



ENERGY TRANSITIONS
COMMISSION

The future of fossil fuels: How to steer fossil fuels 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 – Summary report

Disclaimer

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

Copenhagen Economics has sole responsibility for the content and findings of this document, which should not be interpreted as recommendations made by the ETC.

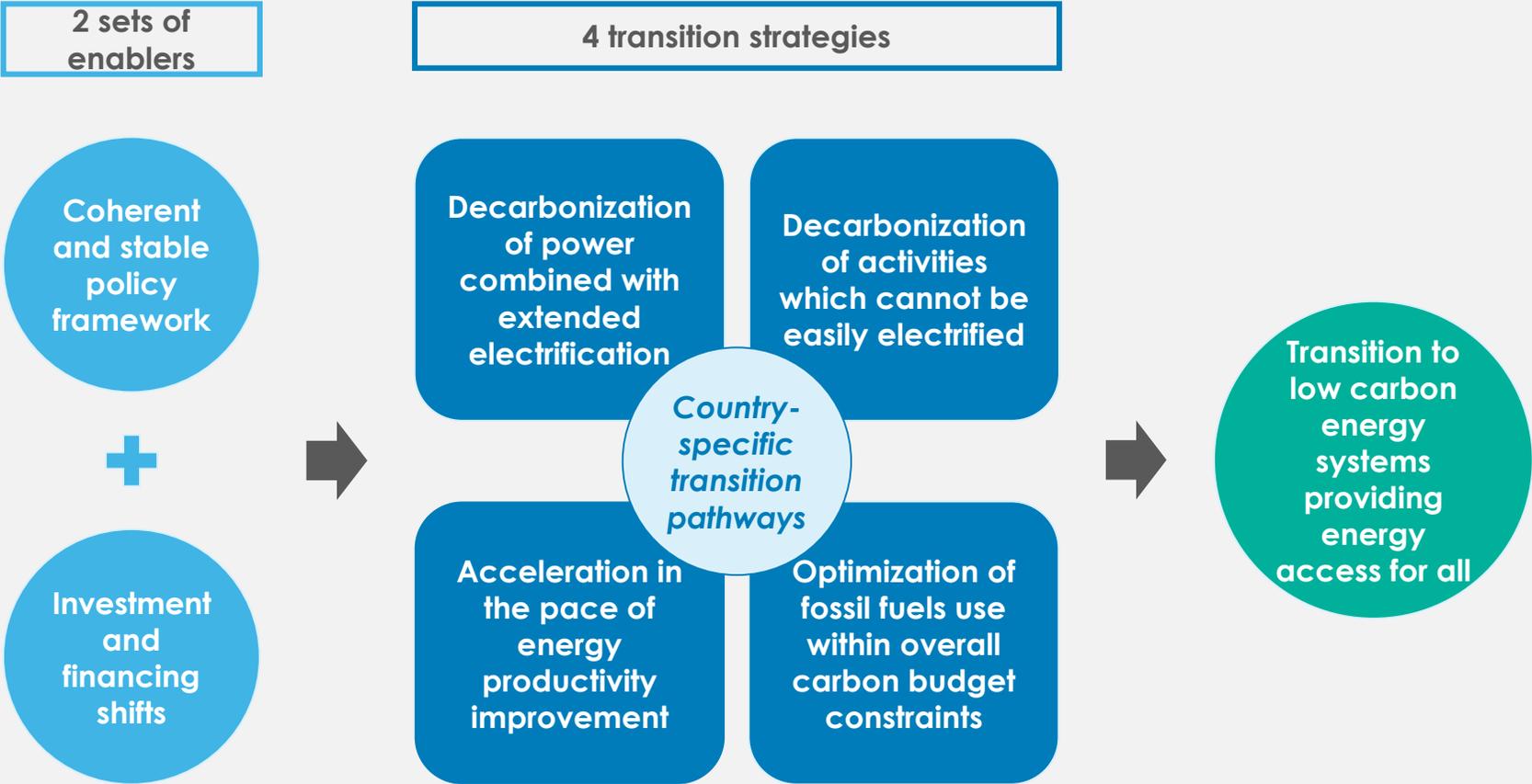
The ETC will seek further input through a consultation period from December 2016 to March 2017. The conclusions presented here may be revised as a result. Copenhagen Economics and the ETC invite your comments and input.

Contact us at: info@energy-transitions.org

And follow us on twitter: [@ETC_energy](https://twitter.com/ETC_energy)

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

Summary report

January 2017

Executive summary

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 to 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

Executive summary (1/3)

1. Energy needs are growing fast. Absent a profound energy transition, CO₂ emissions would increase by 50-70% by 2040, to 50-60 billion tonnes CO₂ per year.

