ to emissions (see below)

Summary Findings

1. Rapidly growing energy needs set the scene for an energy transition
2. A 2°C objective implies a strict carbon budget
3. Fossil fuel use would fall by one-third by 2040 to meet 2°C objectives
- 4. The role of fossil fuels changes by 2040 in a 2°C energy system**
5. A 2°C energy transition has profound impacts on fossil fuel markets
6. Carbon capture is a key factor in a 2°C energy transition
7. Appendix: scenario methodology

Summary Findings – The role of fossil fuels by 2040 in a 2°C scenario

Fossil fuels continue to provide the majority of energy in 2040 even in a 2°C scenario. However, the pattern of use will change significantly: away from coal and towards gas, and increasingly concentrated in industry, where alternatives are more difficult to find.

- **Coal would be increasingly concentrated in steelmaking and industry.** This includes as feedstock for steelmaking but also for high-temperature applications (notably, metals and minerals). By 2040, most of thermal coal use in the power sector would be phased out, even if CCS could be mobilised. Coal consumption therefore would be increasingly concentrated in metallurgical coal, and in a small amount of residual coal-fired power that has not yet been phased out, or fitted with CCS.
- **Oil would be concentrated in transport use and as feedstock for chemicals production.** A significant share of future passenger transport needs would need to be served through electrification, modal shifts, and increased efficiency. In other transport, much depends on the availability and desirability of using biofuels at scale. Applications where replacing oil is particularly difficult include heavy-duty road transport, aviation, and shipping. By 2040, some 25% of oil may be used as feedstock for chemicals (compared to 10% today).
- **Natural gas would continue to be used across the energy system.** In power, it has half the emissions intensity of coal and therefore can persist longer. However, by 2040, its global share in the power sector must decline to 10-15%, even with substantial CCS volumes. In buildings, natural gas use for heating and hot water is replaced to a significant extent by electrification and increased efficiency, while industrial use may increase, as natural gas provides a cleaner alternative to coal for high-temperature heat.

Our approach: we use an energy systems model calibrated to the Central scenario to investigate the role of fossil fuels in 2040

Represent the full energy system

Use a detailed energy system model (the “Global Calculator”) that represents the detailed energy service in each end-use sector, as well as power and fuels production.

Complement with other existing analyses

Update the model and supplement the analyses with data from the International Energy Agency’s 2016 Energy Technology Perspectives.

Incorporate ETC insights

Incorporate key insights from the work of the Energy Transitions Commission, including on the importance of electrification, the degree of energy productivity improvement required, and the extent and patterns of use of CCS.

Calibrate to the Central scenario

Calibrate the overall scenario to match key features of the “Central” scenario derived from the IPCC database: in terms of CO₂ emissions, total energy demand, and the consumption of coal, oil, and natural gas.



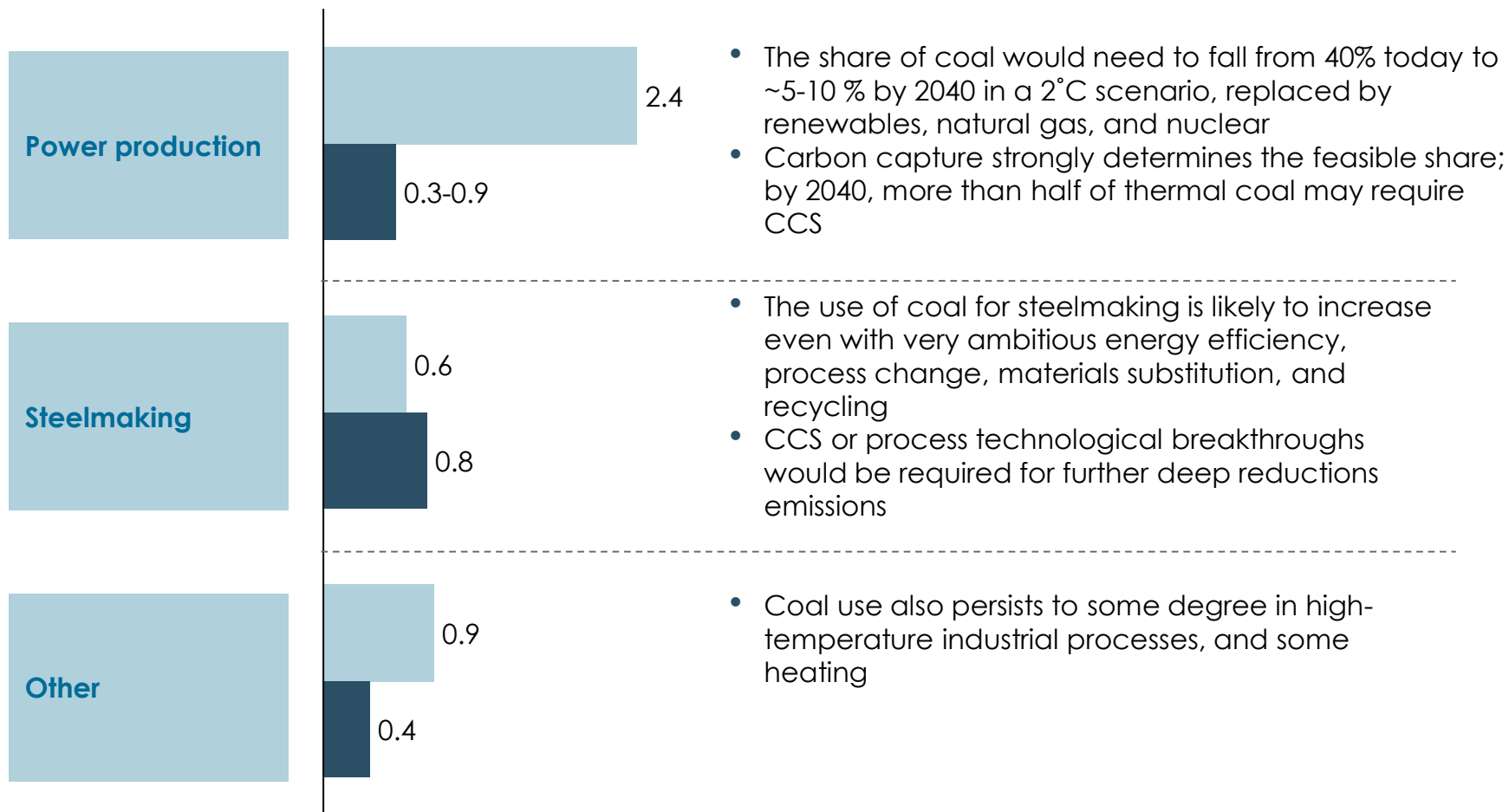
Detailed representation of fossil fuel use across end-use sectors in an illustrative scenario

Coal will be needed as a feedstock in industry; its use as a fuel in power production is likely to fall significantly

2013 2040

Coal consumption, illustrative scenario

Billion tonnes of oil equivalent



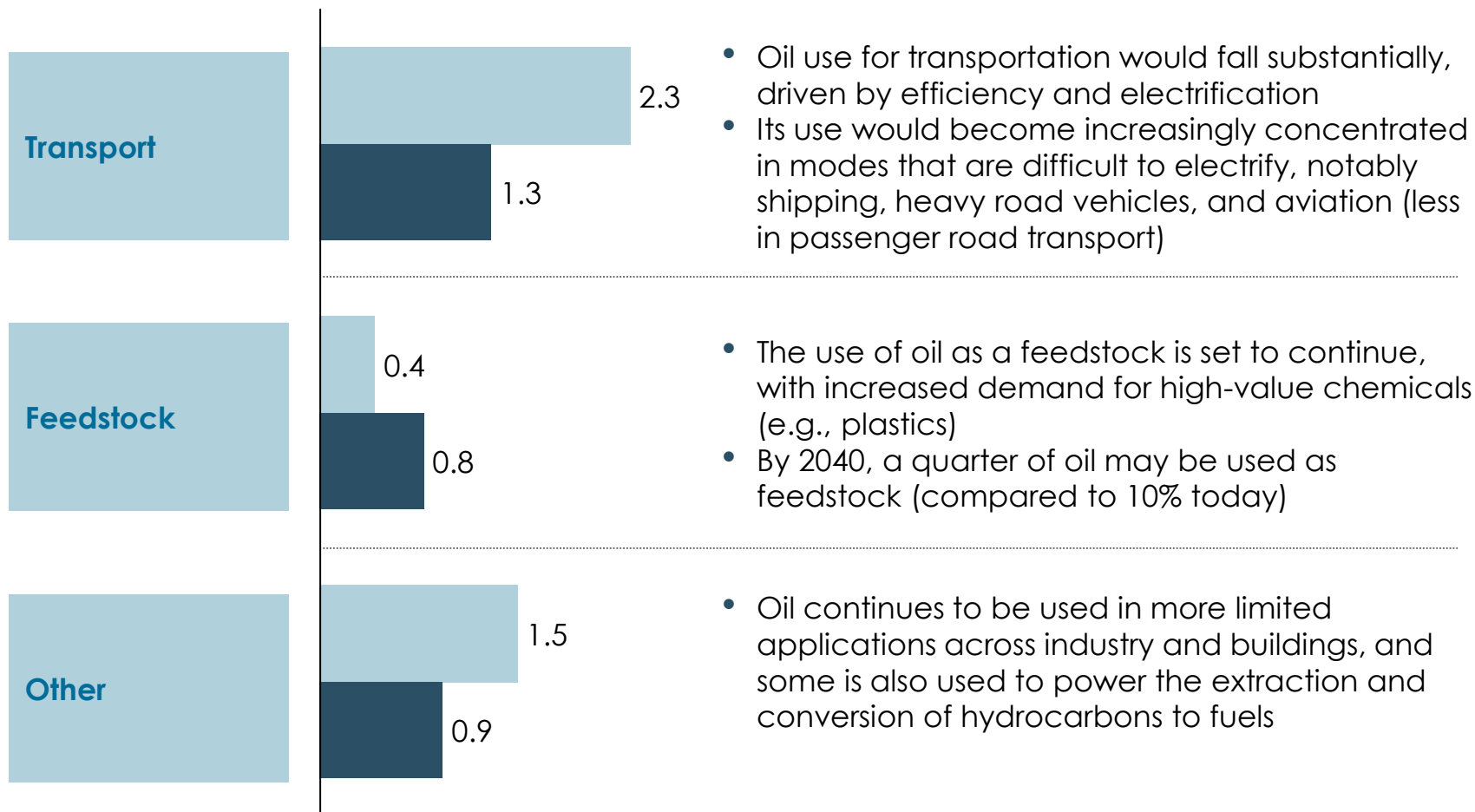
Source: Copenhagen Economics analysis

Oil will probably still used as a transport fuel and, increasingly, as a feedstock for the production of chemicals

Oil consumption, illustrative scenario

Billion tonnes of oil equivalent

2013 2040



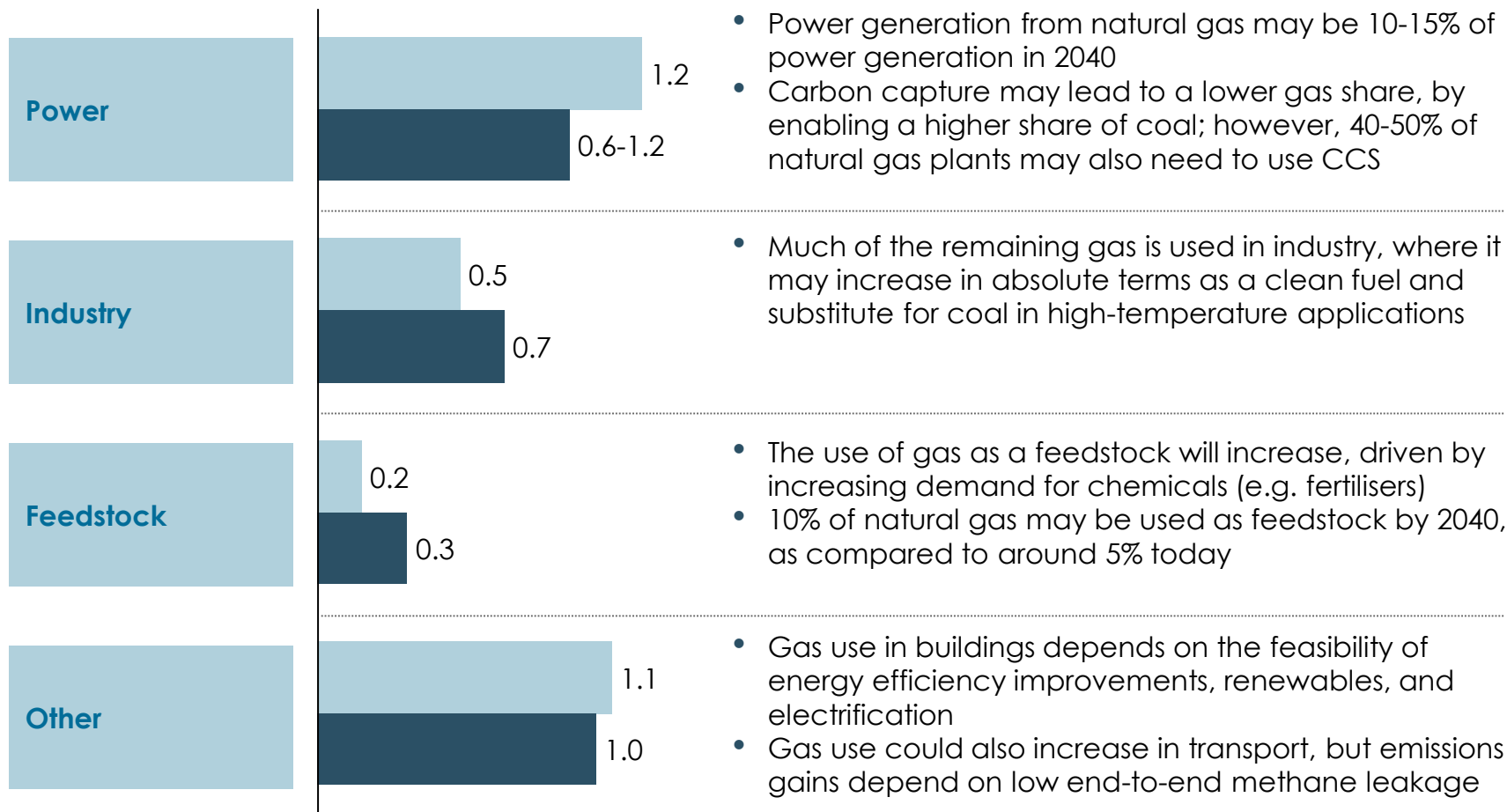
Source: Copenhagen Economics analysis

Natural gas use stays roughly level, but is increasingly used as feedstock rather than as a fuel

2013 2040

Natural gas consumption, illustrative scenario

Billion tonnes of oil equivalent

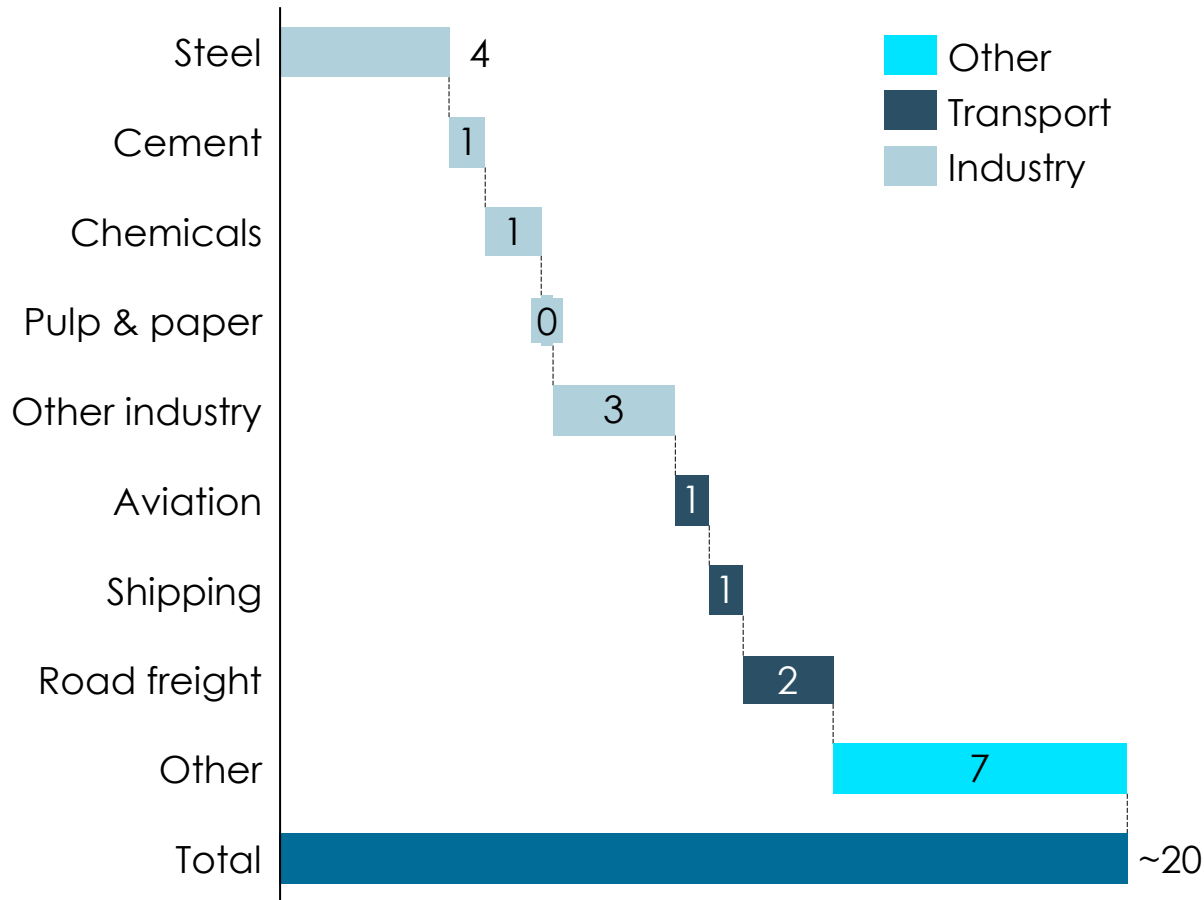


Source: Copenhagen Economics analysis

By 2040, two-thirds of remaining emissions may result from applications that are not amenable to electrification

2040 emissions in hard-to-electrify sectors

Gt CO₂

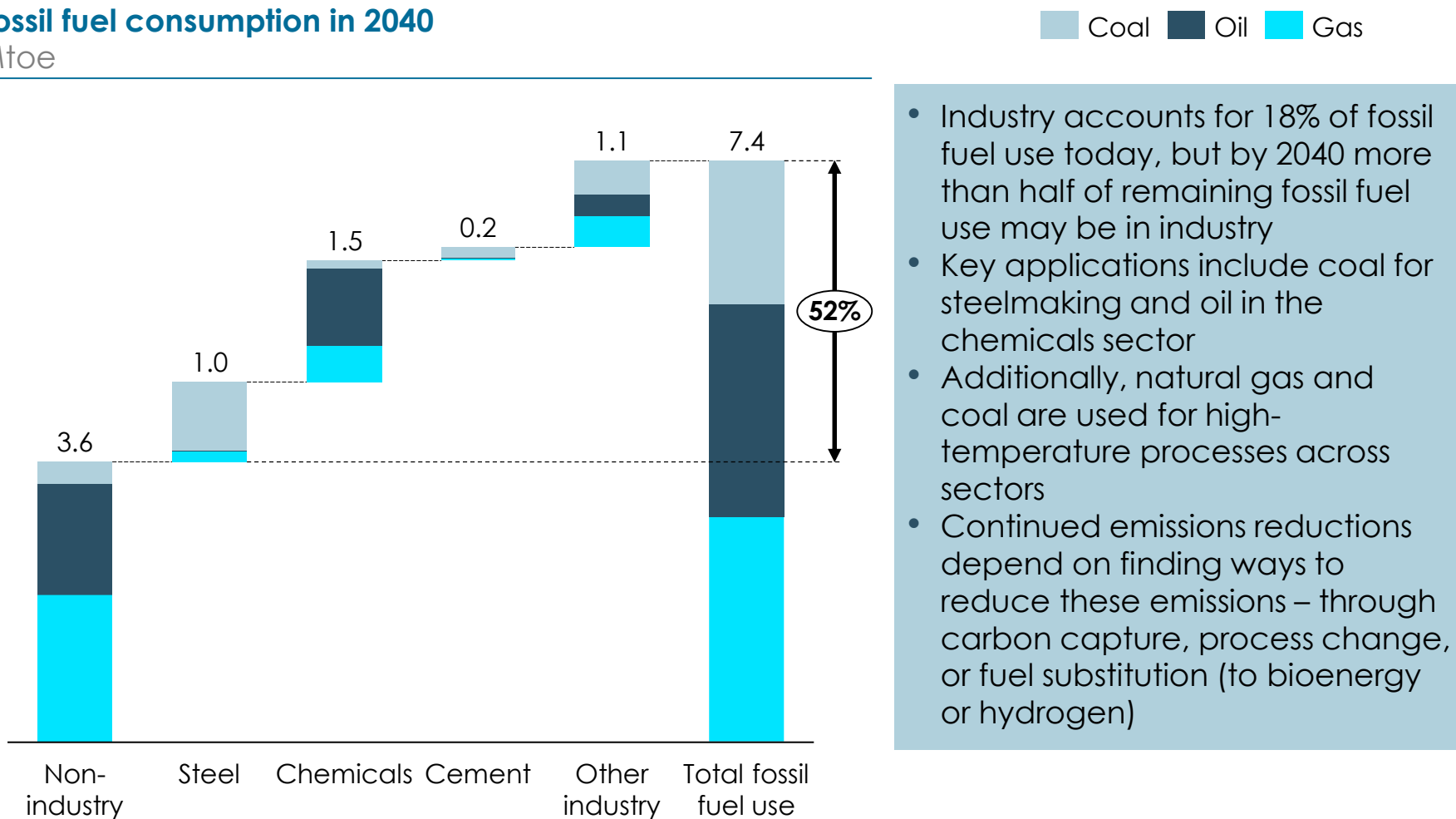


- ~9 Gt of emissions may still remain in industry, of which nearly half are emissions from the steel industry
- 3-4 Gt of emissions in aviation (freight and passenger), as well freight transport by ship and road will still come from oil-based transport fuels

Industry may account for half of remaining fossil fuel use in 2040 in a 2°C scenario (vs. 18% today)

Fossil fuel consumption in 2040

Mtoe



- Industry accounts for 18% of fossil fuel use today, but by 2040 more than half of remaining fossil fuel use may be in industry
- Key applications include coal for steelmaking and oil in the chemicals sector
- Additionally, natural gas and coal are used for high-temperature processes across sectors
- Continued emissions reductions depend on finding ways to reduce these emissions – through carbon capture, process change, or fuel substitution (to bioenergy or hydrogen)

Summary Findings

1. Rapidly growing energy needs set the scene for an energy transition
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3. Fossil fuel use would fall by one-third by 2040 to meet 2°C objectives
4. The role of fossil fuels changes by 2040 in a 2°C energy system
- 5. A 2°C energy transition has profound impacts on fossil fuel markets**
6. Carbon capture is a key factor in a 2°C energy transition
7. Appendix: scenario methodology

Summary Findings – Fossil fuel markets and investment

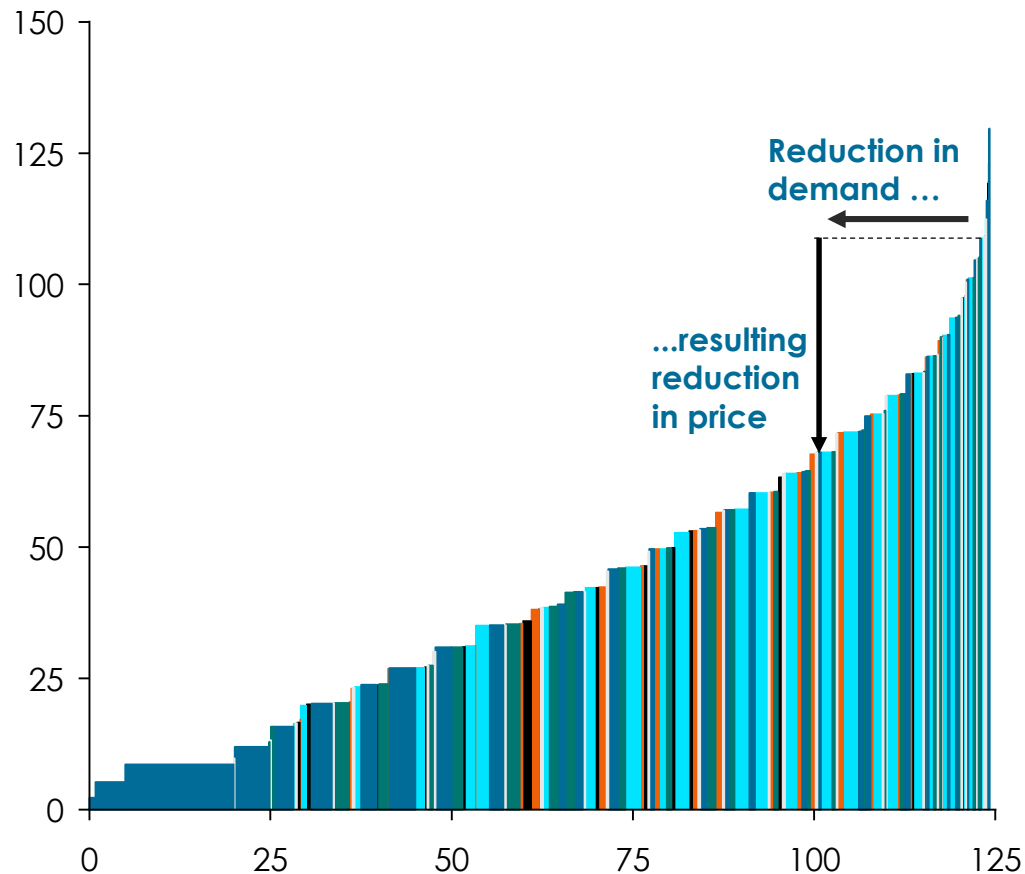
A 2°C energy transition would have profound implications for fossil fuel markets. The primary impact is on the rate of growth and resulting lower prices. However, even in a rapid energy transition, continued investment in hydrocarbon production capacity would be required, as most of supply in 2040 would come from new fields due to natural decline of existing production.

- **Fossil fuel prices would be lower in a 2°C scenario**, reflecting less need to mobilise high-cost reserves to meet demand. The uncertainty about resulting technology and market dynamics is large, but a range of assessment suggest significant change.
 - For oil, prices may fall from USD 90-120/bbl in a reference case, to 50-80/bbl. Consumers would save ~USD 1 trillion per year, even at the lower demand levels.
 - For natural gas, prices vary regionally, but on average may fall from USD 10 to 6/MMBTU. The regional impact differs significantly depending on transmission infrastructure.
- **Continued investment will be necessary**: the majority of 2040 hydrocarbon supply would come from new developments even in a 2°C scenario.
 - Production from existing fields declines at 4-6% per year, faster than demand declines even in a stringent 2°C scenario.
 - Some 60% of oil demand and 75% of natural gas demand in 2040 will be met by fields that are yet to be developed.
- **Some 70% of investment in oil and gas extraction will therefore still be required in a 2°C scenario compared to a reference case**. Cumulative investment in upstream oil production falls from approx. USD 14 trillion in a baseline scenario to USD 10 trillion (-25%), while natural gas investment falls from USD 6.7 to 4.4 trillion (-35%). Investment rates start to fall off from the 2030s.

Lower oil demand in a 2°C scenario means fewer high-cost resources need to be mobilised to meet demand

Cost curve for cumulative oil production by region, 2016-2040

USD per barrel of oil; 1,000 million tonnes of oil equivalent per year



■ Asia ■ ME and Africa
■ Europe ■ North America
■ FSU ■ South America

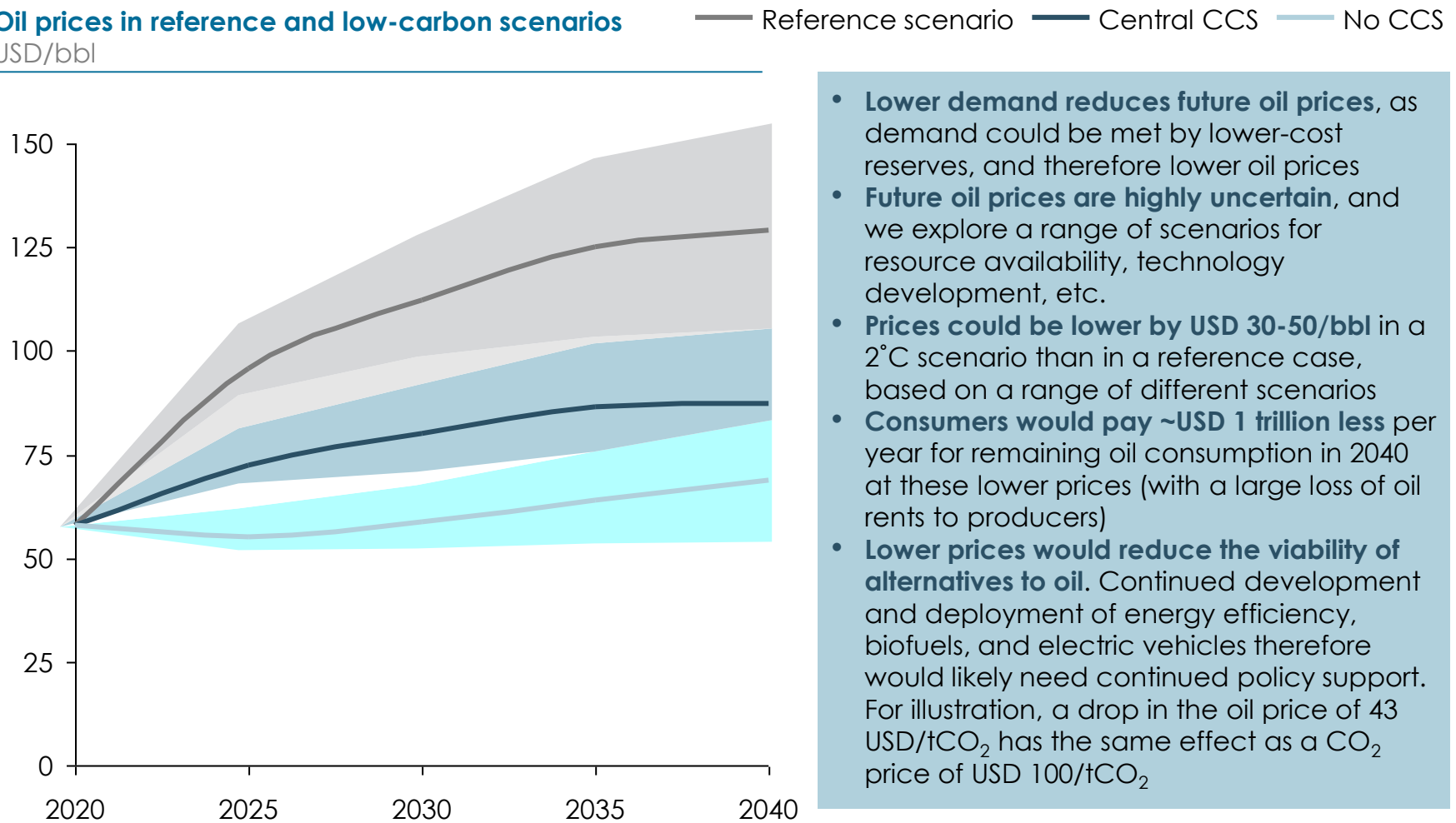
- We use a model of the oil and natural gas markets to explore implications of lower oil demand in a 2°C scenario
- The core of the model is field-by-field data on production potential and economics. Data from Rystad is complemented by assumptions about future developments (such as the spread of non-conventional oil technologies)
- For each field, factors such as maintenance opex and government take at different oil prices are accounted for, creating an effective supply curve for each individual field.

Source: Copenhagen Economics oil market model; Rystad data; IEA World Energy Outlook 2015 (2015)

Oil prices could be USD 30-60/bbl lower in a 2°C scenario, saving consumers USD 1 trillion per year in 2040

Oil prices in reference and low-carbon scenarios

USD/bbl



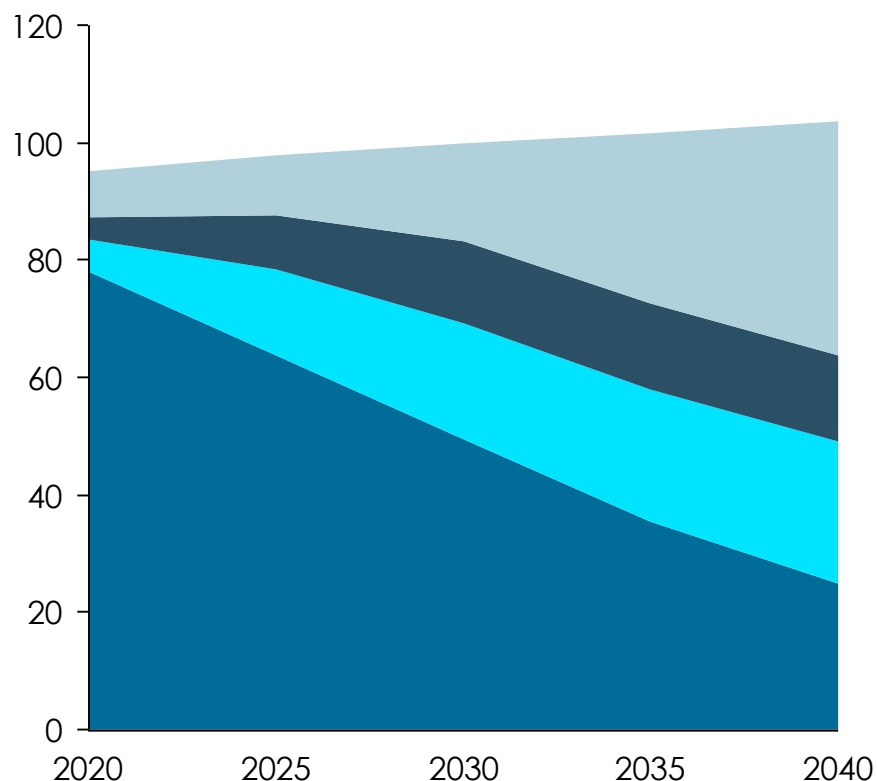
- **Lower demand reduces future oil prices**, as demand could be met by lower-cost reserves, and therefore lower oil prices
- **Future oil prices are highly uncertain**, and we explore a range of scenarios for resource availability, technology development, etc.
- **Prices could be lower by USD 30-50/bbl** in a 2°C scenario than in a reference case, based on a range of different scenarios
- **Consumers would pay ~USD 1 trillion less** per year for remaining oil consumption in 2040 at these lower prices (with a large loss of oil rents to producers)
- **Lower prices would reduce the viability of alternatives to oil.** Continued development and deployment of energy efficiency, biofuels, and electric vehicles therefore would likely need continued policy support. For illustration, a drop in the oil price of 43 USD/tCO₂ has the same effect as a CO₂ price of USD 100/tCO₂

Note: The "Reference scenario" uses the oil demand in IEA's New Policies scenario.
Source: Copenhagen Economics oil market model; Rystad data; IEA World Energy Outlook 2015

Production from existing fields declines fast, and an additional 24-39 mbpd production capacity would be required by 2040

Oil production by scenario and field status

Million barrels per day



Reference No CCS
Central CCS Existing fields

- **Oil demand in a 2°C scenario falls by one-third** over 15 years: from a peak of approx. 95 mbpd in the mid 2020s, to less than 65 mbpd by 2040
- **Even so, production from existing oil fields declines faster than demand.** Even with significant reinvestment, aggregate production capacity falls by 6% per year (and close to 7% with lower investment levels)
- **60% of 2040 oil production in a 2°C scenario must come from new sources.** Fields currently producing or under development will provide approx. 25 mbpd production capacity in 2040. Approx. 40 mbpd of new capacity therefore has to be developed
- **Natural decline provides an opportunity to avoid “stranded assets”.** Even a rapid decline in demand after 2030 requires some new investment in capacity

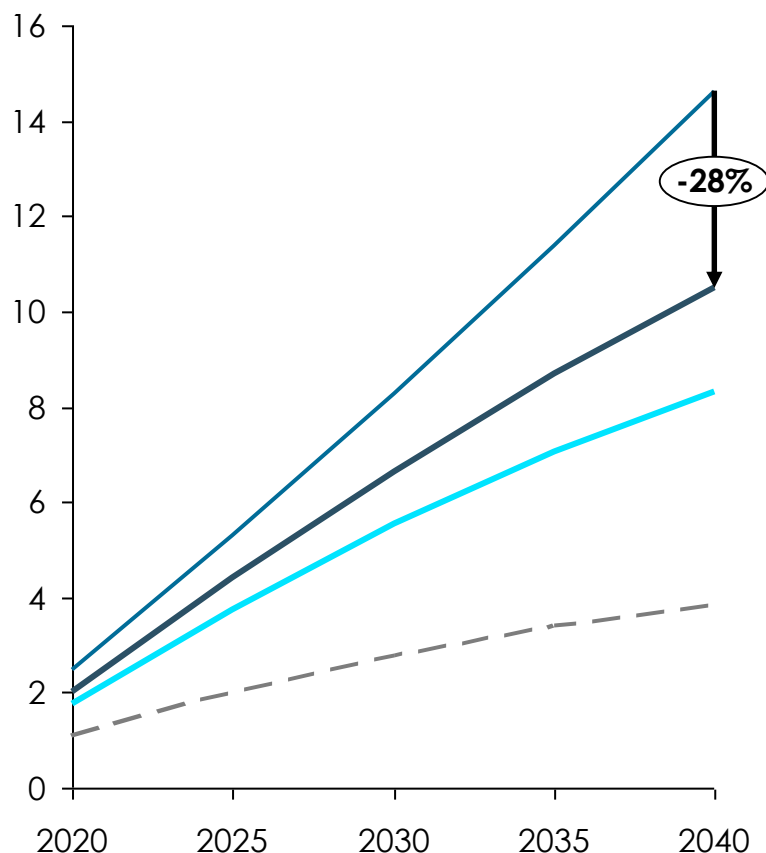
Note: “Existing fields” include fields currently producing and under development. Decline rates are calculated for the rate of investment that can be supported by prevailing oil prices as estimated by the model. The “Reference scenario” uses the oil demand in IEA’s New Policies scenario.

Source: Copenhagen Economics oil market model; Rystad data; IEA World Energy Outlook 2015 (2015)

Investment in oil production falls by 28-43% in a 2°C scenario – most of baseline investment will thus still be required

Cumulative investment in oil production, 2015-2040

Trillion USD



Existing fields Central CCS
No CCS Reference

- In a reference scenario (oil demand at 104 mbpd by 2040), USD 14 trillion of cumulative investment is required up to 2040
- Investment needs fall by one-quarter in a Central scenario (63 Mbpd in 2040), to 10 trillion. Even with the more rapid decline in the No CCS scenario, USD 8 trillion of investment is required
- The large majority of investment under a reference scenario will be required also under a 2°C scenario. Cumulative investment thus falls by much less (28%) than does 2040 demand (44%)
- Three factors jointly explain why investment falls much less than does annual demand:
 - Close to USD 4 trillion is required to maintain production from existing fields
 - New fields continue to be mobilised, as production from existing fields declines faster than demand
 - Demand declines gradually, and cumulative production up to 2040 therefore falls less than do production levels in 2040

Note: The "Reference scenario" uses the oil demand in IEA's New Policies scenario.

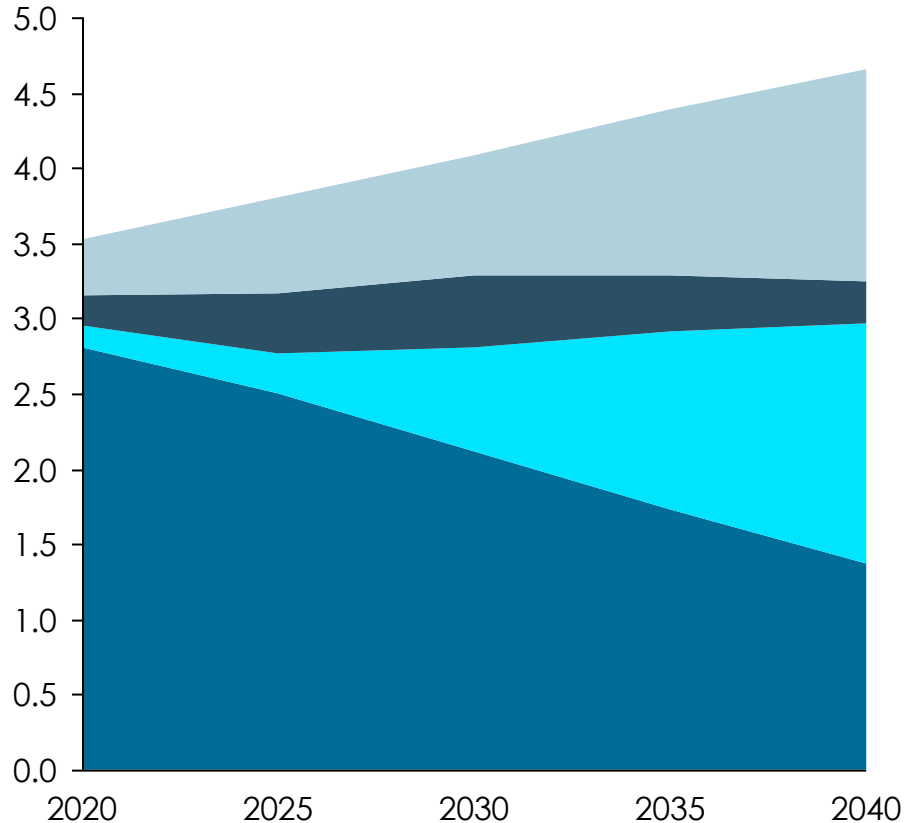
Source: Copenhagen Economics oil market model; Rystad data; IEA World Energy Outlook (2015); IEA World Energy Outlook (2014)

An additional 1600-1900 BCM/year of natural gas production capacity would be required by 2040

Natural gas production by scenario and field status

Thousand billion cubic metres per year

Reference No CCS
Central CCS Existing fields



- **Natural gas demand stays relatively flat in a 2°C scenario.** The variation is less dependent on CCS, and more on other factors
- **Production from existing natural gas fields declines.** Even with significant reinvestment, aggregate production capacity falls by 4% per year
- **More than half of 2040 natural gas production in a 2°C scenario comes from new sources.** Fields currently producing or under development will provide less than 1400 Bcm/year production capacity in 2040. Some 1900 Bcm/year of new capacity (~60% of the total) therefore has to be developed

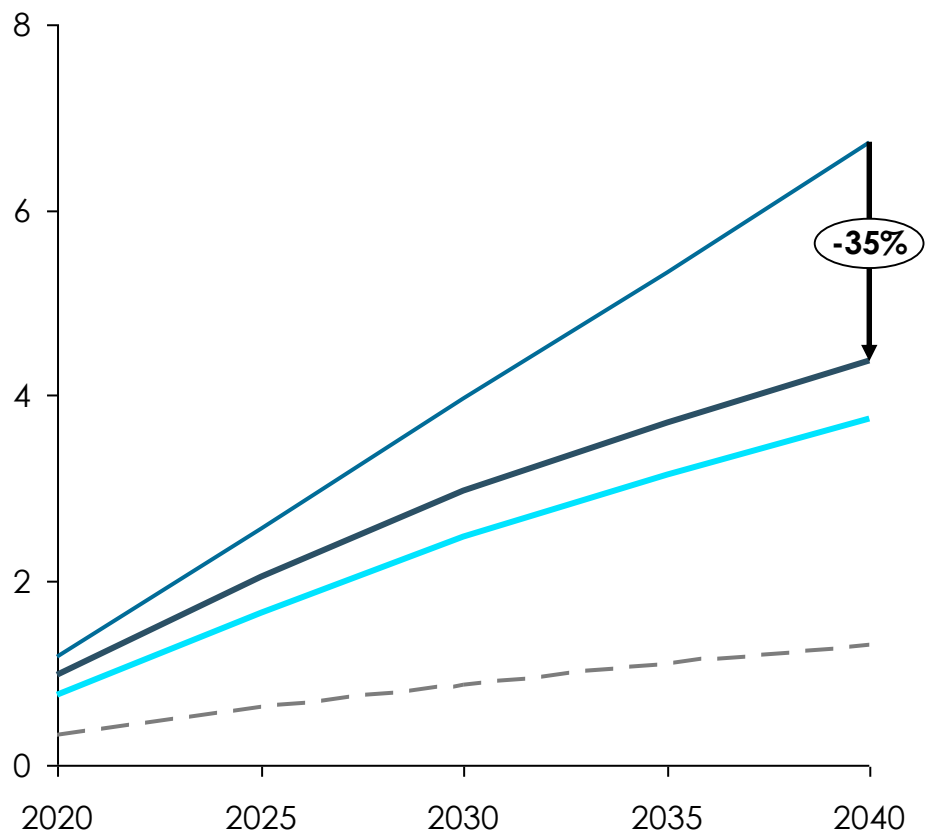
Note: "Existing fields" include fields currently producing and under development. Decline rates are calculated for the rate of investment that can be supported by prevailing oil prices as estimated by the model. The "Reference scenario" uses the oil demand in IEA's New Policies scenario.

Source: Copenhagen Economics natural gas market model; Rystad data; IEA World Energy Outlook 2015 (2015)

Investment in natural gas production falls by 35-45% in a 2°C scenario

Cumulative investment in natural gas production, 2015-2040

Trillion USD



Existing fields Central CCS
No CCS Reference

- In a reference scenario (natural gas demand at 5200 Bcm/year by 2040), USD 7 trillion of cumulative investment is required until 2040
- Investment needs fall by one-third in a Central scenario (3200 Bcm/year in 2040), to just over 4 trillion. In the No CCS scenario, just under USD 4 trillion of investment is required
- 2040 demand levels are 38% lower, and total cumulative investment until 2040 falls by 35%

Note: The "Reference scenario" uses the gas demand in IEA's New Policies scenario.
Source: Copenhagen Economics natural gas market models; Rystad data; IEA WEO (2015); IEA WEO (2014)

Summary Findings

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Summary Findings – CCS* of CO₂ in a 2°C energy transition

Carbon capture and sequestration (CCS) plays a major role in pathways to limit warming to 2°C, with many analyses predicated on volumes of 10 or even 20 Gt CO₂ of CCS per year. However, CCS faces large barriers, and there may be other solutions: process change, bioenergy, and hydrogen in industry; renewable energy in power; and different forms of “negative emissions” technologies.

- **Very large volumes of CCS feature in nearly all 2°C scenarios.** Volumes reach close to 10 Gt by 2040, and then 20 Gt (or even 40 Gt) per year.
- **We define three CCS scenarios**, based on existing pathways, to analyse the impact on fossil fuels.
 - No CCS: CCS is not available. Only a handful of scenarios find it is possible to meet future energy needs under these conditions.
 - Central CCS: carbon capture reaches 8 Gt, of which 3 Gt of CCS on fossil fuels. This level of CCS requires 2040 fossil fuel use to fall by one-third on current levels.
 - High CCS: CCS reaches 18 Gt/year after 2040. Although the majority of available pathways assume such volumes, the feasibility is highly speculative.
- **Reaching even the central CCS scenario faces profound challenges of scale, infrastructure, and cost:**
 - Scale: There are fewer than 30 CCS plants in the world. Volumes of 7-8 Gt by 2040 would require more than two installations each week 2020-2040.
 - Infrastructure: carbon capture of 7-8 Gt per year would require capture, transport, and storage of a volume of CO₂ similar to current total oil and natural gas production.
 - Cost: carbon capture is unusually dependent on a strong and predictable carbon price, and unlike other mitigation options have few other benefits or drivers.
- **CCS may be particularly important in industry.** More than half of remaining fossil fuel use may be in industry by 2040, making CCS key to a continued energy transition towards net zero emissions. Other options include process changes, bioenergy, and hydrogen.
- **Negative emissions are a feature of nearly all analyses that meet a 2°C objective** while meeting energy needs. Most analyses rely on bioenergy and CCS, which is currently unproven at scale.