- Population and GDP are likely to grow by ~20% and ~90%, respectively.
- Demand for energy services would grow by 50% or more, driven by urbanisation, industrialisation, infrastructure build-out, and a growing global middle class.
- Energy intensity will continue to improve by up to 75% by 2040, driven by ongoing structural shifts to less energy intensive economic activity and improving technology.
- Even so, energy demand will increase by 30-60% if developments follow the trends seen in the past.
- The current energy system is highly carbon intensive, with coal, oil, and natural gas providing 85% of all energy.
- An energy transition must involve both higher rates of energy intensity improvement and a rapid shift to zero-carbon energy to avoid large increases in emissions.

2. Limiting climate change depends on restricting cumulative future emissions. The “carbon budget” to limit warming to 2°C amounts to ~900 billion tonnes of carbon dioxide (Gt CO₂) 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.

- This carbon budget gives a probability of two-thirds that warming will not exceed 2°C.
- A more stringent target rapidly reduces the budget, to ~200 Gt CO₂ for a 1.5°C target.
- Most 2°C scenarios see emissions halved by 2040; net zero emissions are required in later years.
- Technologies to remove CO₂ from the atmosphere (“negative emissions”) may be a prerequisite.
- Current fossil fuel reserves exceed the budget by a factor of 3-6; coal reserves alone would create ~2,000 Gt of emissions.
- Addressing “lock-in” by existing and planned fossil fuel infrastructure is a key aspect of an energy transition.

Executive summary (2/3)

3. In a successful 2°C 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 achieved, with profound consequences for energy use and energy markets.

- Our analysis of future fossil fuel use draws on 1000+ existing pathways, basing our conclusions on those that meet climate objectives.
- The level of fossil fuel use compatible with a 2°C scenario depends strongly on the level of feasible carbon capture; we define three CCS/U scenarios (No CCS, Central, High).
- A 2°C pathway requires a 30% reduction in fossil fuel use by 2040 under a “Central CCS” scenario, increasing to a 50% reduction if no CCS/U were feasible.
- Meeting energy needs with these reduced levels of fossil fuel use requires sharply increased energy efficiency/productivity as well as a rapid rise of zero-carbon energy.
- The impact differs across fuels: a sharp and immediate fall in coal; a 2020s peak and decline for oil; and no or little growth in natural gas.

4. 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.

- Coal consumption would be increasingly concentrated in industry, as feedstock for steelmaking and in high-temperature applications such as metals and minerals production. By 2040, most of thermal coal use in the power sector must be phased out.
- Oil would be concentrated in transport use (with emphasis on heavy freight transport, aviation and shipping) and as feedstock for chemicals. Electrification, modal shifts and efficiency drive down the use of oil for passenger transport.
- Natural gas would continue to be used across the energy system as a relatively cleaner fuel. In power its share still declines to ~15% by 2040; in buildings, it is driven down by increased use of electricity and higher energy efficiency; in industry, its consumption is likely to increase.

Executive summary (3/3)

5. Fossil fuel prices would be lower in a 2°C scenario, with less need to mobilise high-cost reserves to meet demand. However, additional investment in oil and gas will still be required. Even in a 2°C scenario, the majority of hydrocarbon supply in 2040 would come from new developments.

- For oil, prices may fall from USD 90-120/bbl in a reference case, to 60-80/bbl.
- For natural gas, prices vary regionally, but on average may fall from 10 to 6 USD/MMBTU.
- Some 60% of oil demand and 75% of natural gas demand in 2040 will be met by new fields.
- Cumulative investment would be 70% of a reference case, with oil investment falling from approx. USD 14 trillion to 10 trillion (-25%) and natural gas investment falling from USD 6.7 trillion to 4.4 trillion (-35%).

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

- CCS/U volumes reach 10 Gt/year by 2040, and approach 20+ Gt thereafter in many pathways.
- We base our analyses of future fossil fuel use on a “Central CCS” scenario of 7-8 Gt by 2040 and 11 Gt thereafter, but also analyse the implications of no CCS/U, or of still higher volumes.
- Achieving 7-8 Gt faces profound challenges of scale, infrastructure, and cost:
 - Scale: required volumes would imply more than two new plants each week to 2040.
 - Infrastructure: volume of CO₂ to be transported and stored per year would be similar to current total oil and natural gas production volume.
 - Cost: carbon capture is dependent on a strong and predictable carbon price.
- CCS/U is integral to most visions for “net zero” emissions in the long run, with “negative emissions” (combined with bioenergy) offsetting emissions from some residual fossil fuel use.