* For simplicity, CCS is used to capture CO₂ capture and sequestration through storage or transformation to CO₂ based products

Carbon capture and sequestration can in principle employ a large number of routes

CARBON CAPTURE

Separation, clean-up, and concentration of CO₂ from other gases, as a precursor to sequestration

Fossil fuel / industrial process CO₂

- Separation and clean-up of CO₂ from large point sources with high concentration
 - Post-process, Oxy-fuel, syngas/hydrogen, etc.

Atmospheric CO₂

- Capture of CO₂ at low concentrations, e.g., through:
 - Biomass, capturing CO₂ through photosynthesis
 - Weathering, speeding up formation of rock
 - Direct air capture, using chemical processes to concentrate CO₂

SEQUESTRATION

Permanent removal of CO₂ from atmosphere, while avoiding negative side-effects or leakage

Storage

- CO₂ storage in geological formations

Transformation

Minerals

- Storage in rocks or minerals

Products

- Bio/CO₂-based plastics, carbon fibre, etc.

Uptake

Land

- Re- / afforestation
- Soil carbon sequestration

Ocean

- Ocean fertilisation
- Increased alkalinity

UTILISATION - EXAMPLES

*Additionally, derive positive value from either **process** or **product** of sequestration*

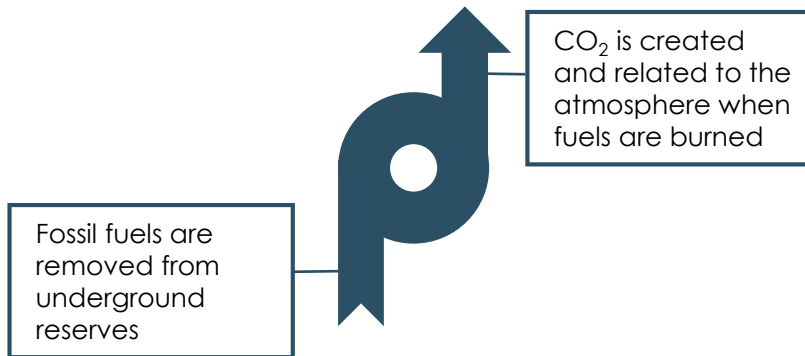
- Enhanced oil recovery (subject to monitoring)
- Replace conventional construction materials and aggregates
- Replace conventional products based on fossil fuel feedstock
- Increase soil quality, eg through mulching
- N/A (high uncertainty about effects)

- **Capture technology maturity** differs. Capture of concentrated CO₂ is proven at demonstration/lab scale for a range of applications, but still modest. Weathering and direct air capture are at the concept stage, with high energy penalties. Biomass uptake is large.
- **Sequestration potential** also varies. Geological storage is increasingly well understood, and the estimated technical potential large. Transformation is mostly at the R&D stage; products also differ in how long they lock in CO₂ before return to the atmosphere. Uptake in land already is important a key component of the carbon cycle (and conversely, deforestation a major source of negative sequestration). The feasibility and effects of increasing ocean CO₂ uptake are highly uncertain.
- **Utilisation** also varies. Enhanced oil recovery is proven and has underpinned most sequestration to date. CO₂-based products are at R&D stage, with construction materials a large potential volume market. Agricultural / forestry practices have proven potential.

Carbon capture technology can be applied to both fossil fuels and bioenergy

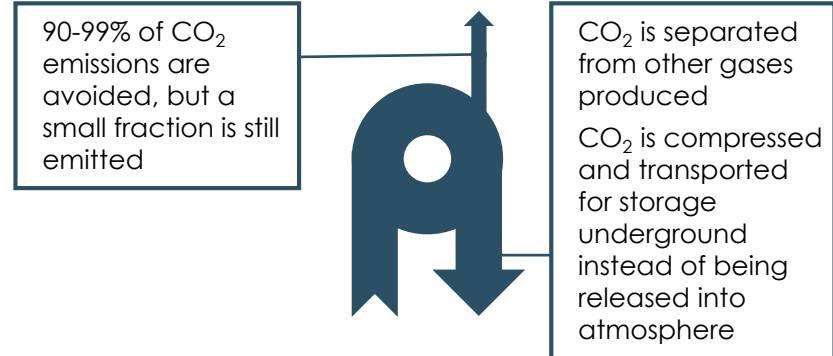
Fossil fuels without CCS

Burning fossil fuels gives rise to CO₂ emissions



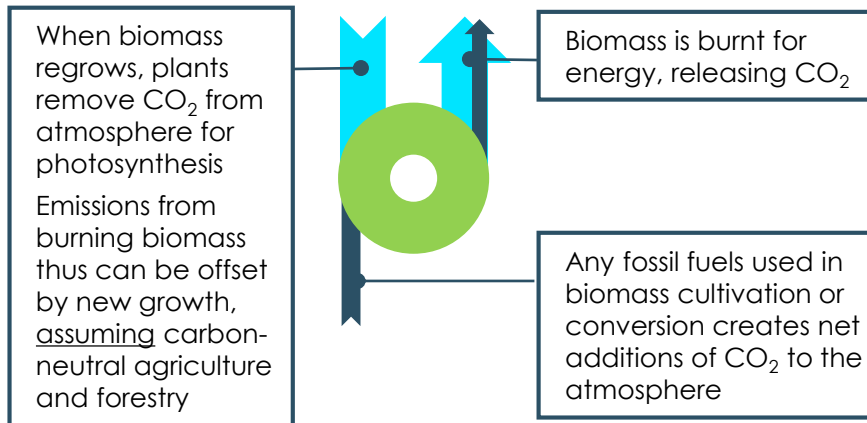
Fossil fuels with CCS

CCS removes most (but not all) CO₂ when burning fossil fuels



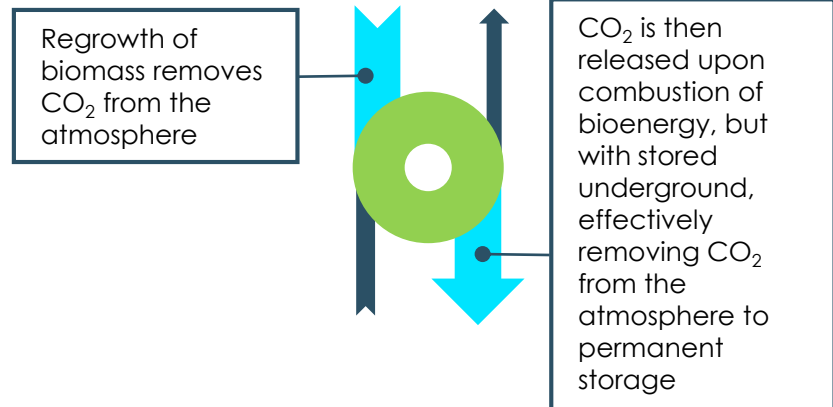
Bioenergy without CCS

Bioenergy can have zero emissions if growth is carbon-neutral





Bioenergy with CCS

CCS on bioenergy can create "negative" emissions



Source: Adapted from IEA (2016), Status of biomass with carbon capture and storage

Carbon capture affects the carbon budget in two ways

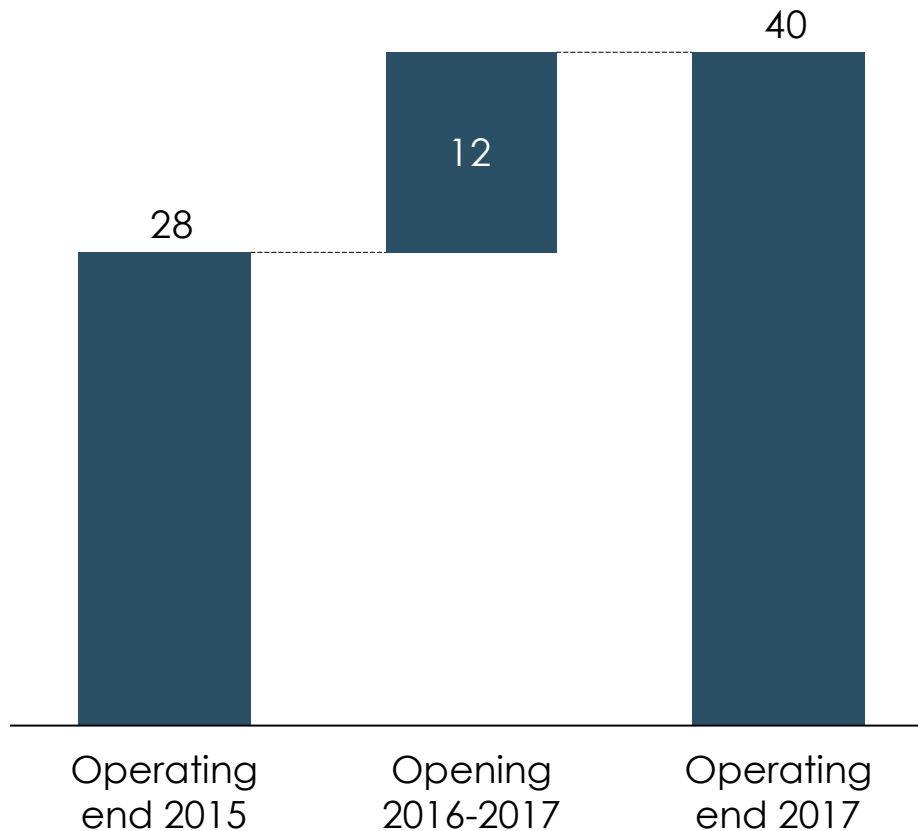
	Effect on carbon budget	Key potential applications
<div>Fossil fuels</div> 	<ul style="list-style-type: none">• Reduces the carbon intensity of coal and natural gas, making possible continued use with less claim on the carbon budget• “Frees up” carbon budget for other applications	<ul style="list-style-type: none">• Coal and natural gas fired power plant• Industrial applications, including steel, cement, refining, and other large point sources• Less applicable to oil use, which is concentrated in small point sources transport
<div>Bioenergy</div> 	<ul style="list-style-type: none">• Provides energy services (e.g., power) without net CO₂ emissions, thus freeing up carbon budget space• Additionally, can potentially move CO₂ from the atmosphere to permanent stores (“negative emissions”), offsetting some remaining CO₂ emissions from other sources• Extent of carbon budget gain depends critically on whether production of biofuels affects CO₂ levels, for example through land-use change	<ul style="list-style-type: none">• Potential uses in power plants and other large point sources, such as industry.• Largely speculative: one operational plant.

Source: Adapted from IEA (2016), Status of biomass with carbon capture and storage

Current CCS capacity is ~30 million tonnes CO₂ per year, far below the 7+ billion tonnes needed by 2040 in most scenarios

CCS capacity 2015 and projected to 2017

Million tonnes CO₂ per year



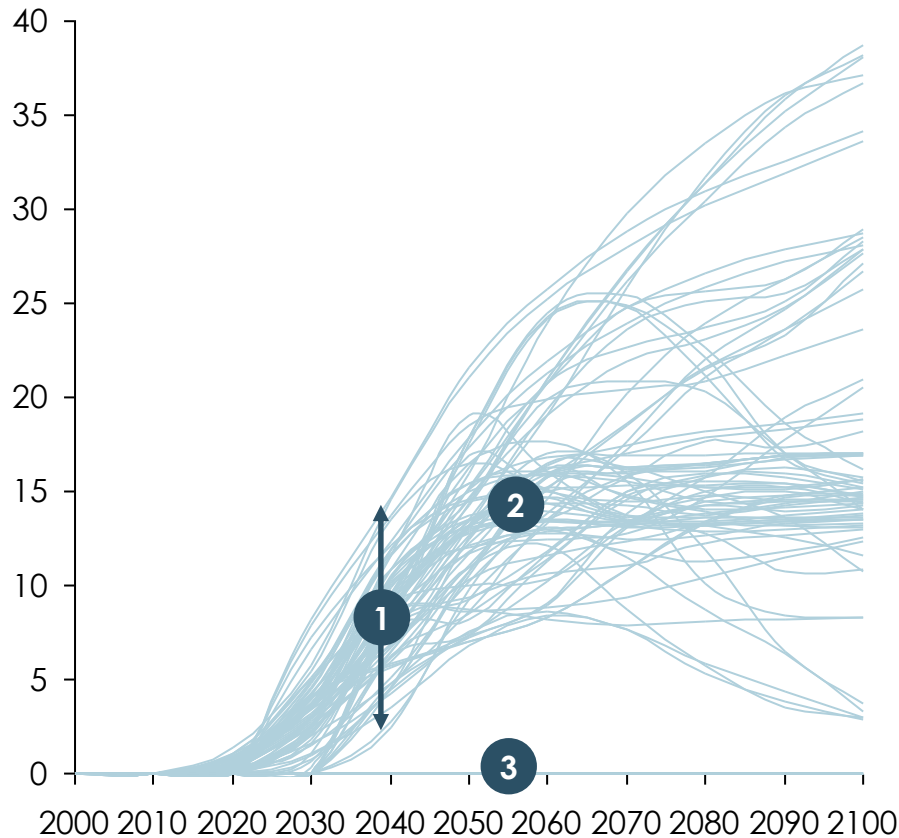
- Current operating and planned CCS capacity is 40 million tonnes CO₂ per year from 22 plants:
 - 15 plants with of 28 Mt CO₂/year capacity currently operating
 - 7 additional plants with 12 Mt CO₂/year capacity opening by 2018
- Another 11 plants with 15 Mt CO₂/year capacity are in advanced planning as of end of 2015
- Bioenergy with CCS currently have capacity of ~1 million tonnes CO₂ per year

Source: Copenhagen Economics analysis based on IEA (2013) – Technology Roadmap Carbon capture and storage; Global CCS Institute (2016) – Introduction to industrial carbon capture and storage; Global CCS Institute (2015), The global status of CCS 2015: Summary report; IEA (2016), Status of biomass with carbon capture and storage

CO₂ capture and sequestration (CCS) is a key factor already by 2040, with continued growth to balance the carbon budget

CO₂ capture through CCS/U in 2°C scenarios

Gt CO₂ per year



- Nearly all pathways rely on large volumes of CCS to meet 2°C objectives while also meeting energy needs
- CCS is favoured by many researchers because a) “negative emissions” help reduce the demands of a very stringent carbon budget, and b) models tend to favour solutions in the far future (whose costs are “discounted”)
- The volume of CCS therefore quickly becomes very large:
 - 1** In 2040, CCS volumes will already be large: only a few scenarios have CCS below 5 Gt per year, and the median is 8 Gt. Of this, some 3 Gt is on fossil fuels, and 5 Gt through BECCS
 - 2** CCS grows still larger thereafter. Scenarios cluster around 12-15 Gt CO₂, and very few scenarios foresee less than 10 Gt CO₂ per year. Although scenarios differ, most of this is for BECCS (see below)
 - 3** Only 7 out of 84 pathways meet energy and climate needs entirely without CCS

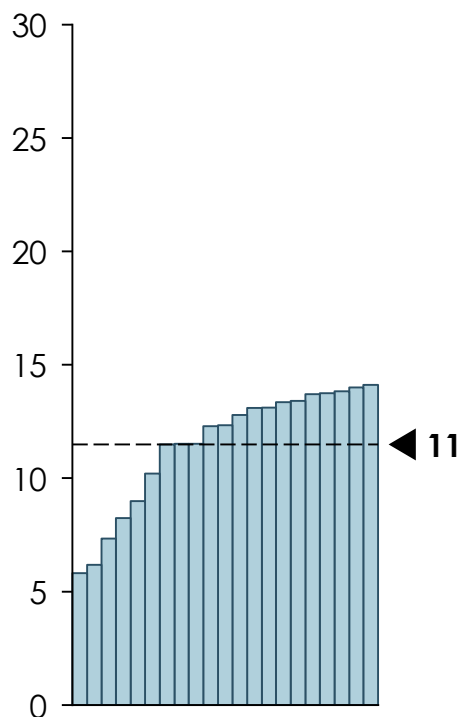
Notes: Total CO₂ captured per year through CCS in 84 AR5 scenarios.
Source: Copenhagen Economics analysis of data from AR5 database.

We define three scenarios for fossil fuel use based on the maximum level of CO₂ capture and sequestration used

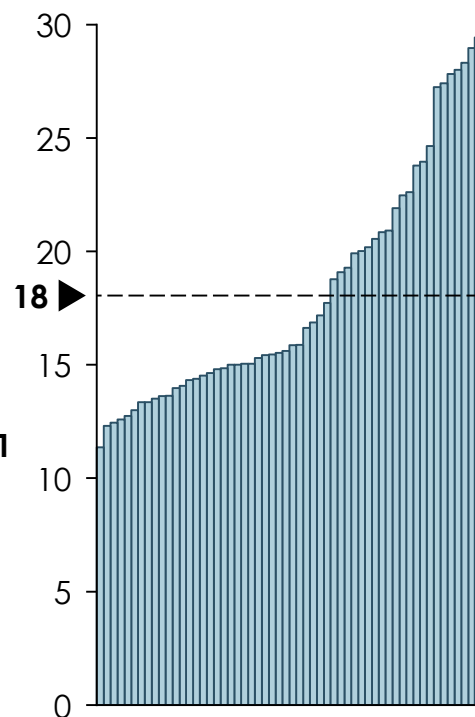
Average CO₂ capture from CCS on fossil fuels and bioenergy
2040-2100 in 2°C pathways

Gt CO₂ per year

Central CCS scenario



High CCS scenario



To derive scenarios, we split pathways into three groups depending on the maximum level of annual carbon capture:

- **No CCS:** no or marginal carbon capture at any point. Only seven pathways meet 2°C objectives without the use of CCS
- **Central CCS:** 28 scenarios where CCS never exceeds 15 Gt CO₂. Most see high CCS deployment, with an average across pathways of 11 Gt CO₂ per year, 2040-2100
- **High CCS:** 56 scenarios where CCS eventually reaches levels between 15-40 Gt CO₂ per year, with an average value of 18 Gt CO₂ per year, 2040-2100.

The future FF use trajectories are based on the central CCS scenarios.

Note: We restrict analyses to scenarios with no more than 40 Gt CO₂ per year in any year. 84 of 241 considered scenarios meet this criteria (cf. Appendix). Central scenario/High CCS consists of scenarios with no more than 15/40 Gt CO₂ captured through CCS in any given year

Source: Copenhagen Economics based on IPCC AR5 WG3 database of modelling results

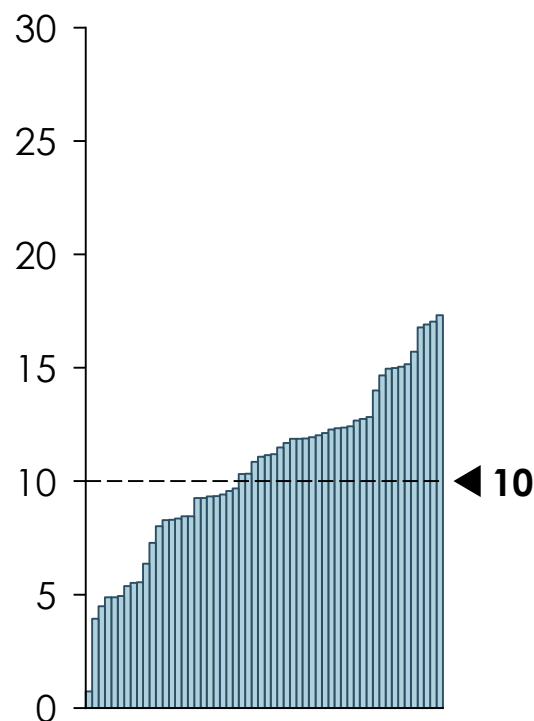
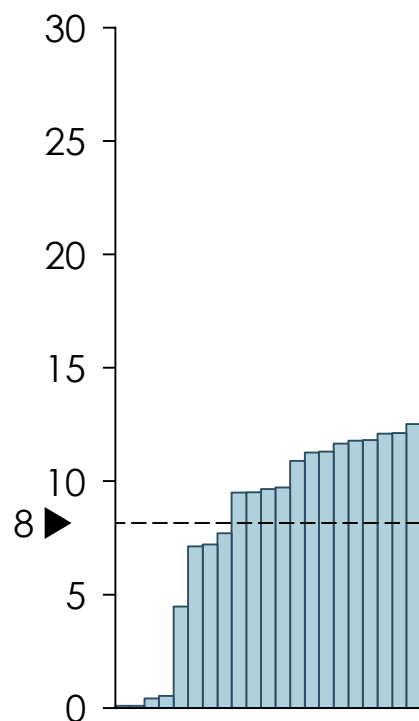
“Negative emissions” through bioenergy and CCS features in nearly all pathways, and is the main application of CCS

Average CO₂ capture from CCS on bioenergy
2040-2100 in 2°C pathways

Gt CO₂ per year

Central CCS scenario

High CCS scenario



- Nearly all 2°C scenarios rely very heavily on “negative emissions”: typically, the capture of CO₂ from combustion of biofuels
- In both the Central and the High CCS scenarios, the average level of CCS with bioenergy is 8-10 Gt CO₂ per year. For comparison, current global emissions from power production are around 12 Gt CO₂
- While the analyses typically assume a combination of bioenergy and carbon capture, negative emissions also could in principle be provided through a range of other means, so need not imply CCS only

Note: We restrict analyses to scenarios with no more than 40 Gt CO₂ per year in any year. 84 of 241 considered scenarios meet this criteria (cf. Appendix). Central scenario/High CCS consists of scenarios with no more than 15/40 Gt CO₂ captured through CCS in any given year

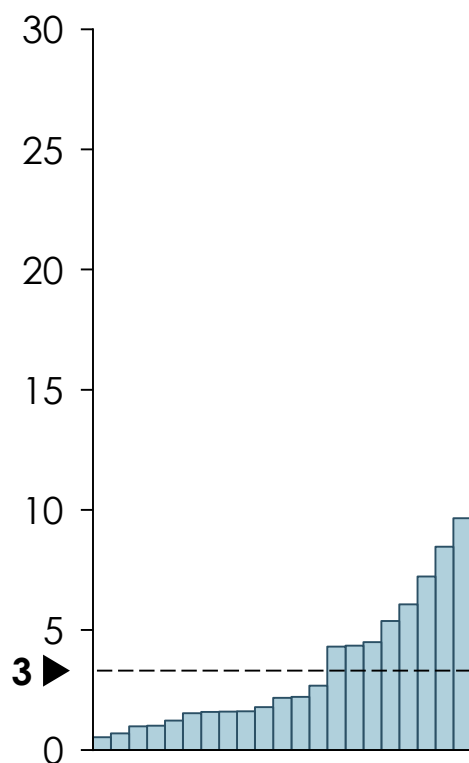
Source: Copenhagen Economics based on IPCC AR5 WG3 database of modelling results

Long-term CCS on fossil fuels is ~3 Gt CO₂ in the Central scenario, and ~7 Gt CO₂ in the High scenario

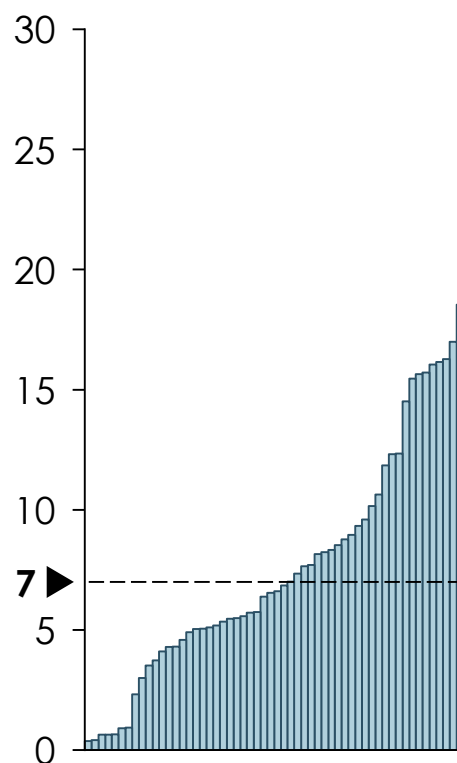
Average CO₂ capture from CCS on fossil fuels
2040-2100 in 2°C pathways

Gt CO₂ per year

Central



High CCS



- Central CCS: an average of 3 Gt CO₂ per year from fossil fuels in the 2040-2100 period. This corresponds to less than one-tenth of the current level of total fossil fuel use. Some pathways suggest much higher volumes (but less on bioenergy)
- High CCS: average CCS on fossil fuels is 7 Gt per year in the 2040-2100 period, corresponding to fossil fuel use at approx. one-fifth of current levels. However, around half of scenario suggest higher volumes

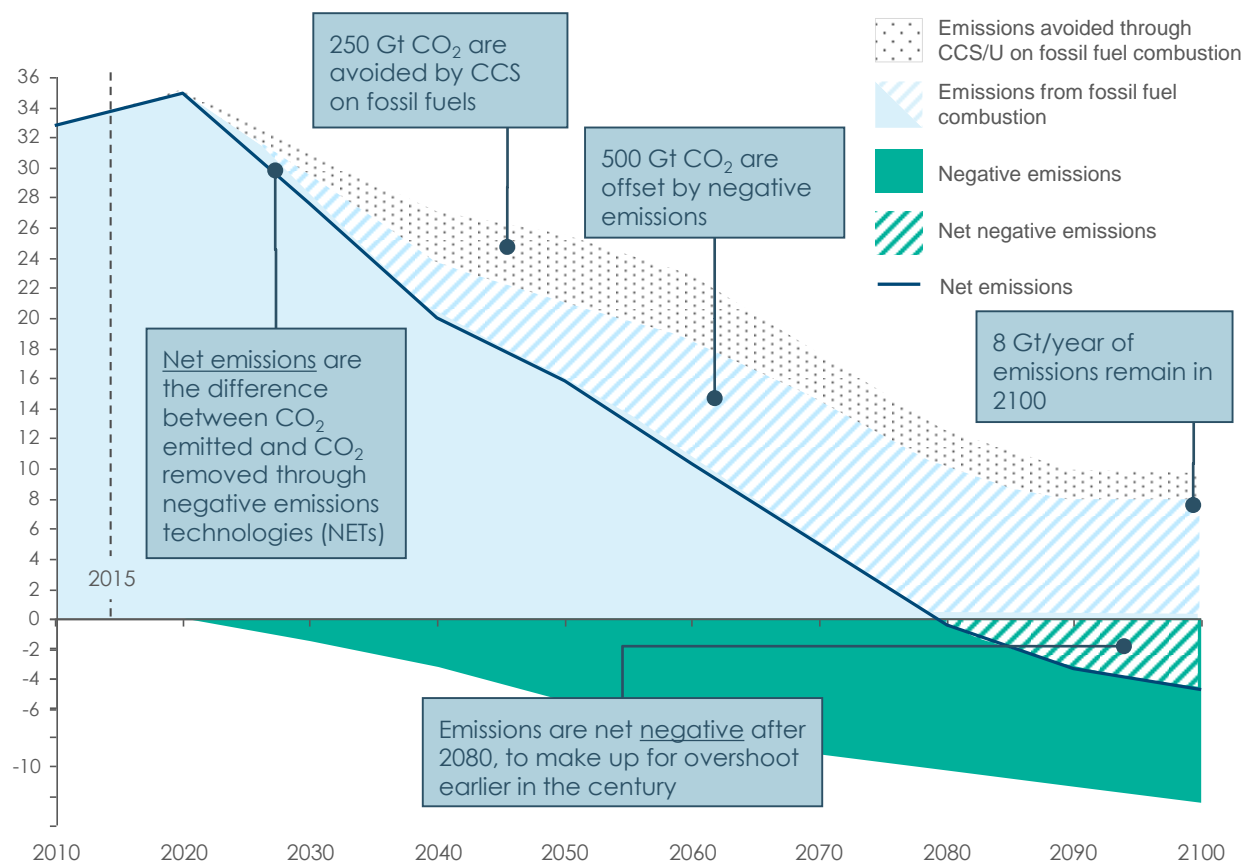
Note: We restrict analyses to scenarios with no more than 40 Gt CO₂ per year in any year. 84 of 241 considered scenarios meet this criteria (cf. Appendix). Central scenario/High CCS consists of scenarios with no more than 15/40 Gt CO₂ captured through CCS in any given year

Source: Copenhagen Economics based on IPCC AR5 WG3 database of modelling results

In most pathways, “net zero” emissions result from low remaining CO₂ release combined with “negative emissions”

Balance of emissions in Central CCS scenario* 2010-2100

Gt CO₂ per year



- “Negative emissions” through CO₂ capture and sequestration on bioenergy (BECCS) and other negative emission technologies (NETs) remove ~3 Gt CO₂ in 2040, and 12 Gt CO₂/year in 2100
- By 2080, emissions are net negative, i.e. more emissions are removed from the atmosphere through NETs, than are emitted each year
- In 2100, CO₂ emissions from fossil fuel combustion are ~8 Gt/year. Negative emissions are ~12 Gt/year, resulting in net negative emissions of 4 Gt/year.
- Cumulatively, NETs remove ~500 Gt CO₂ by 2100, corresponding to 55% of the total carbon budget.
- ~250 Gt of CO₂ emissions are avoided through CCS/U on fossil fuel combustion. CCS/U on fossil fuels peak in the 2050s, although some pathways foresee continued higher levels

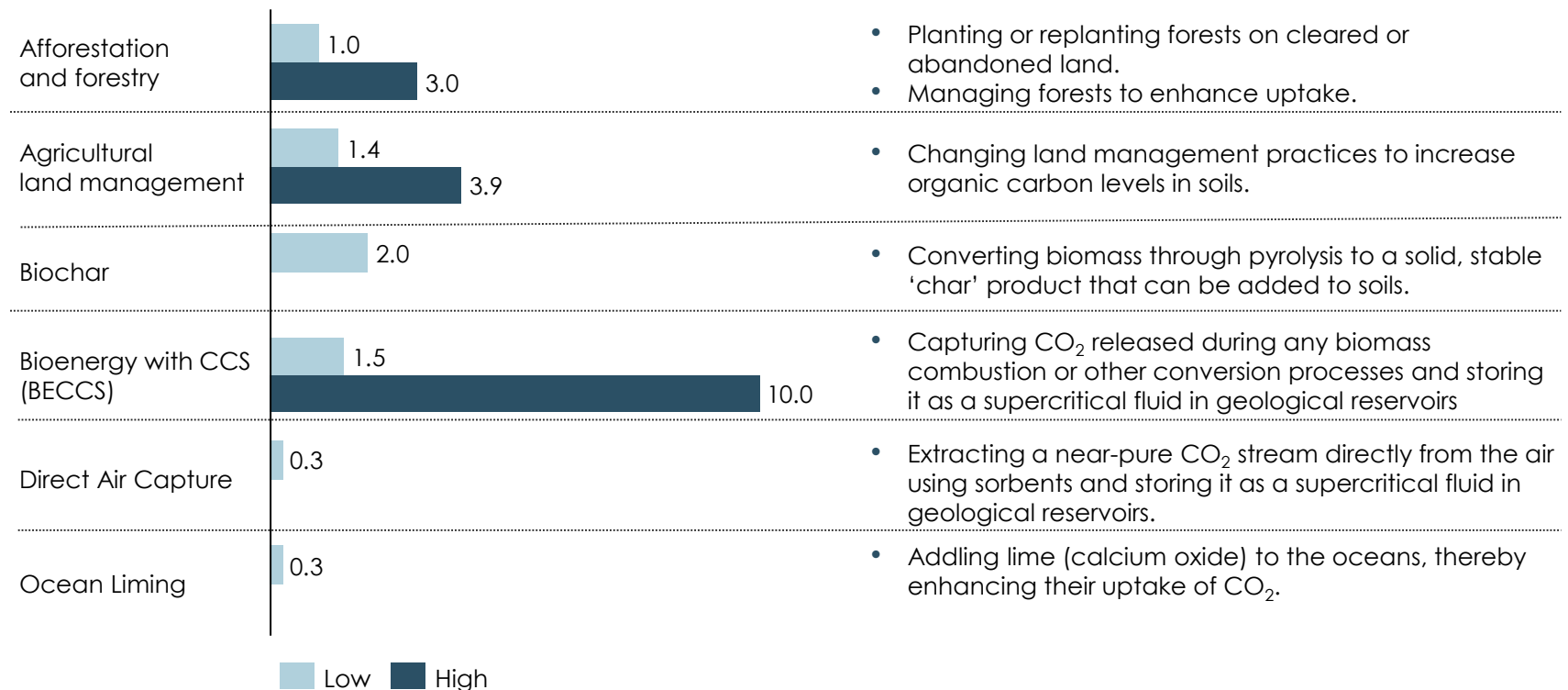
Notes: * The Central CCS scenario is the median of 28 scenarios which do not see CCS exceed 15 Gt CO₂ per year in any year up to 2100.

Source: Copenhagen Economics analysis of data from AR5 database.

Carbon capture of bioenergy is one of several potential future “negative emissions” technologies

Estimated potential to sequester CO₂ in 2050

CO₂ per year



Description

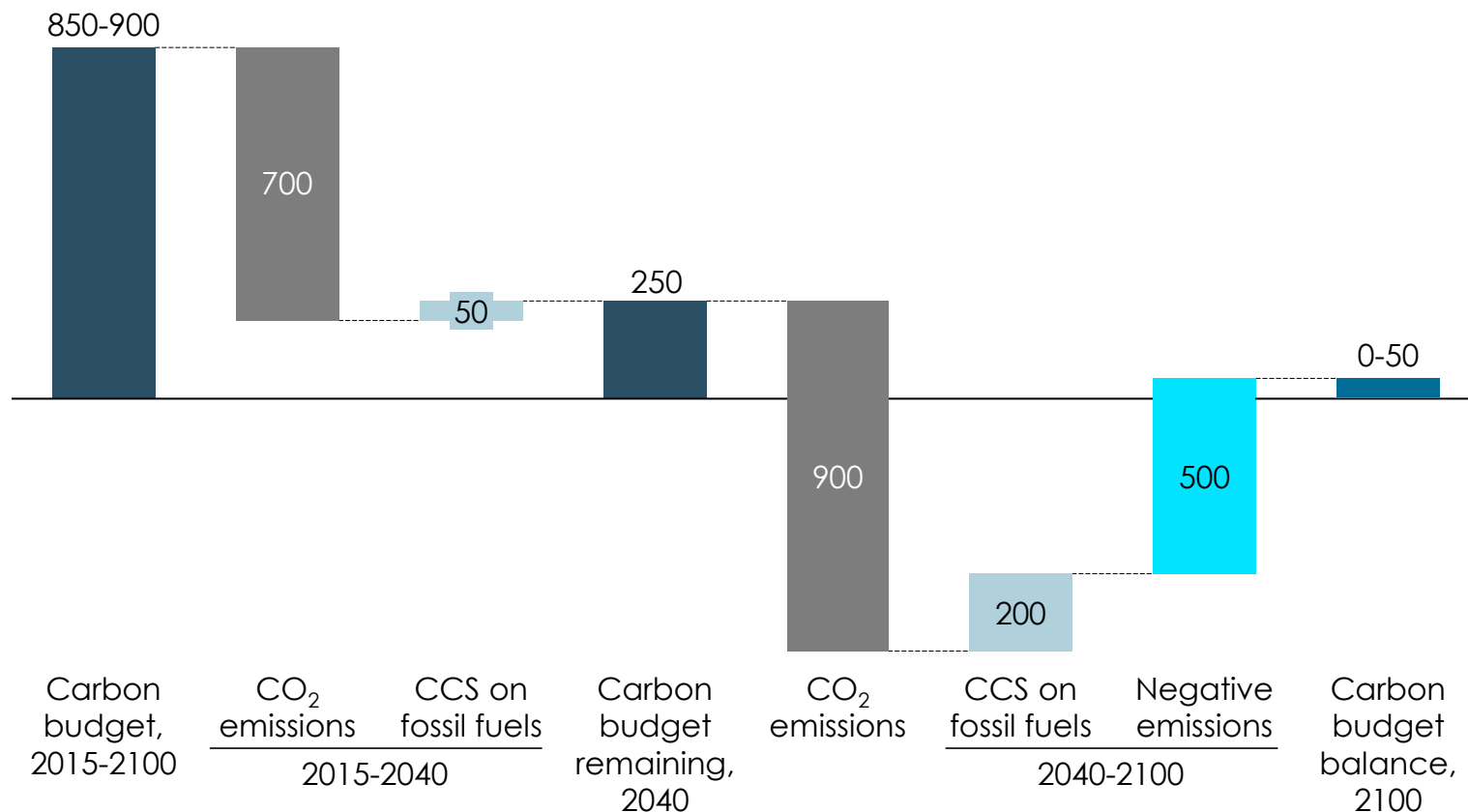
- Planting or replanting forests on cleared or abandoned land.
- Managing forests to enhance uptake.
- Changing land management practices to increase organic carbon levels in soils.
- Converting biomass through pyrolysis to a solid, stable 'char' product that can be added to soils.
- Capturing CO₂ released during any biomass combustion or other conversion processes and storing it as a supercritical fluid in geological reservoirs
- Extracting a near-pure CO₂ stream directly from the air using sorbents and storing it as a supercritical fluid in geological reservoirs.
- Adding lime (calcium oxide) to the oceans, thereby enhancing their uptake of CO₂.

Source: Data from Caldecott et al. (2015) – Stranded carbon assets and negative emissions technologies. High value for BECCS is median 2040 value in CCS High scenario based on AR5 database.

Cumulatively, CCS and negative emissions technologies offset ~750 Gt CO₂ emissions to 2100, or ~85% of the CO₂ budget to 2100

Cumulative emitted and captured CO₂, 2015-2040 and 2040-2100, in Central CCS scenario

Gt CO₂



Notes: Excluding land-use change.

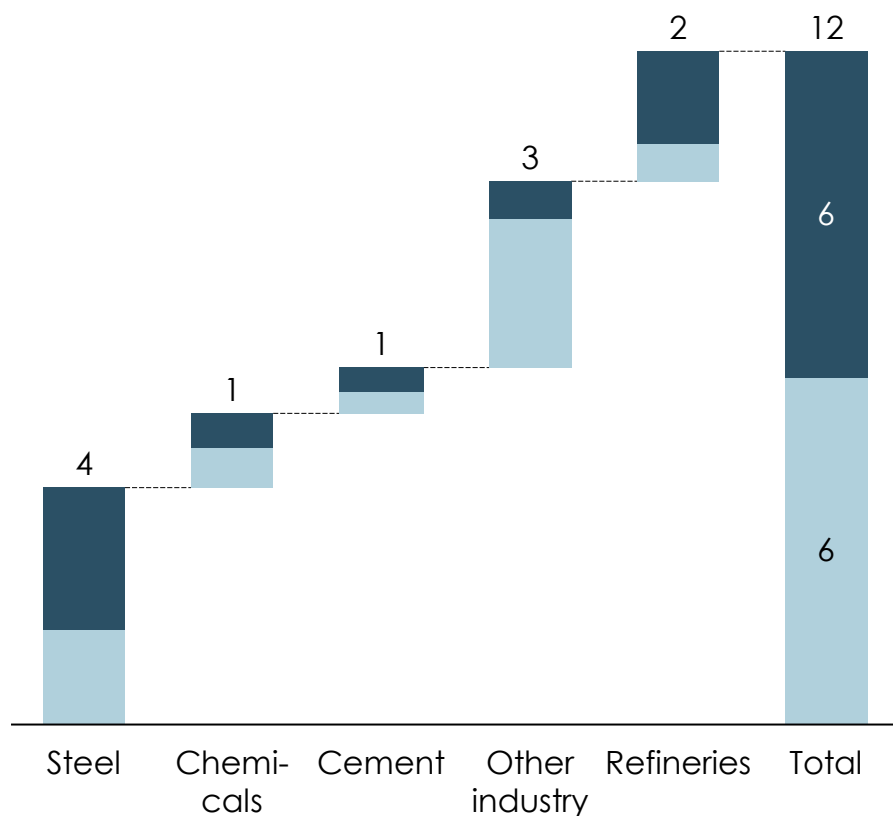
Source: Copenhagen Economics analysis based on AR5 database

CCS is particularly important for industry: 12 Gt CO₂ of emissions may remain in 2040, with CCS technically possible for around 6 Gt CO₂

CO₂ emissions in 2040

GtCO₂

- Emissions potentially amenable to capture
- Emissions not amenable to capture



- A 2 °C scenario requires sharp reductions in emissions across power, buildings, and transport through zero-carbon power, electrification, energy efficiency, bioenergy, and substitutions.
- By contrast, deep emissions reductions in industry are harder. While industry and refining accounts for 28% of emissions today, they could account for as much as 60% of remaining emissions in 2040 in a 2 °C scenario (12 Gt CO₂ out of 20 Gt CO₂).
- CCS is one potential solution. The figure shows a stretch scenario for CCS in industry, but costs may increase rapidly if many small installations need to use carbon capture.
- Bioenergy, process changes, and hydrogen may offer alternative long-term options to reduce these emissions.

Note: Estimated potential share of CO₂ captured with industrial CCS technology varies between sources. Typical ranges for plants are: steel 40-80%; chemicals 50-95%; cement 60-90%; refineries ~80%; other 30-100%. Oil & Gas includes gas processing plants and refineries. These potentials are best seen as "technical potentials", not assessments of what is economically feasible.

Source: Copenhagen Economics analysis based on IEA (2013) – Technology Roadmap Carbon capture and storage; Global CCS Institute (2016) – Introduction to industrial carbon capture and storage; Global Calculator

The central scenario is technically feasible, but face challenges of scale, infrastructure, and financing so it is a stretch

Scale

- Existing analyses suggest 2°C targets require CCS to reach 7-8 Gt CO₂ per year by 2040
- Scaling up CCS to these levels would require ~2,300 installations, or 2.2 plants per week in the period 2020-2040

Infrastructure

- 7-8 Gt CCS requires the transport of a volume of material similar to current oil (4.2 Gt) and natural gas (3.1 Gt) combined

Cost

- The cost of CCS is estimated at 50-100 USD/t CO₂ depending on application
- However, even high-cost CCS may be required to decarbonise selected industrial production, such as steel and cement

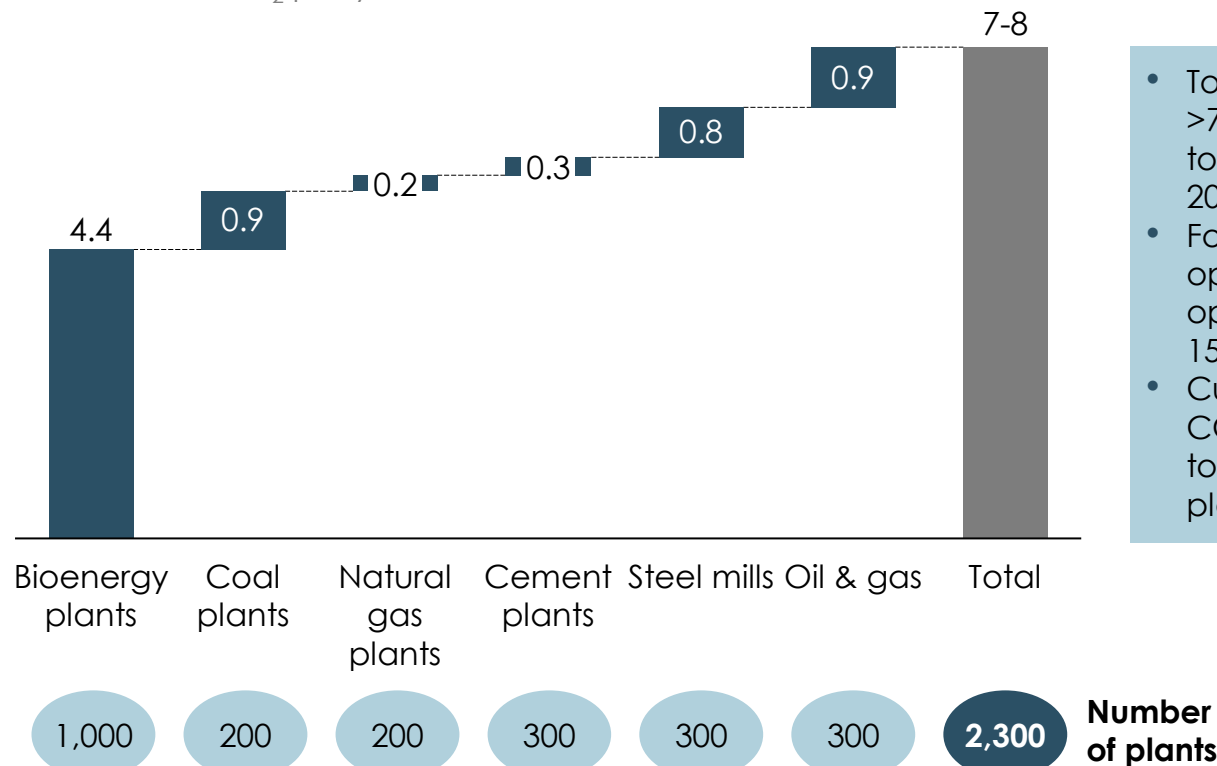
- The “Central CCS” 7-8 Gt CO₂ by 2040 is a stretch scenario, requiring a step change from current trends
- There may be other solutions: bioenergy, process change, and hydrogen in industry; renewable energy in power; and different forms of “negative emissions” technologies.

Scaling up CCS/U to reach 7-8 Gt by 2040 would require ~2,300 CCS/U installations, 2.2 plants per week 2020-40

Illustrative example:

What mix of CCS installations could capture 7-8 Gt CO₂ per year?