Executive summary

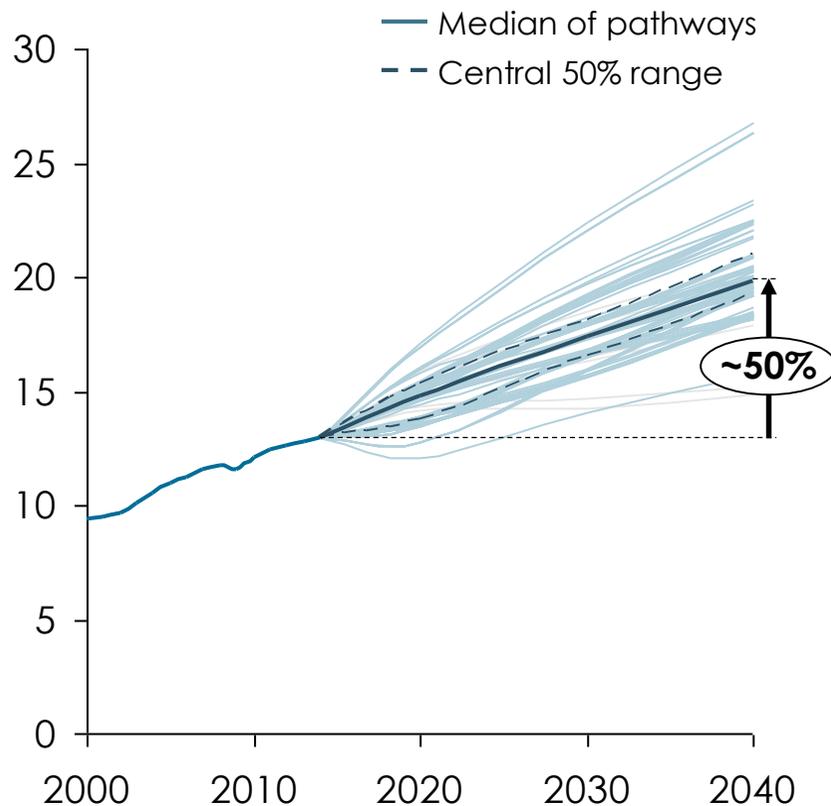
1. Rapidly growing energy needs set the scene for an energy transition

2. A 2°C objective implies a strict carbon budget
3. Fossil fuel use would fall by one-third to 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

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

Primary Energy Demand

Billion tonnes of oil equivalent per year



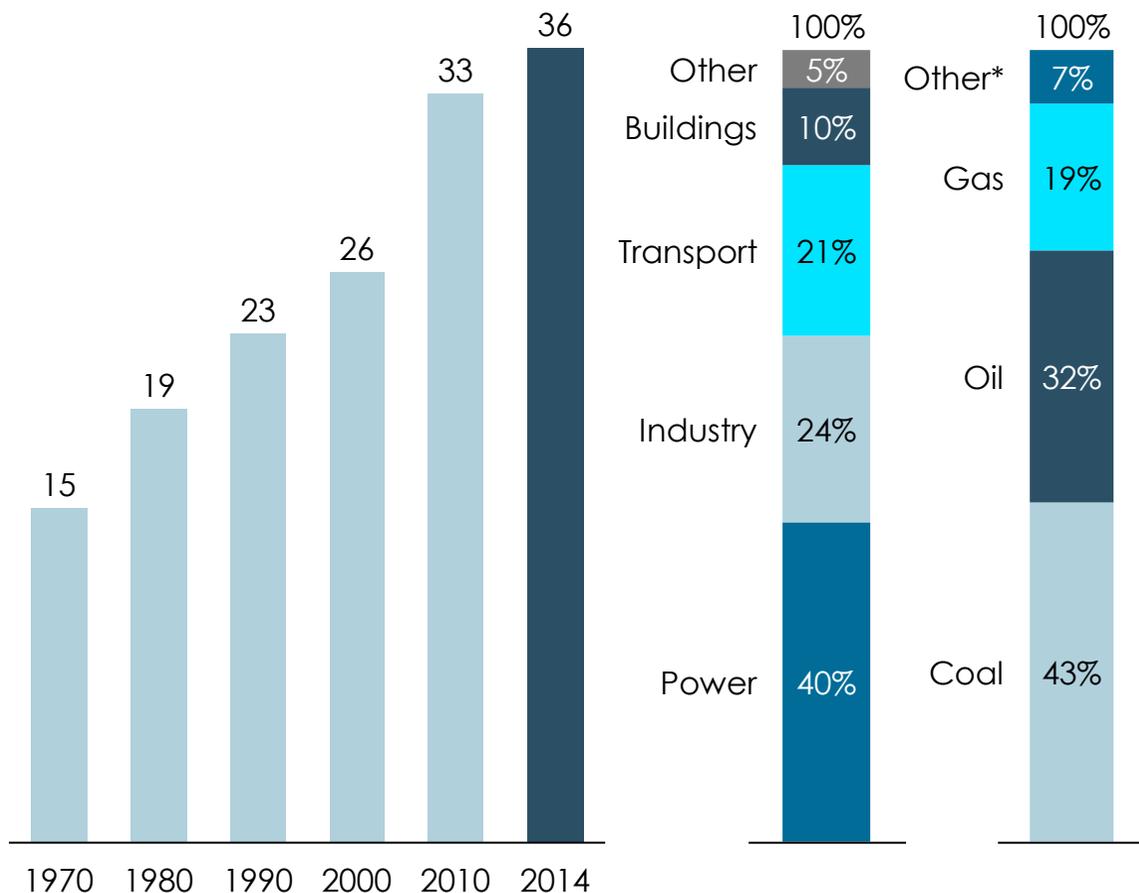
- Development will require increased energy supply. By 2040, world population may grow by 20% and GDP per capita 90%. Even with much lower energy intensity (less energy per unit GDP) than today, energy needs grow significantly
- Projections see energy demand increase by ~50% to 2040, but with large uncertainty.
- We review more than 30 scenarios, that reveal large uncertainty about key factors:
 - 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.