Billion tonnes CO₂ per year



- To reach 2,300 plants capturing >7 Gt per year, 115 plants need to be constructed per year, 2020-2040
- For comparison, one large-scale operation entered into operation every two years 2000-15
- Current operating and planned CCS capacity is 0.04 billion tonnes CO₂ per year from 22 plants

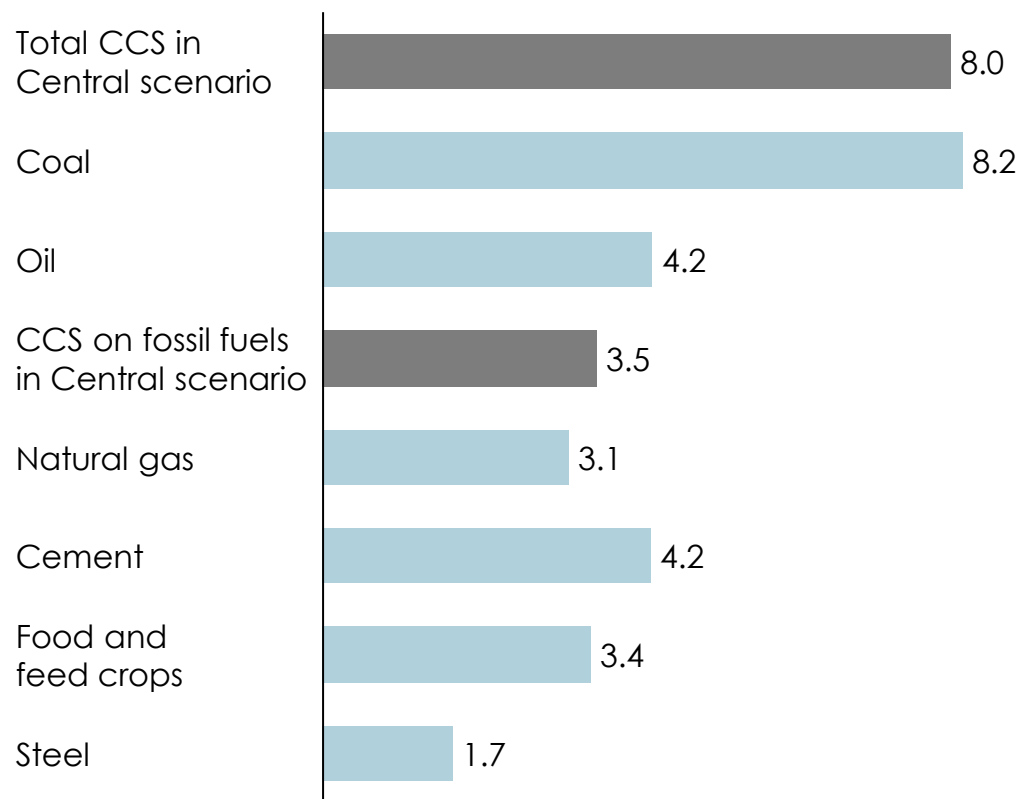
Note: Estimated potential share of CO₂ captured with industrial CCS technology varies between sources. Typical ranges for plants are: steel 40-80%; chemicals 50-95%; cement 60-90%; refineries ~80%; other 30-100%. Conservative point estimates have been chosen where available. CCS projects under advanced planning stage consist of 11 projects expected to take final investment decisions by mid-2016.

Source: Copenhagen Economics analysis based on IEA (2013) – Technology Roadmap Carbon capture and storage; Global CCS Institute (2016) – Introduction to industrial carbon capture and storage; Global CCS Institute (2015), The global status of CCS 2015

Infrastructure: 8 Gt CCS requires the transport of a volume larger than current volumes of oil and natural gas

Mass of selected materials flows

Billion tonnes per year

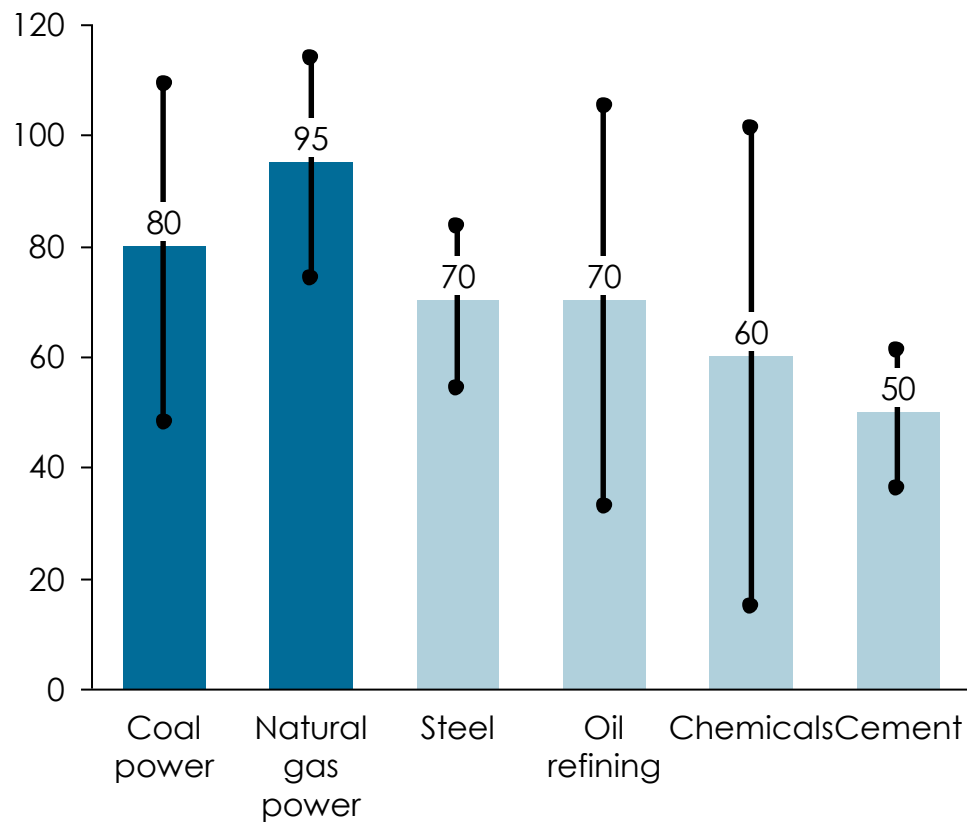


- The figure shows the annual flow of different materials, compared to the mass of CCS volumes proposed in pathways underlying the Central CCS scenario
- As this shows, the amount of CO₂ is very large, exceeding the current mass of all oil and natural gas production
- In addition to capturing facilities, infrastructure requirements include compressors, pipeline networks and temporary storage facilities that cumulatively need to be able to process a mass of CO₂ close to twice current oil production
- CCS requirements could be reduced if a combination of zero-carbon energy and other “negative emissions” technologies could replace some of the CCS on bioenergy

Costs: The cost of avoiding CO₂ emissions with CCS is 50-100 USD/tonne depending on application

Cost of CCS per tonne of avoided CO₂ emissions

2015 USD



- There are large uncertainties in the cost of CCS, and ranges of possible costs have widened rather than narrowed over time
- Cost estimates have increased over time. For example, estimates 10 years ago cited lower ranges of 35-75 USD/t CO₂ for natural gas plants and 30-50 USD/t CO₂ coal plants
- Costs could differ even for similar technology, including with:
 - Scale: CCS is capital intensive with significant returns to scale. Capturing CO₂ from small point sources is therefore costly.
 - Infrastructure: proximity to suitable storage can vary significantly, making infrastructure costs highly variable
- Overall, there may therefore be a relatively steep supply curve for reaching the large volumes envisaged in existing pathways

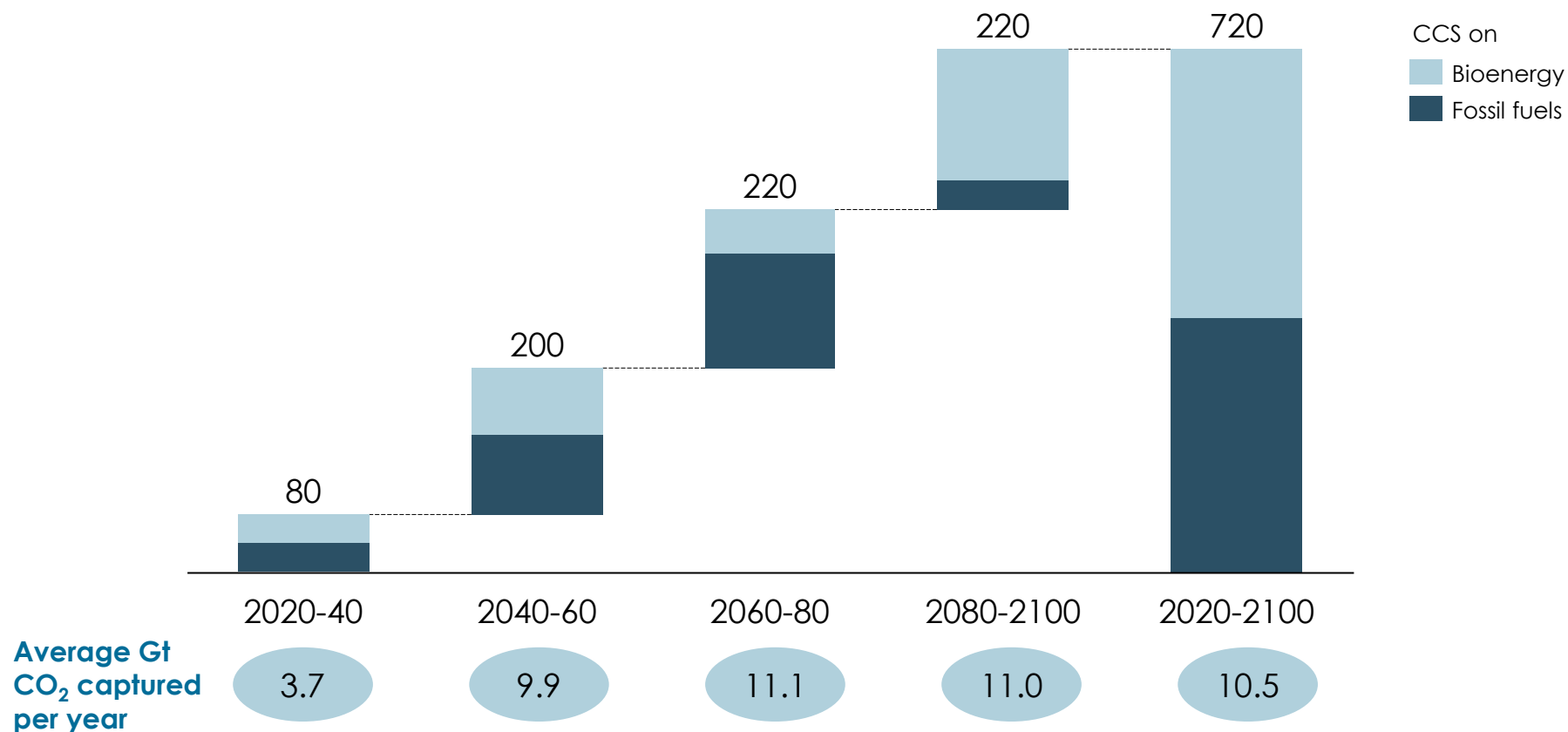
Note: Figures show avoided cost of emissions. The central values show average value of ranges given in sources below. The error bars show full range of estimates.

Sources: IEA (2013), Carbon capture and storage Technology Roadmap; Element Energy (2010), Potential for the application of CCS to UK industry and natural gas power generation. Report for Committee on Climate Change; Global CCS Institute (2015), The costs of CCS and other low-carbon technologies in the United States – 2015 update.

An average of ~4 billion tonnes of CO₂ may need to be captured per year by 2040; ~3 times more per year after 2040

CO₂ captured and stored or utilised using CCS/CCU technologies, 2020-2100, central scenario

Gt CO₂

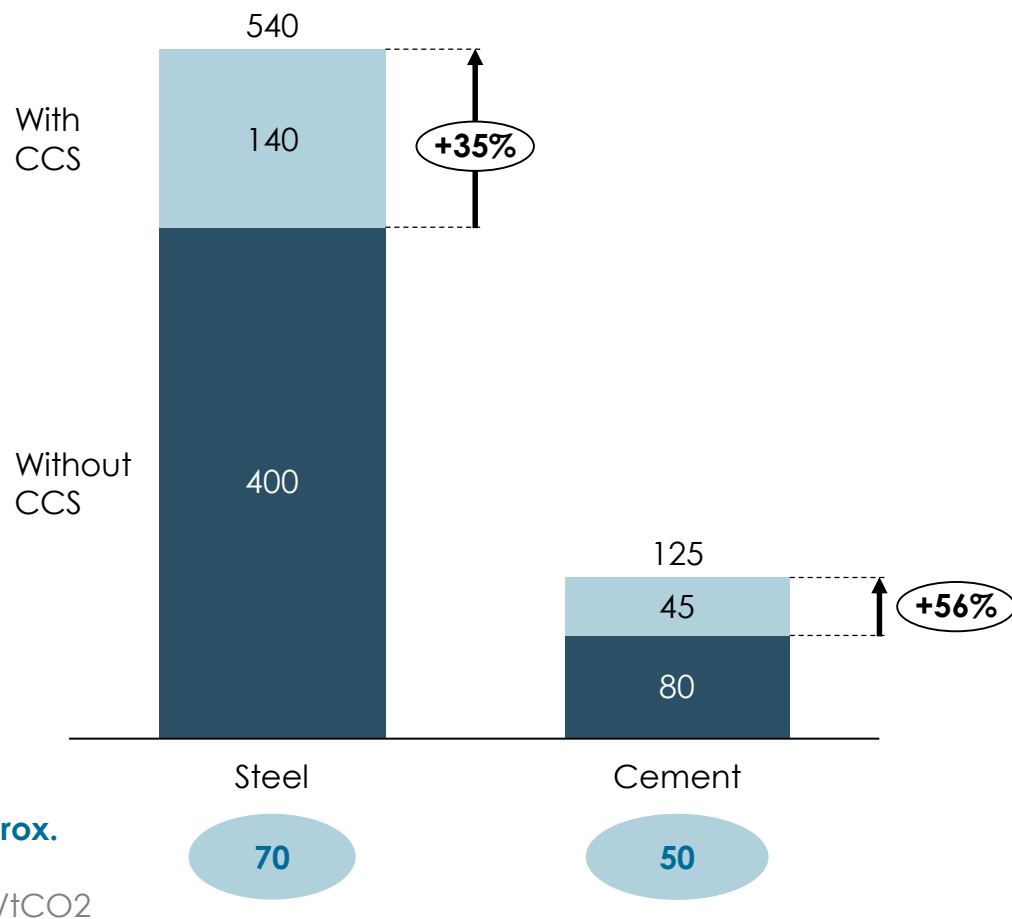


Note: Central scenario limits CO₂ captured through CCS to 15 Gt in any given year
Source: Copenhagen Economics based on IPCC AR5 WG3 database of modelling results

CCS costs for steel and cement may correspond to 35-55% of the cost of finished product

Cost per tonne of finished product with and without CCS

2015 USD per tonne product



- While costs are uncertain, available estimates suggest the cost of CCS on cement and steel would raise production costs substantially
- For steel, CCS could add a cost of around one-third of the underlying cost of steel production.
- For cement, CCS could add a cost of 50+% of the underlying cost.

Source: IEA (2013), Carbon capture and storage Technology Roadmap; Element Energy (2010), Potential for the application of CCS to UK industry and natural gas power generation. Report for Committee on Climate Change; Global CCS Institute (2015), The costs of CCS and other low-carbon technologies in the United States – 2015 update.

Summary Findings

1. Rapidly growing energy needs set the scene for an energy transition
2. A 2°C objective implies a strict carbon budget
3. Fossil fuel use would fall by one-third by 2040 to meet 2°C objectives
4. The role of fossil fuels changes by 2040 in a 2°C energy system
5. A 2°C energy transition has profound impacts on fossil fuel markets
6. Carbon capture is a key factor in a 2°C energy transition

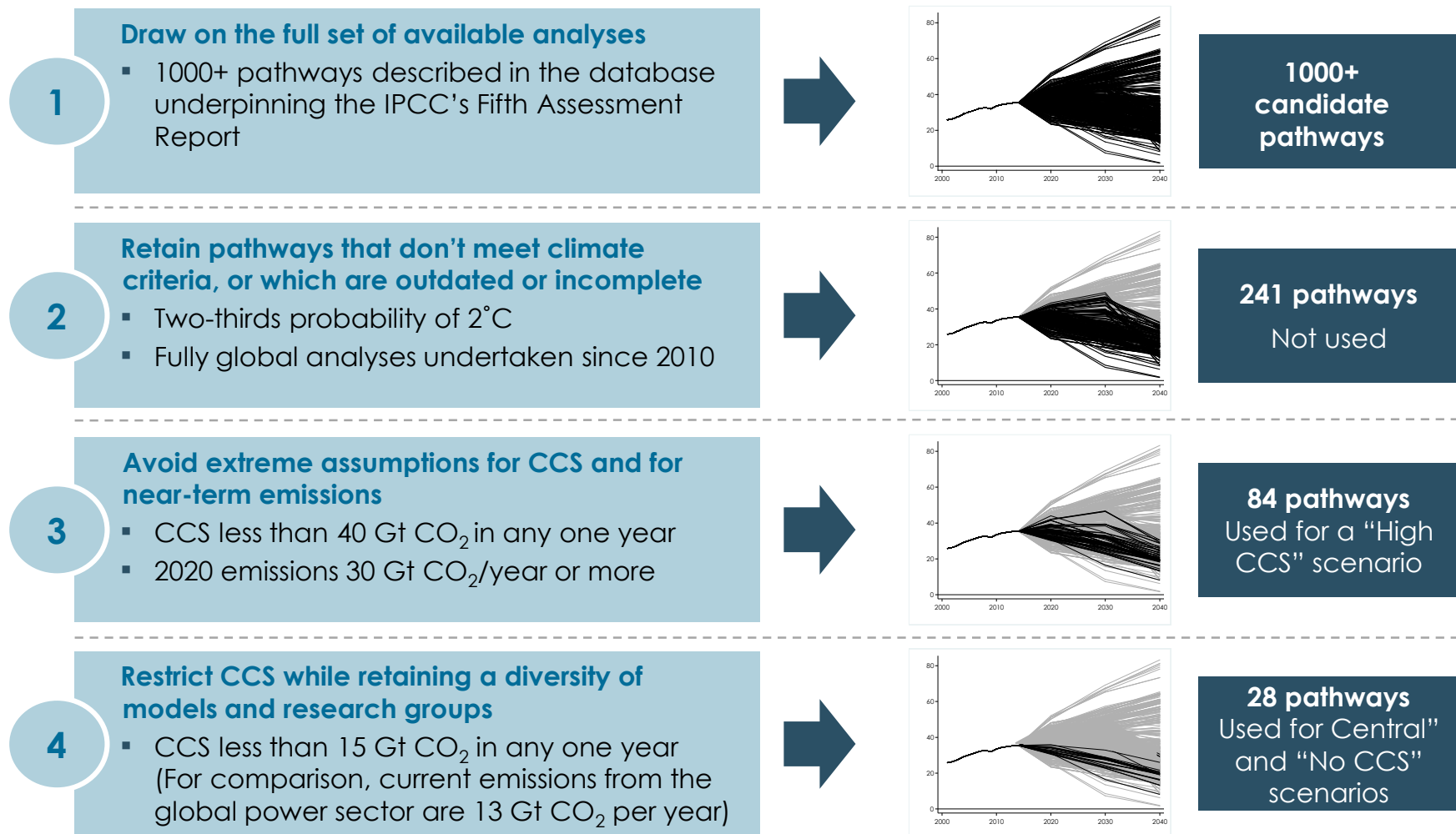
7. Appendix: scenario methodology

Scenario selection and insights – summary

We use a top-down methodology to draw on practically all available (1000+) analyses of emissions pathways. 241 mitigation pathways span the key drivers (economic and demographic baseline, technology, policy) of fossil fuel demand within a 2°C constraint. The results confirm the need to avoid reliance on single scenarios or reference points. There is large uncertainty on underlying drivers as well as specific outcomes.

- We draw on all available (1000+) pathways. Sources include the IPCC database, IEA analyses, additional baseline scenarios (IEA, EIA, WEC, Exxon, Shell, BP) and more detailed regional analyses. These collectively span nearly all analyses available.
- Of the 241 WB2D pathways, we select 84 that meet a set of criteria. Pathways are filtered for climate ambition (2°C or less with >2/3 certainty), quality (peer review, post-2010 analysis), and availability (detailed, global data).
- Scenarios have five key sources of variation:
 - Methodology: Models and projections vary (drastically) in their assumptions
 - Baseline: differences in population, GDP, energy intensity, etc.
 - Climate ambition: we only select mitigation scenarios meeting 2°C or less with >2/3 probability
 - Technology availability: CCS, nuclear, energy efficiency bio-energy, solar and wind.
 - Policy developments: delay in mitigation, fragmented vs. global effort
- Results vary enormously. Even within 2°C scenarios, key quantities including energy use or CO₂ emissions can vary by a factor 3 or more even by mid-century.
- Analyses built on single scenarios or reference points are risky. Analyses that build on a single scenario risk adopting single, particular views on key underlying drivers. Conclusions therefore also risk a lack robustness.
- There is a need to explore underlying assumptions. Outliers result from particular assumptions – the ETC need to explore these to form a range of views on possible future outcomes.

We limit our analysis to scenarios that meet climate objectives and avoid aggressive levels of carbon capture



Source: Copenhagen Economics analysis of data from AR5 database.

Our approach: we use existing analyses to characterise the level of feasible fossil fuel consumption in a 2°C scenario

Represent joint development and climate objectives

Use analyses that explicitly account both for the need to meet future energy needs for development, and model the ability to service these needs while reducing emissions.

Capture the full set of analyses

Avoid reliance on single scenarios or models by analysing the implications of the full set of 1000+ pre-existing pathways scenarios

Use a small set of objective criteria

We limit the analysis to scenarios that a) meet ambitious climate ambition targets, b) are not outdated, and c) are fully global but otherwise avoid restricting the set of pathways used.

Limit the extent of carbon capture

We additionally limit the extent of carbon capture, using cut-off thresholds of 40 Gt CO₂ (similar to current total global CO₂ emissions) and 15 Gt CO₂ (larger than current emissions from the global power sector).

Accept uncertainty and ensure variation

We ensure that the resulting selection of pathways reflects a range of model representations, research teams, scenario assumptions, policy parameters, etc.

Summarise results through central values

Where we show single values, we use the median value as a reasonable summary of the underlying variation

1000+ pathways

~100 baselines
~300 $<2^{\circ}\text{C}$
pathways

- 10 models
- 6 research projects
- 5-7 technology variants
- 3-4 policy variants

Scenario analysis

The scenarios span from a wide variety of potential pathways to meeting climate objectives

Global CO₂ emissions from energy use in 400pp scenarios, Gt CO₂ per year

We condense and compare scenarios by focussing on median and quartile values

- 1) Define the "corners" spanning all values in the given year, across all scenarios. This step is bounded by the minimum and maximum values in each year.
- 2) Identify the median, first and third quartile values in each year.
- 3) Compare individual scenarios or groups of scenarios against these maximum and median benchmarks.

We draw on analyses from three main sources

IPCC AR5 database

Database of long-term scenarios reviewed in the Fifth Assessment Report (AR5) of Working Group III of the Intergovernmental Panel on Climate Change (IPCC). This includes 56 models and 274 scenarios, spanning baseline developments as well as “mitigation” (climate) scenarios

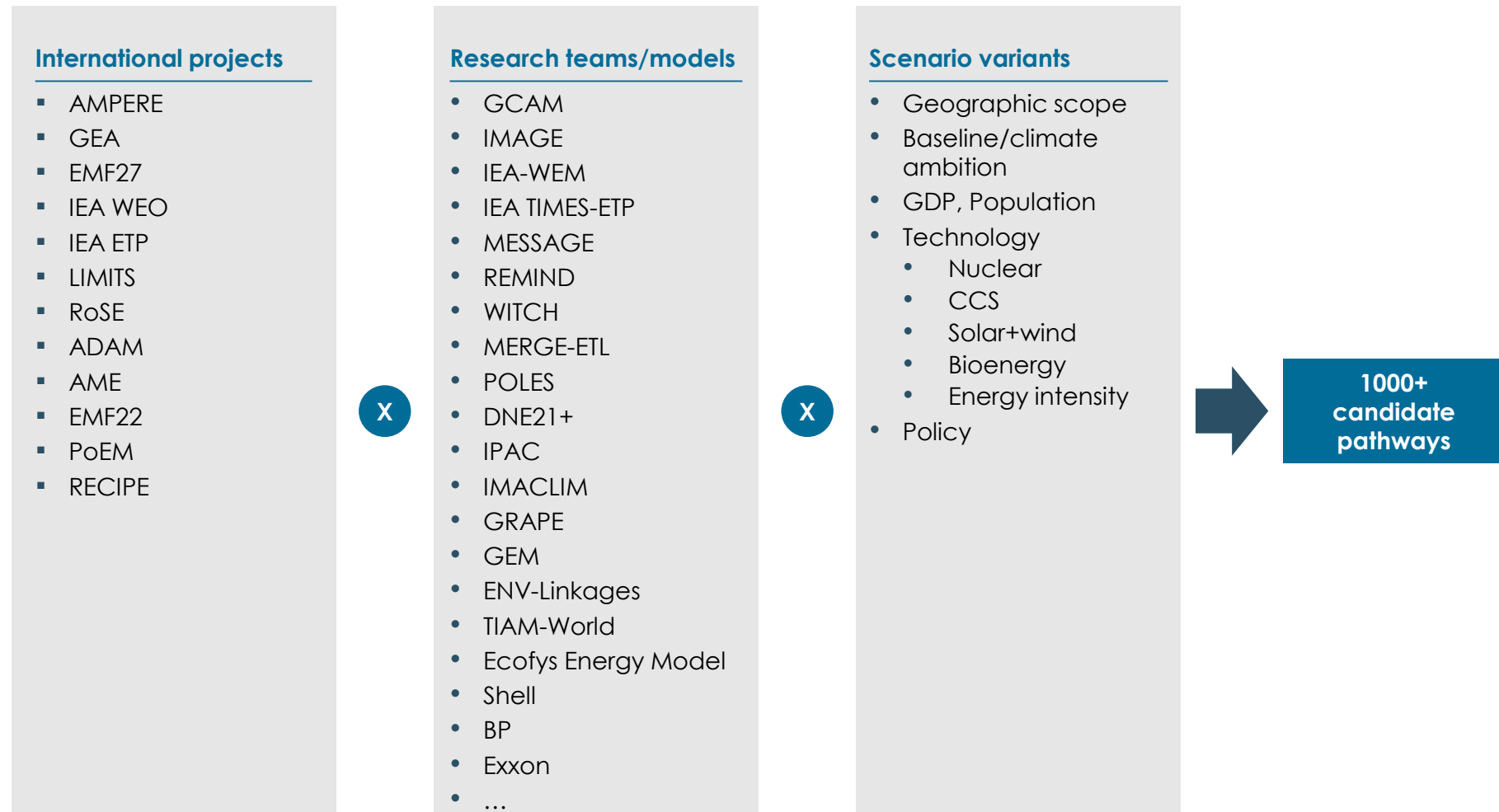
International Energy Agency

Data from scenarios in the IEA World Energy Outlook (WEO) 2015 and Energy Technology Perspectives (ETP) 2016 – six scenarios in total

Additional baseline scenarios

Baseline scenarios for the global energy sector from the International Energy Agency, US Energy Information Administration, World Energy Council, BP, Exxon, and Shell (10 scenarios in total)

The data contain more than 1000 pathways, spanning a range of international projects, modelling efforts, and scenario variants



Source: Copenhagen Economics analysis of data from AR5 database.

The majority of scenarios were produced from six major recent international modelling exercises

Modelling exercise	Description
AMPERE (multi-model study)	<ul style="list-style-type: none"> 22 participating research institutions. Delayed mitigation scenarios with the world following moderate mitigation until 2030, and adopting long-term concentration goals thereafter.
LIMITS (multi-model study)	<ul style="list-style-type: none"> Delayed mitigation scenarios with the world following two levels of moderate fragmented action through 2020 or 2030, and adopting two long-term concentration goals thereafter. Three different effort-sharing schemes are considered.
EMF27 (multi-model study)	<ul style="list-style-type: none"> Delayed and limited participation scenarios with developed (Annex I) countries adopting 80% emissions reductions until 2050 and developing (non-Annex I) countries adopting a global 50% emissions reduction by 2050 after 2020, and resource exporting countries not undertaking emissions reductions.
Global Energy Assessment (GEA)	<ul style="list-style-type: none"> Three pathway groups of 42 pathways in total that vary in their level of energy demand, used for the modelling of specific supply-side pathways. "Efficiency" emphasises demand-side and efficiency improvement, "Supply" emphasises supply-side transformation with high energy demand, "Mix" emphasises regional diversity at intermediate level of demand.
ROSE (multi-model study)	<ul style="list-style-type: none"> Multi-model ensemble experiment involving four global integrated assessment models and one regional energy system model covering China. The specification of scenarios is based on (1) underlying assumptions on future socio-economic development determined by population and economic growth; (2) reference assumptions on long-term fossil fuel availability, with a focus on variations of coal, oil, and gas; and (3) stringency and timing of climate protection targets and framework of international climate policy.
IEA World Energy Outlook, IEA Energy Technology Perspectives	<ul style="list-style-type: none"> In WEO, three scenarios that assume current policies (CPS) as of year of publication continue indefinitely, new policies (NPS) are introduced to support the achievement of current policy commitments, or an energy pathway consistent with the goal of limiting global increase in temperature to 2°C (450 Scenario) by limiting concentration atmospheric CO₂ to 450 ppm. In ETP, three scenarios that study pathways consistent with long-term temperature increase of 2, 4 and 6° C (2DS, 4DS, 6DS).

Note: AMPERE Work Package 2 used for this study.

Source: IPCC (2013), ch. 6; Global Energy Assessment (2012), ch. 17., Web sites of modelling exercises.

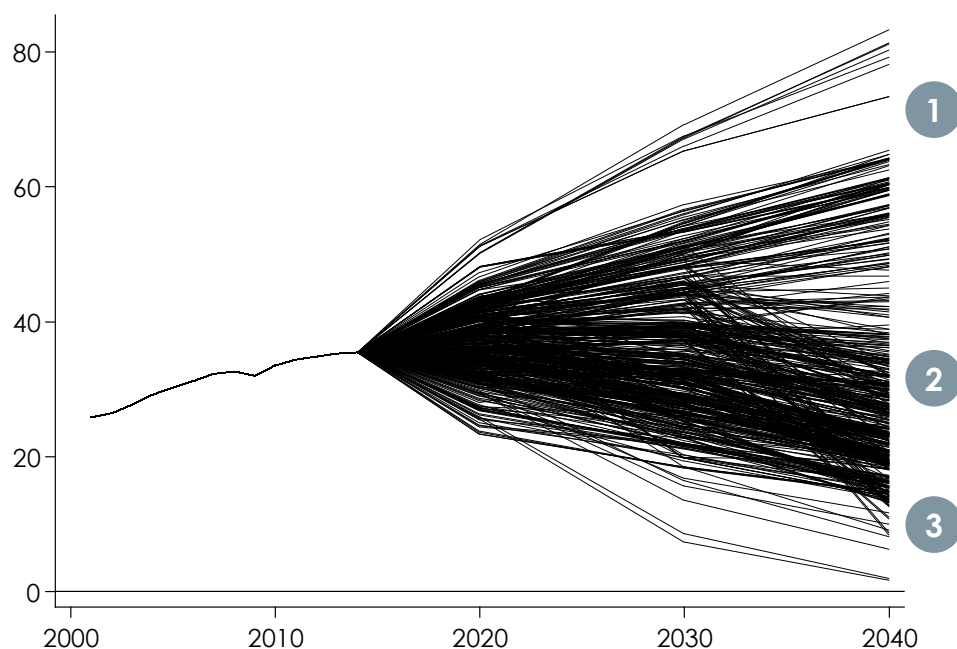
We include scenarios modelled in 10 models with a range of methodologies – and therefore differing results

	Description
BET	<ul style="list-style-type: none"> Integrated assessment model developed by Central Research Institute of Electric Power Industry, Japan.
IMACLIM	<ul style="list-style-type: none"> Recursive dynamic computable general equilibrium model, developed by SMASH-CIRED.
IMAGE	<ul style="list-style-type: none"> “Integrated Model to Assess the Global Environment”, an energy system partial equilibrium model developed by PBL Netherlands Environmental Assessment Agency and used by the Dutch Government, European Commission, UNEP and OECD.
MERGE	<ul style="list-style-type: none"> A “Model for Evaluating the Regional and Global Effects of GHG Reduction Policies”, an integrated assessment model developed at Stanford University.
MESSAGE	<ul style="list-style-type: none"> “Model for Energy Supply Strategy Alternatives and their General Environmental Impact”, a systems engineering optimisation model developed by IIASA
POLES	<ul style="list-style-type: none"> Energy system partial equilibrium model developed by CNRS-LEPII, Enerdata, EU-JRC-IPTCS
REMIND	<ul style="list-style-type: none"> “Regional Model of Investments and Development”, an energy-economy climate model developed by the Potsdam Institute for Climate Impact Research (PIK),
TIAM	<ul style="list-style-type: none"> TIMES Integrated assessment model, versions of which have been developed by e.g. the US-EIA and IEA (for use in the ETP).
WITCH	<ul style="list-style-type: none"> Integrated assessment model developed by FEEM
IEA WEM	<ul style="list-style-type: none"> Large-scale simulation model designed to replicate how energy markets function and is the principal tool used to generate detailed sector-by-sector and region-by-region projections for the World Energy Outlook (WEO) scenarios.

Source: Respective web sites of model developers.

The data contain a wide range of emissions pathways that result from the very different assumptions about the future of the energy system

Global CO₂ emissions from full set of AR5 pathways 2000-2040
Gt CO₂ per year



Already in 2040, emissions range from nearly zero to 80 billion tonnes of emissions per year in different pathways

- 1 Baseline or reference** pathways result from scenarios where little or no policy action is taken to combat climate change. The 900 Gt carbon budget is exhausted by 2040 in many pathways
- 2 Mitigation scenarios** assume that some level of climate policy is taken, the ambition of which may vary. This results both in pathways that meet a 2 degree objective, and those that do not.
- 3 Some mitigation scenarios** are extremely ambitious, relying on immediate and deep emissions reductions, out of line with short-term emissions trends and at great socioeconomic cost.

Note: 1000+ emissions pathways from the AR5 database
Source: AR5 database

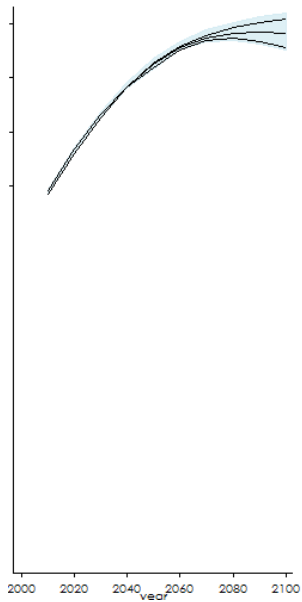
Scenarios vary in assumptions about baseline developments, technology availability, and policy implementation

	Sources of variation	Examples
Baseline and “state of the world”	<ul style="list-style-type: none"> Different rates of economic and population growth Rates of energy and carbon intensity 	<ul style="list-style-type: none"> Low/medium/high economic growth High population trajectory
Technology	<ul style="list-style-type: none"> Limits on the availability of certain technologies and resources In some scenarios, technologies may be excluded completely (CCS/U, nuclear), or restrictions may be imposed on the availability of certain fuel or energy sources (bioenergy, solar and wind) 	<ul style="list-style-type: none"> No CCS/U No new nuclear Limited supply of bioenergy Limits on solar and wind power
Policy	<ul style="list-style-type: none"> Scenarios with short-term targets that are less ambitious than those that would be “optimal” for a transition to 2100 (cf current INDC pledges or currently implemented policies) Fragmented vs. global action: mitigation limited to a sub-set of world regions 	<ul style="list-style-type: none"> “Optimal” (immediate action) Low short-term target High short-term target

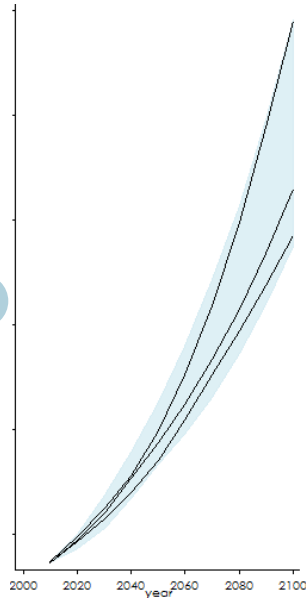
Source: IPCC (2014) – Annex II Metrics & Methodology in Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change

Scenarios differ in their assumptions about population, GDP growth, energy productivity, and carbon intensity of energy

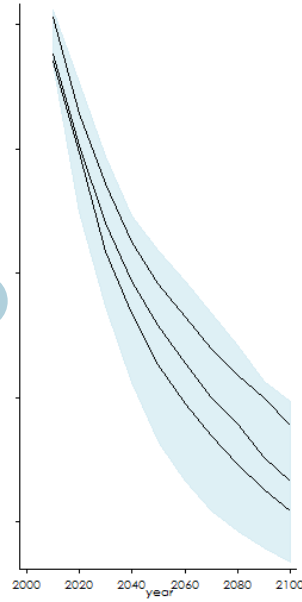
Population



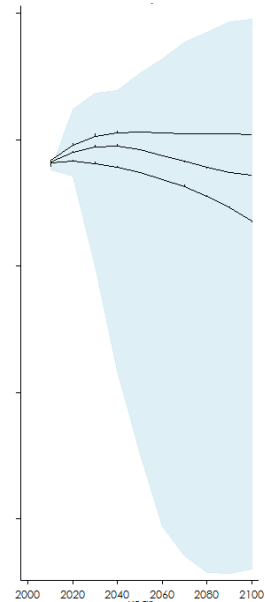
GDP per capita



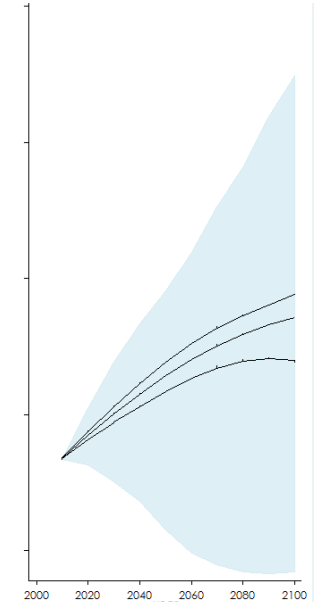
Energy intensity



Carbon intensity



CO₂ emissions



X

X

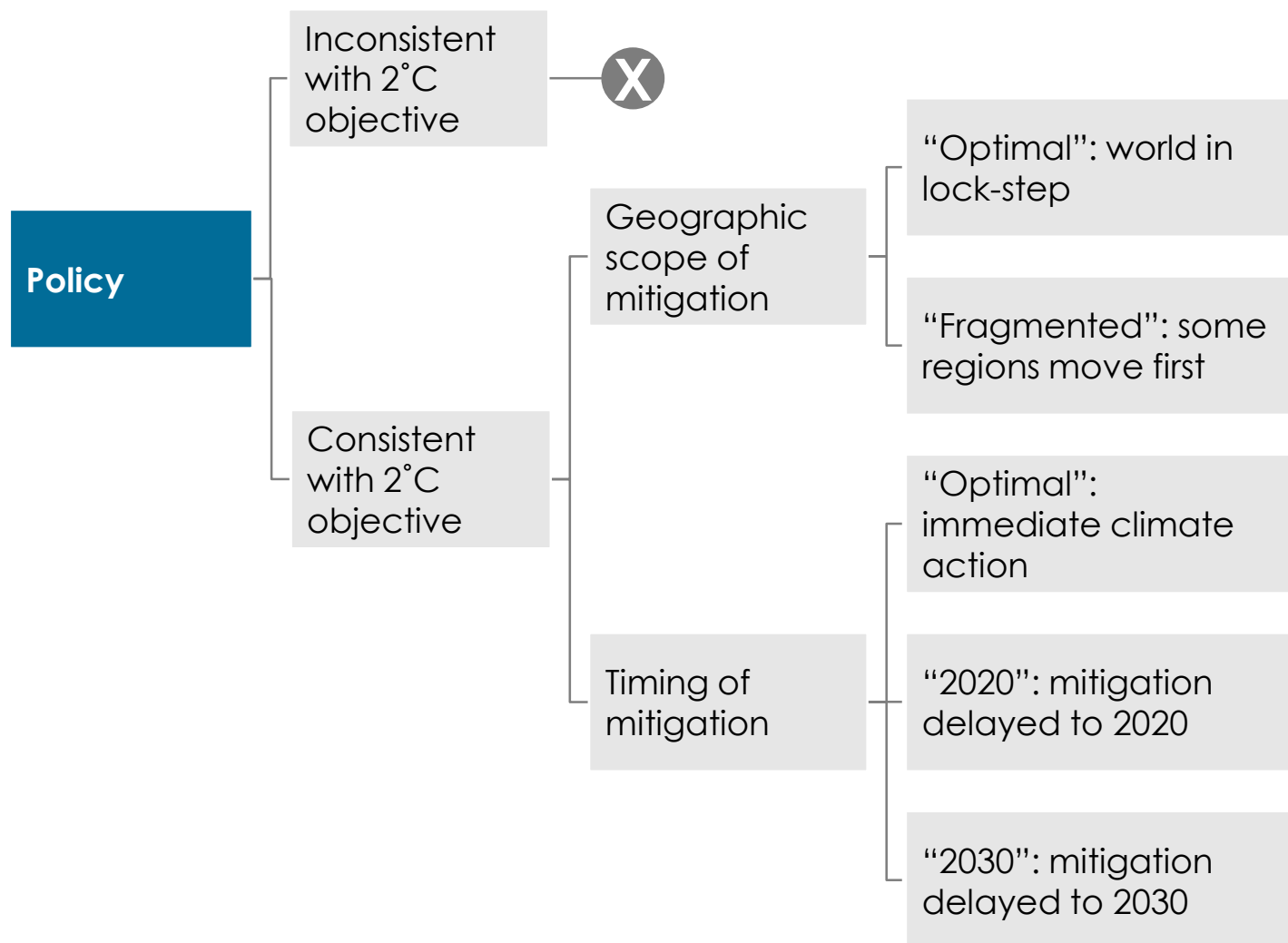
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Note: The coloured field shows the entire range of values for each variable. The lines show (from top to bottom), the 3rd quartile, median, and 1st quartile of each value in each year.

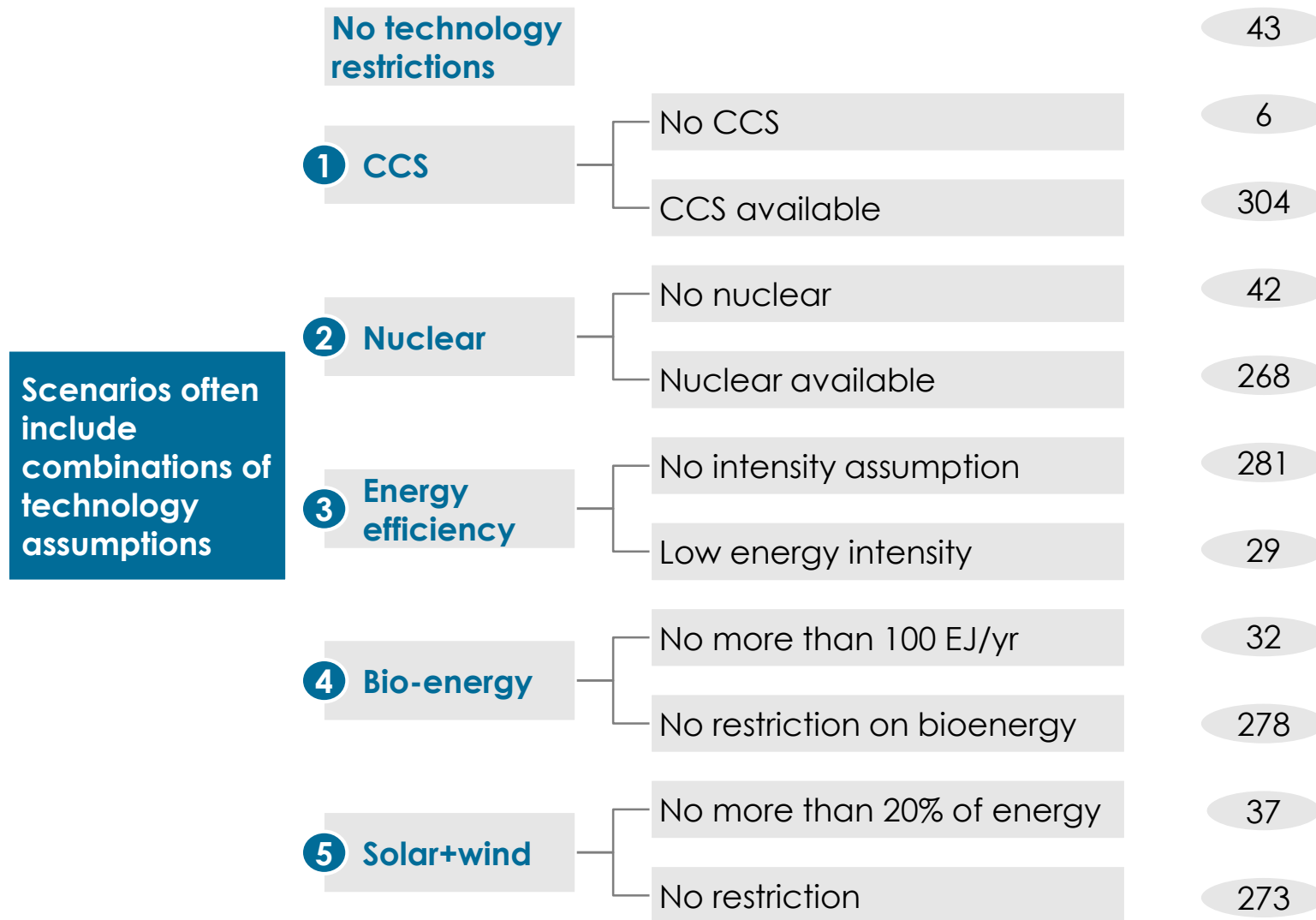
Source: AR5 database

Policy assumptions span climate ambition, geographic, and time dimensions



Source: Copenhagen Economics analysis based on AR5 database.

Technology assumptions span five major categories



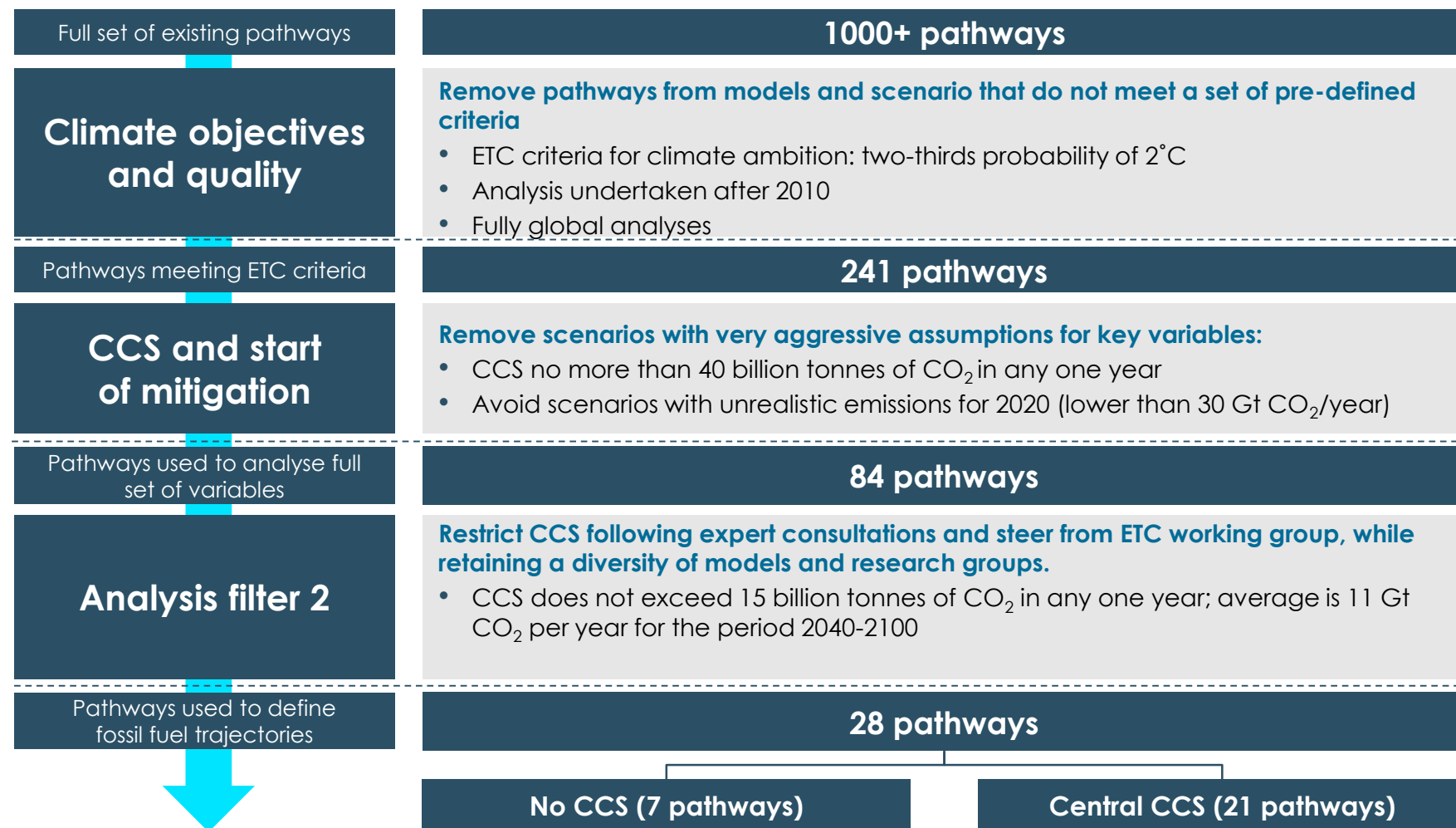
Source: Copenhagen Economics analysis based on AR5 database.

We restrict analysis to scenarios that meet a 2°C climate objective (as a starting point for well-below 2°C)

	Description	Examples	Role in analysis
Reference scenarios	<ul style="list-style-type: none"> Scenarios describing a development with no or no further climate policy 	<ul style="list-style-type: none"> IEA WEO, IEA ETP 6DS&4DS, EIA, BP, Exxon, Shell energy outlooks GEA, AMPERE, LIMITS, ROSE, etc harmonised baselines 	<ul style="list-style-type: none"> Used as point of reference: to analyse magnitude of change of mitigation scenarios
"450+" scenarios	<ul style="list-style-type: none"> Mitigation scenarios resulting in CO₂ concentrations of 550 parts per million or more Not compatible with 2/3 probability of meeting a 2°C objective 	<ul style="list-style-type: none"> IEA ETP 4DS "550" scenarios in IPCC database 	<ul style="list-style-type: none"> Not used
"450" scenarios	<ul style="list-style-type: none"> Mitigation scenarios resulting in CO₂ concentrations of 450 parts per million or less Compatible with 2/3 likelihood of meeting a 2°C objective Only a few scenarios below 450 ppm 	<ul style="list-style-type: none"> IEA WEO 450, IEA ETP 2DS 400+ scenarios from IPCC database 	<ul style="list-style-type: none"> Used as main source for analysis of implications for fossil fuels of a well-below 2°C objective

Source: Copenhagen Economics analysis based on AR5 database.

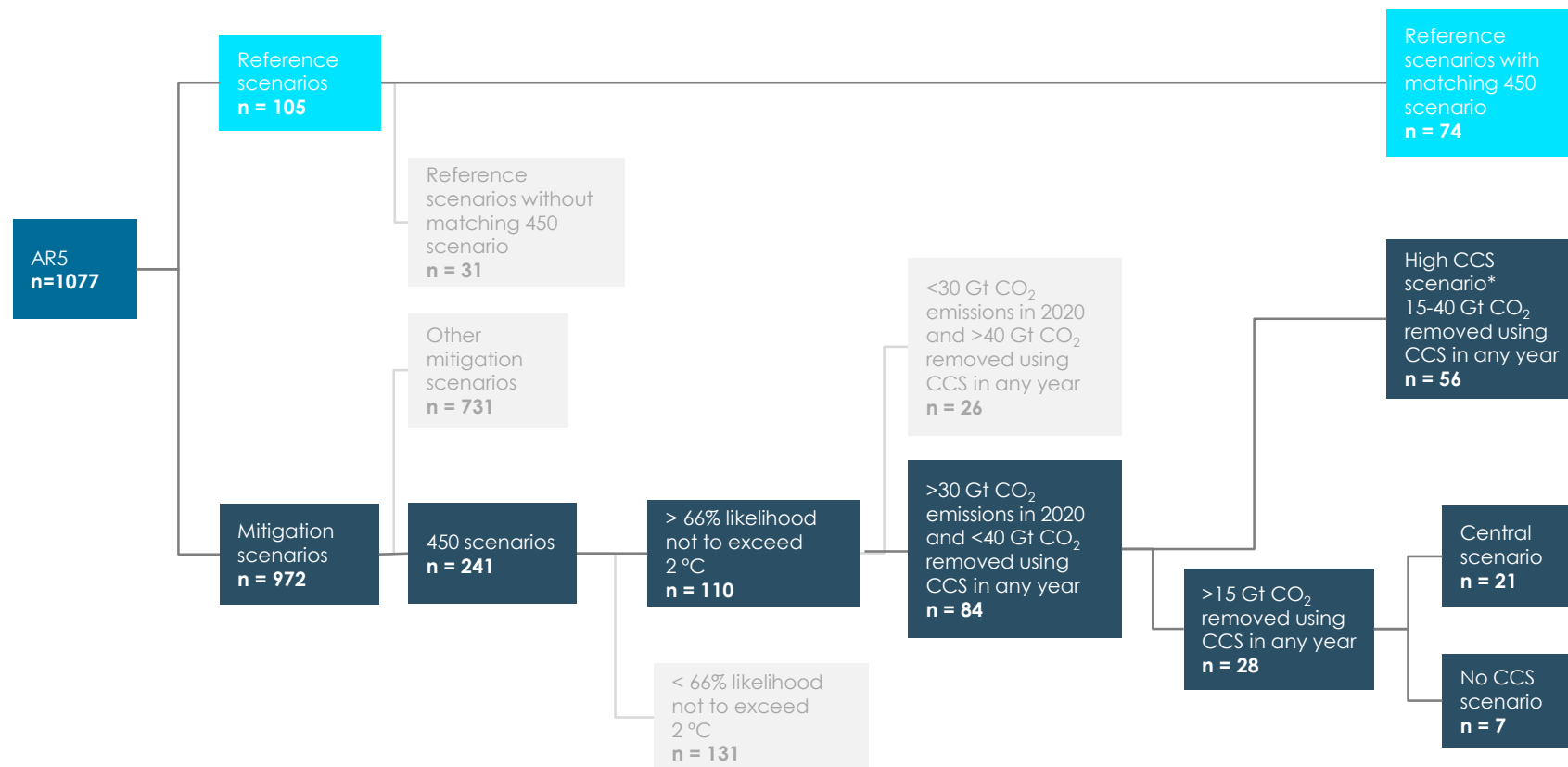
We draw on the full set of existing analyses to derive fossil fuel trajectories consistent with a well-below 2°C objective



Note: We define a 'pathway' as the emissions profile generated from an energy-economic scenario run through a model.

Of >1,000 pathways from the AR5 database, 84 are used to analyse 450 scenarios and 74 to analyse reference scenarios

- Pathways used as reference/baseline scenarios
- Pathways not used in analysis
- Pathways used for mitigation scenarios

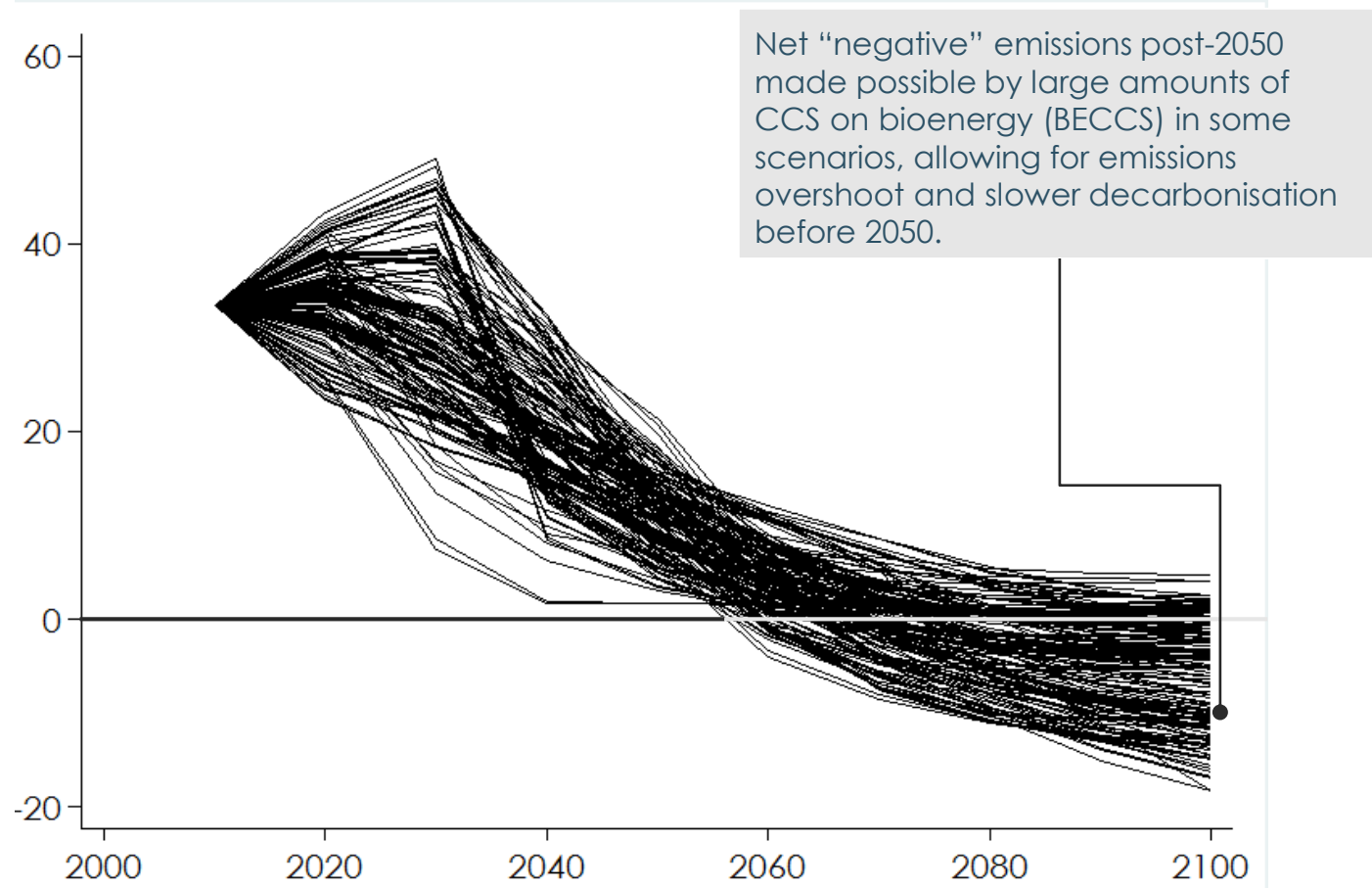


Note: The 241 450-scenarios set out an energy pathway consistent with the goal of limiting the global increase in temperature to 2 °C by limiting the concentration of CO₂ in the atmosphere to around 450 parts per million.

The scenarios span a wide variety of potential pathways to meeting climate objectives

Global CO₂ emissions from energy use in 450 ppm scenarios

Gt CO₂ per year



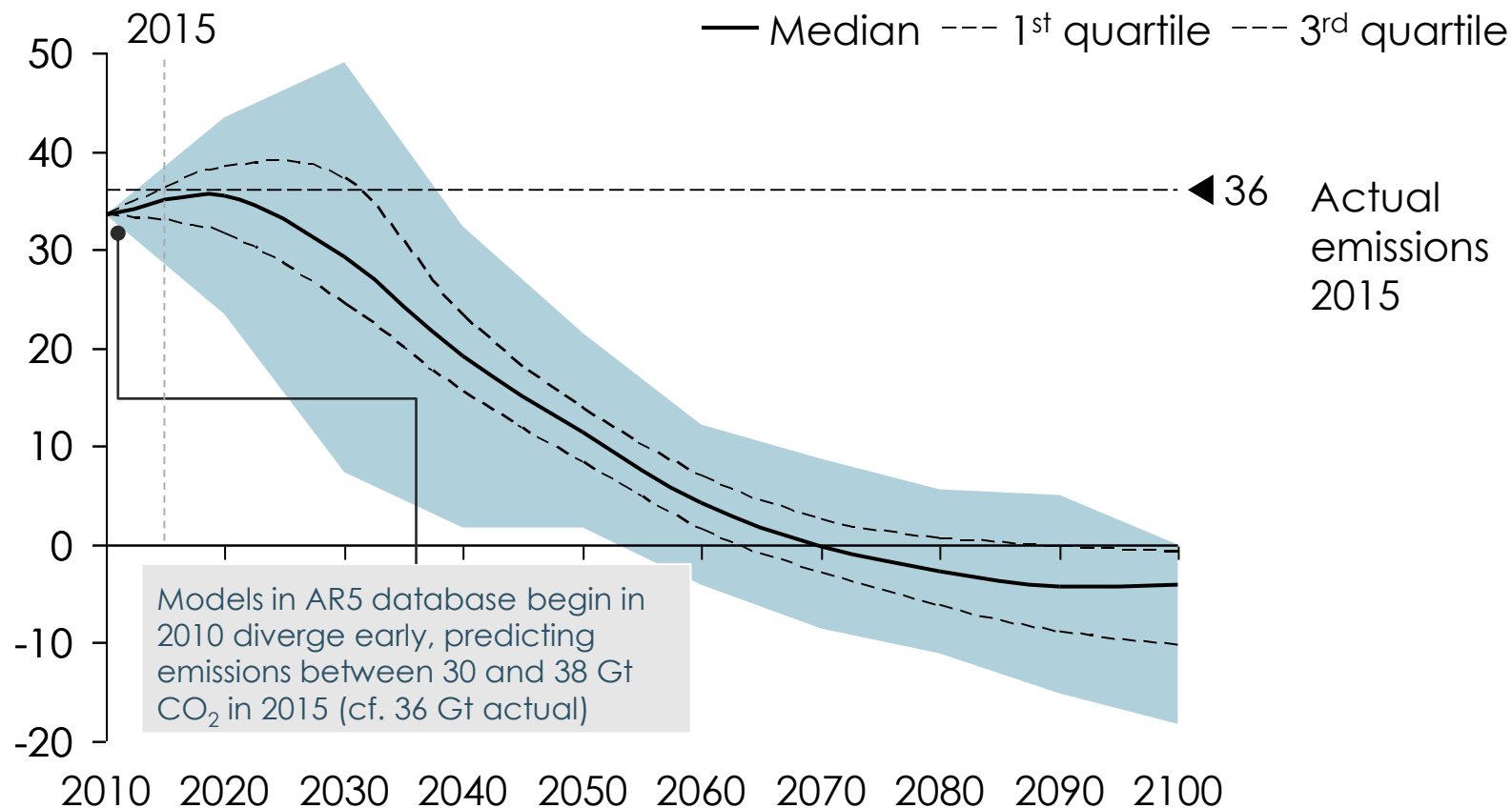
Note: Emissions in 84 scenarios that meet WB2D criteria with more than 2/3 probability and >30 Gt CO₂ emissions in 2020 and no more than 40 Gt CO₂ removed using CCS in any year

Source: AR5 database

There is a large number of scenarios, but 50% typically lie within a relatively constrained corridor for emissions

Global CO₂ emissions from energy use in 450 ppm scenarios

Gt CO₂ per year



Note: Median, 1st and 3rd quartiles of all [241 mitigation scenarios]
Source: AR5 database

Following analysis and consultations, we apply a filter to pathways to remove overly optimistic scenarios

Criteria	Threshold value	Motivation
Availability of CCS/CCU	<ul style="list-style-type: none"> At most 15 Gt/year in any year 	<ul style="list-style-type: none"> High levels of CCS/U implies large and potentially rapid scale-up of infrastructure to capture and transport (and store) carbon dioxide. WB2D scenarios assumes up to 60 Gt CO₂ captured per year, setting threshold lower than 15 Gt/year eliminates too many scenarios to make further analyses.
CO ₂ emissions in 2020	<ul style="list-style-type: none"> At least 30 Gt CO₂ in 2020 (cf. ~36 Gt CO₂ in 2015) 	<ul style="list-style-type: none"> Pathways proposed even <5 years ago risk being out of date, with emissions peaking before 2020. Emissions from fossil fuel combustion and industrial processes where roughly 33.5 Gt in 2010 and 35.7 Gt in 2015. Emissions in 2020 of 30 Gt imply an annual decline rate of 3.6% between 2015 and 2020, which we assume as a maximum break with current trends.

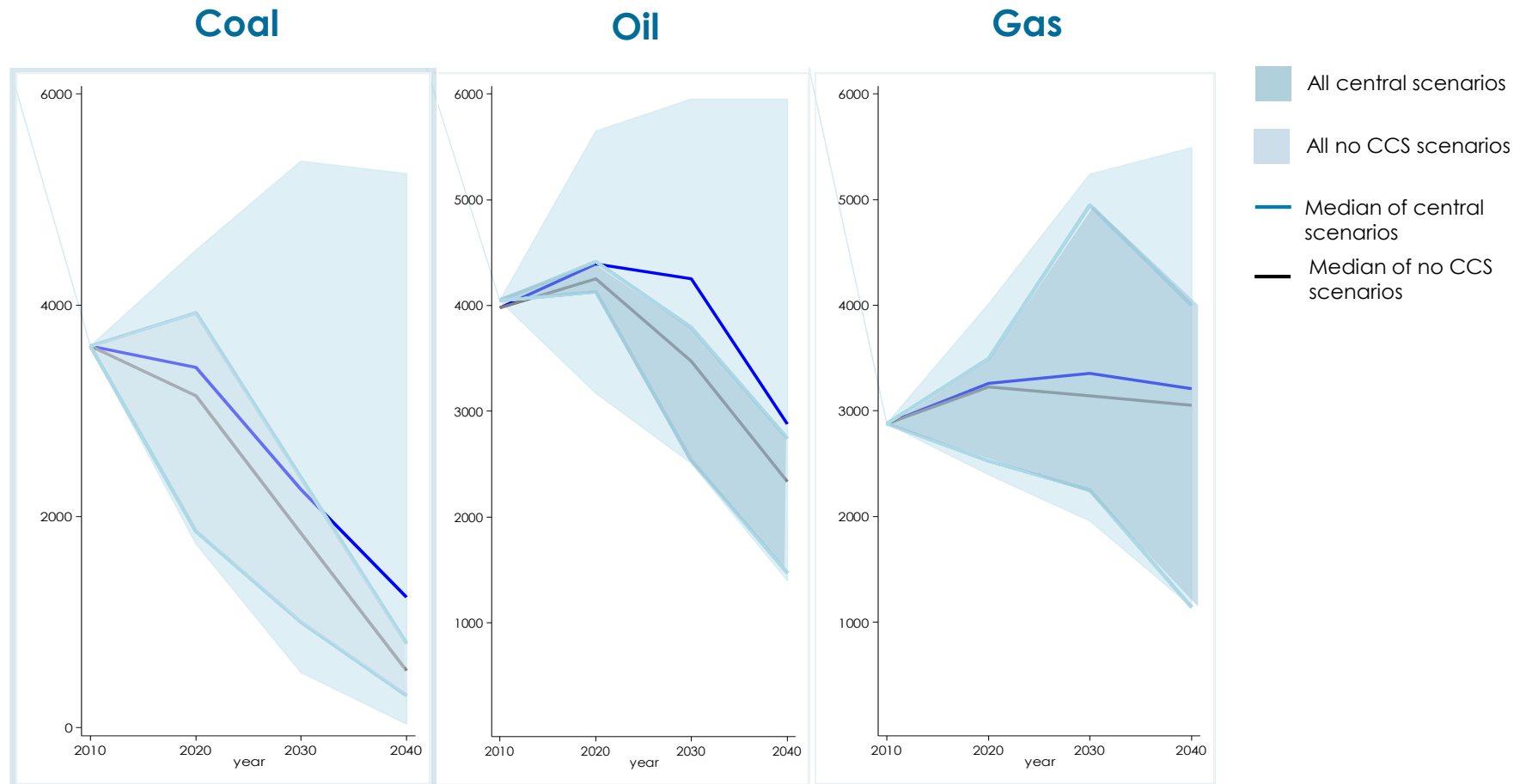
We derive three archetype demand scenarios from the full range of pathways in the IPCC's AR5 database

	Description	Selection process
A Central scenario	<ul style="list-style-type: none"> Scenario that strikes a balance between early, rapid decline of fossil fuels and heavy reliance on CCS/U technologies. 	<ul style="list-style-type: none"> Pathways from scenarios that limit the risk of a global temperature rise of more than 2°C to less than one-third, with 2020 emissions of at least 30 Gt CO₂, and with no more than 15 Gt CO₂ removal from CCS/U in any given year.
B No CCS scenario	<ul style="list-style-type: none"> Scenario with no access to CCS/U technologies. Emissions reductions are achieved through <ul style="list-style-type: none"> Rapid move away from fossil fuel sources through fuel substitution Energy efficiency improvements Reduced energy consumption 	<ul style="list-style-type: none"> Pathways from scenarios that limit the risk of a global temperature rise of more than 2°C to less than one-third, with 2020 emissions of at least 30 Gt CO₂ and have no CCS/U technologies (e.g. "NoCCS" and "EERE" scenarios from AR5 database).
C High CCS scenario	<ul style="list-style-type: none"> Scenario relying on very high levels of CCS/U, particularly in the period 2040-2100 compared to the Central scenario The High CCS scenario is only used for reference occasionally to illustrate the need for fossil fuel reductions, even with implausibly high levels of CCS/U 	<ul style="list-style-type: none"> Pathways from scenarios that limit the risk of a global temperature rise of more than 2°C to less than one third, with 2020 emissions of at least 30 Gt CO₂, and with more than 15 but less than 40 Gt CO₂ removal from CCS/U in any given year.

The median values for each fossil fuel within each group represent the demand pathway for that fuel

Fossil fuel consumption 2010-2040

Million tonnes of oil equivalent



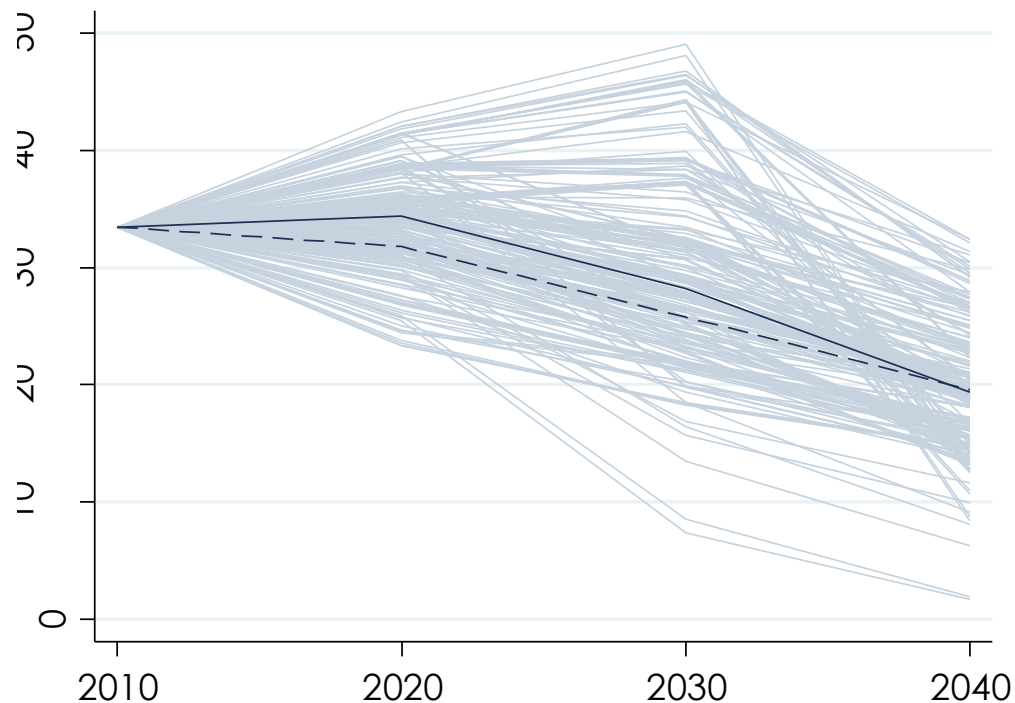
Note: Central scenarios limit the risk of a global temperature rise of more than 2 degrees to less than one third, with 2020 emissions of at least 30 Gt CO₂, and with no more than 15 Gt CO₂ removal from CCS in any given year.

Source: AR5 database

Both scenarios see CO₂ emissions falling to ~20 Gt per year by 2040

Emissions of CO₂, 2010-2040

Billion tonnes per year



— All 450 scenarios
 - - No CCS scenario
 — Central scenario

- **Central and No CCS** scenarios are middle-of-the-road until 2040
- **Some pathways** see drastic cuts already by 2040, with emissions of <10 Gt CO₂, or one-fourth of current emissions
- **Almost all pathways** that are consistent with a 2°C objective have lower emissions in 2040 than today (36 Gt CO₂). Some are at similar levels as today. These are either a) not compatible with 2/3 probability of meeting a 2°C objective or b) require drastic emission cuts post-2040

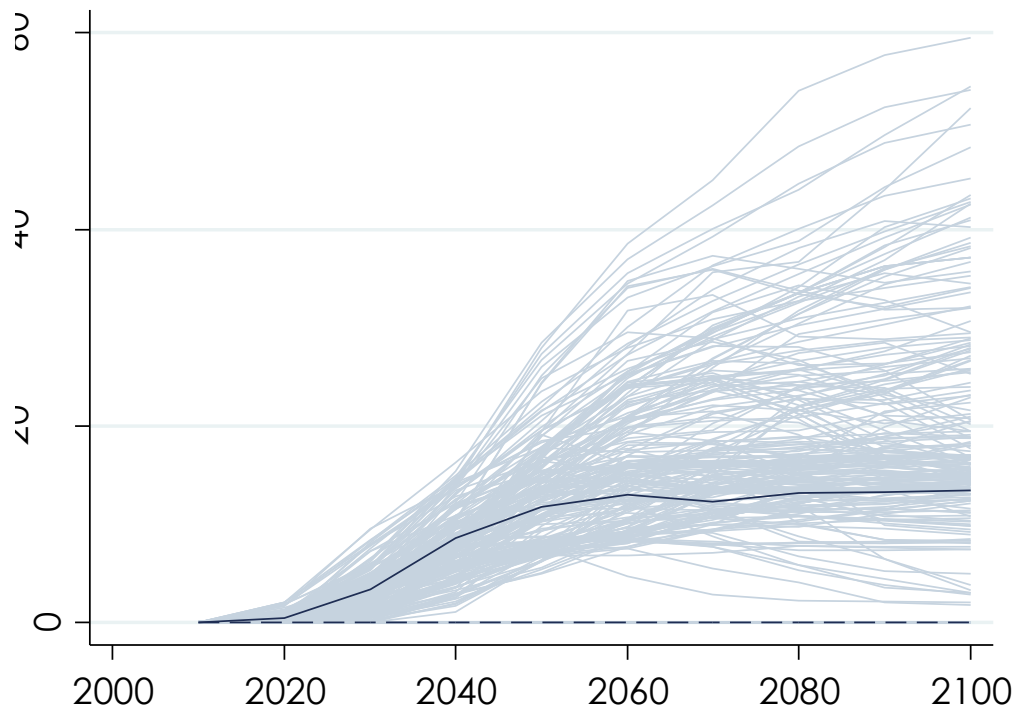
Note: 'All 450 scenarios' include 241 scenarios that are consistent with the goal of limiting the global increase in temperature to 2°C, by limiting the concentration of greenhouse gases in the atmosphere to around 450 parts per million of CO₂.

Source: AR5 database

Levels of CCS/U in our scenarios are in the lower end of the spectrum compared to full set of AR5 450 scenarios

CO₂ captured from CCS/U, 2010-2100

Billion tonnes per year



— All 450 scenarios
 -- No CCS scenario
 — Central scenario

- **Central scenario** has levels of CCS close to the median of all 450 pathways up to 2040. After levelling off, the CCS levels are towards the lower end of all scenarios by 2100
- **The Low CCS** scenario has no CCS
- **Many pathways** cluster at 10-20 Gt CO₂ in 2100. Many are considerably higher.
- **The most ambitious pathways** see levels of 40-60 Gt CO₂ per year in 2100, which implies adding ~500-750 million tonnes of CCS capacity per year from 2020 to 2100, 20-30 times current installed capacity (28 million tonnes CO₂ per year)

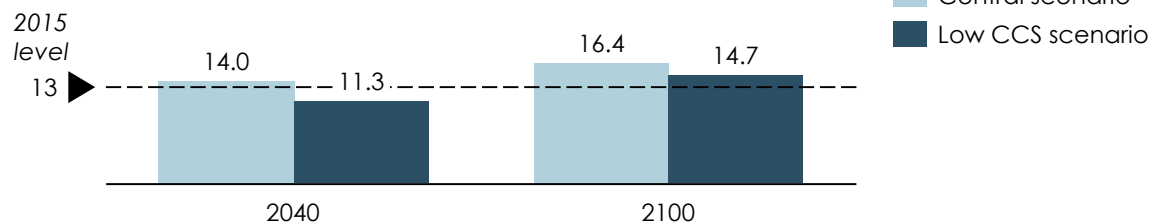
Note: 'All 450 scenarios' include 241 scenarios that are consistent with the goal of limiting the global increase in temperature to 2°C, by limiting the concentration of greenhouse gases in the atmosphere to around 450 parts per million of CO₂.

Source: AR5 database

Comparison of key energy statistics

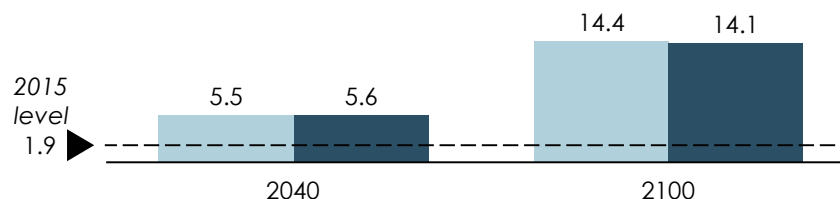
Primary energy demand 2040 and 2100

1000 Mtoe per year



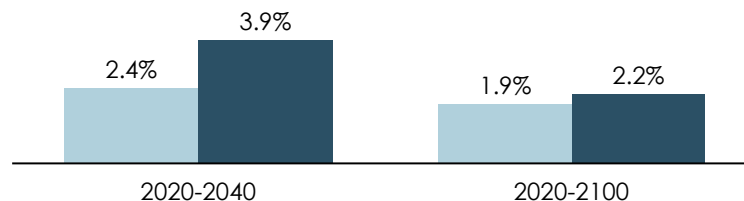
Non-fossil energy supply 2040 and 2100

Mtoe per year



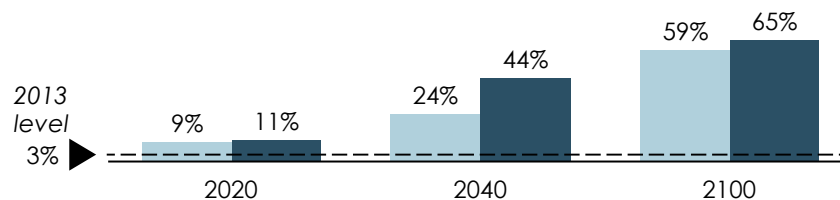
Average annual energy productivity improvement 2020-2040 and 2020-2100

%



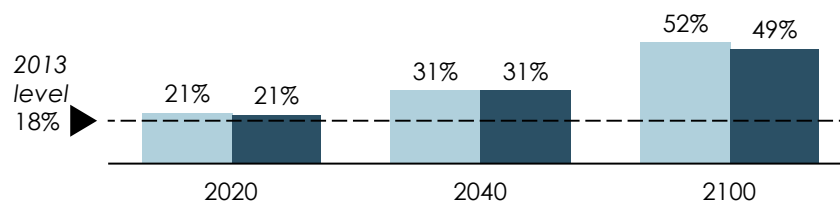
Wind and solar share of electricity generation

%



Electricity share of final energy demand

%



Source: 2013 data from IEA WEO 2015. 2015 data from BP World Energy Statistics 2015.

List of models and scenarios used for ‘Central’ and ‘No CCS’ scenarios

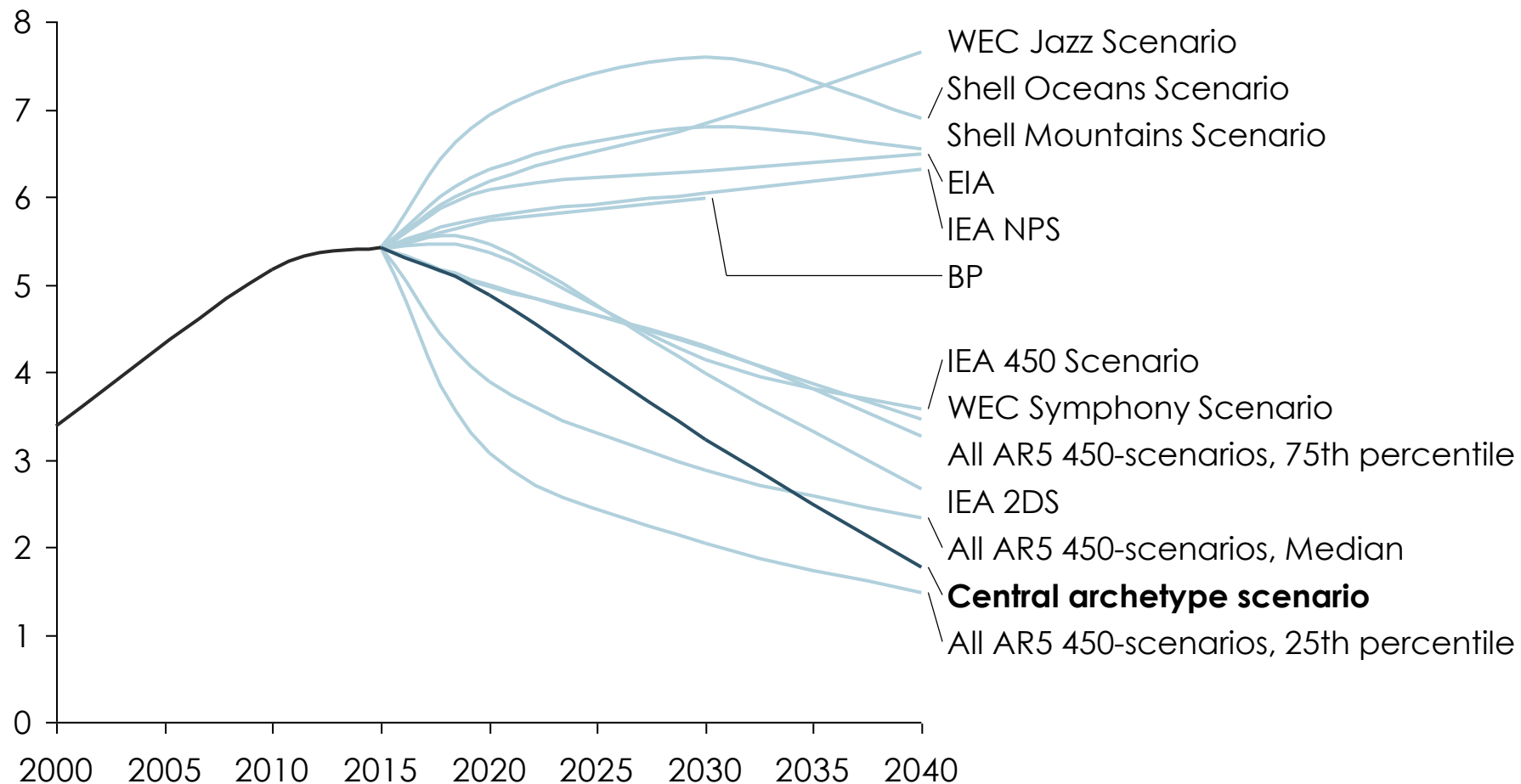
	Modelling exercise	Model	Scenario name	Archetype pathway
1	AMPERE2	MERGE-ETL	AMPERE2-450-LowEI-HST	Central
2	AMPERE2	POLES	AMPERE2-450-LimBio-LST	Central
3	AMPERE2	MERGE-ETL	AMPERE2-450-FullTech-HST	Central
4	AMPERE2	MERGE-ETL	AMPERE2-450-EERE-OPT	No CCS
5	AMPERE2	MERGE-ETL	AMPERE2-450-LimSW-HST	Central
6	AMPERE2	MERGE-ETL	AMPERE2-450-LowEI-OPT	Central
7	AMPERE2	MERGE-ETL	AMPERE2-450-NoCCS-OPT	No CCS
8	AMPERE2	POLES	AMPERE2-450-EERE-OPT	No CCS
9	EMF27	MERGE_EMF27	EMF27-450-Conv	Central
10	EMF27	MERGE_EMF27	EMF27-450-LimBio	Central
11	EMF27	REMIND_1.5	EMF27-450-LimBio	Central
12	GEA	MESSAGE_V.3	GEA_Efficiency_450_conv.transp_noccs	No CCS
13	GEA	MESSAGE_V.3	GEA_Mix_450_adv.transp_noccs	No CCS
14	GEA	MESSAGE_V.3	GEA_Efficiency_450_adv.transp_noccs_nonuc	No CCS
15	GEA	MESSAGE_V.3	GEA_Efficiency_450_adv.transp_nbecs	Central
16	GEA	MESSAGE_V.3	GEA_Mix_450_adv.transp_nbecs	Central
17	GEA	MESSAGE_V.3	GEA_Efficiency_450_adv.transp_noccs	No CCS
18	GEA	MESSAGE_V.3	GEA_Efficiency_450_conv.transp_nbecs	Central
19	GEA	MESSAGE_V.3	GEA_Mix_450_conv.transp_nbecs	Central
20	LIMITS	WITCH	LIMITS-RefPol-450	Central
21	LIMITS	WITCH	LIMITS-StrPol-450	Central
22	ROSE	REMIND_1.4	ROSE_WEAK-2020_DEF	Central
23	ROSE	REMIND_1.4	ROSE_450_HI_Fos	Central
24	ROSE	REMIND_1.4	ROSE_450_DEF	Central
25	ROSE	REMIND_1.4	ROSE_450_FS_Gr_SL_Con	Central
26	ROSE	REMIND_1.4	ROSE_450_SL_Gr	Central
27	ROSE	REMIND_1.4	ROSE_450_HI_Pop	Central
28	ROSE	REMIND_1.4	ROSE_450_FS_Gr	Central

Source: AR5 database

Coal consumption compared to other scenarios and projections

Coal consumption

Billion tonnes per year

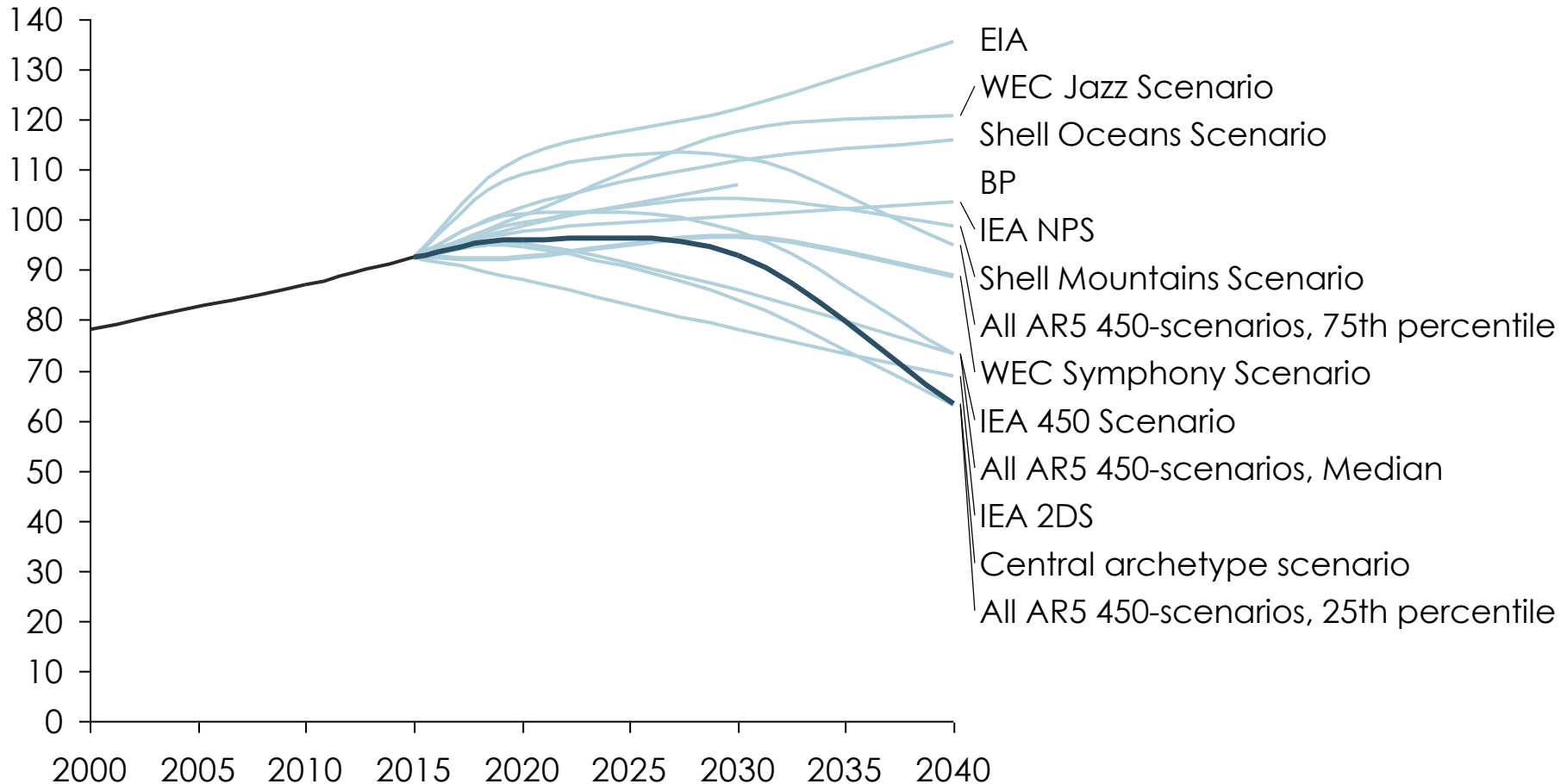


Source: AR5 450-scenarios from AR5 database. IEA 450 and NPS scenarios from IEA World Energy Outlook 2015; IEA 2DS scenario from IEA Energy Technology Perspectives 2015; WEC Jazz and Symphony scenarios from World Energy Council (2013), World energy scenarios: Composing energy futures to 2050; BP Scenario from Energy Outlook 2035: February 2015; Shell scenarios from Shell (2013), The New Lens;

Oil consumption compared to other scenarios and projections

Oil consumption

Million barrels per day

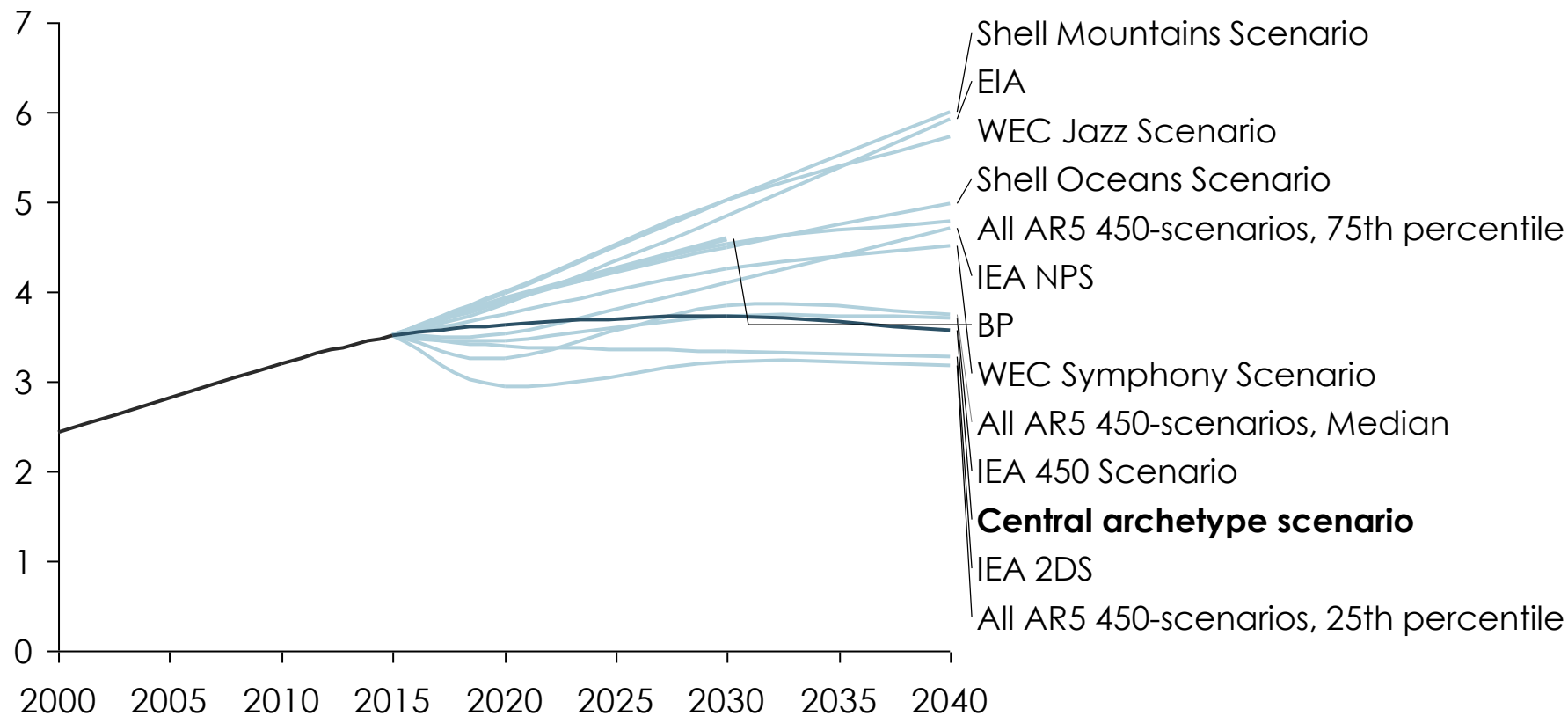


Source: AR5 450-scenarios from AR5 database. IEA 450 and NPS scenarios from IEA World Energy Outlook 2015; IEA 2DS scenario from IEA Energy Technology Perspectives 2015; WEC Jazz and Symphony scenarios from World Energy Council (2013), World energy scenarios: Composing energy futures to 2050; BP Scenario from Energy Outlook 2035: February 2015; Shell scenarios from Shell (2013), The New Lens.

Natural gas consumption compared to other scenarios and projections

Natural gas consumption

Trillion cubic metres per year



Source: AR5 450-scenarios from AR5 database. IEA 450 and NPS scenarios from IEA World Energy Outlook 2015; IEA 2DS scenario from IEA Energy Technology Perspectives 2015; WEC Jazz and Symphony scenarios from World Energy Council (2013), World energy scenarios: Composing energy futures to 2050; BP Scenario from Energy Outlook 2035: February 2015; Shell scenarios from Shell (2013), The New Lens;