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

CO₂ emissions from fossil fuel combustion and industrial processes

Billion tonnes per year; % of total



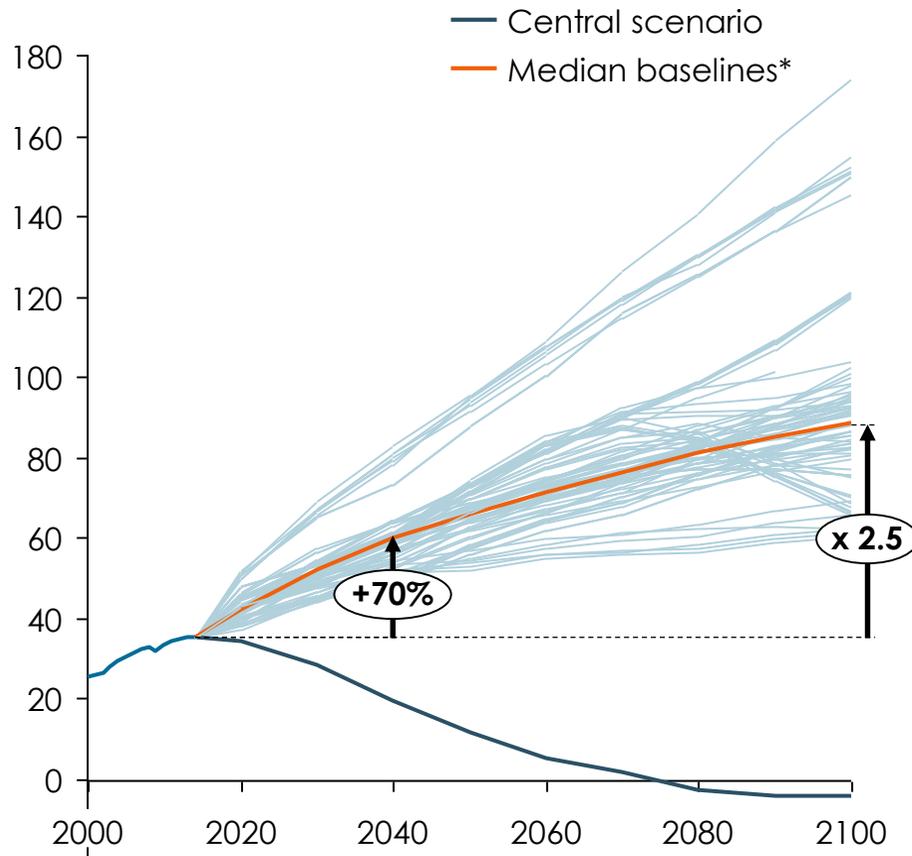
- Emissions today are 36 Gt CO₂, nearly twice 1980 levels, with especially strong growth since 2000. However, the last three years emissions have stabilised, driven in large part stalling coal use in China.
- The global energy system is heavily fossil fuel-based, with 85% of energy from coal, oil, and natural gas.
- As a consequence, it is *carbon intensive*: each tonne of oil equivalent produces on average 2.7 tonnes of CO₂.
- Fossil fuels are used across nearly all sectors – with buildings, industry, transport, and power generation all producing sizeable emissions.

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 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

Executive summary

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

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

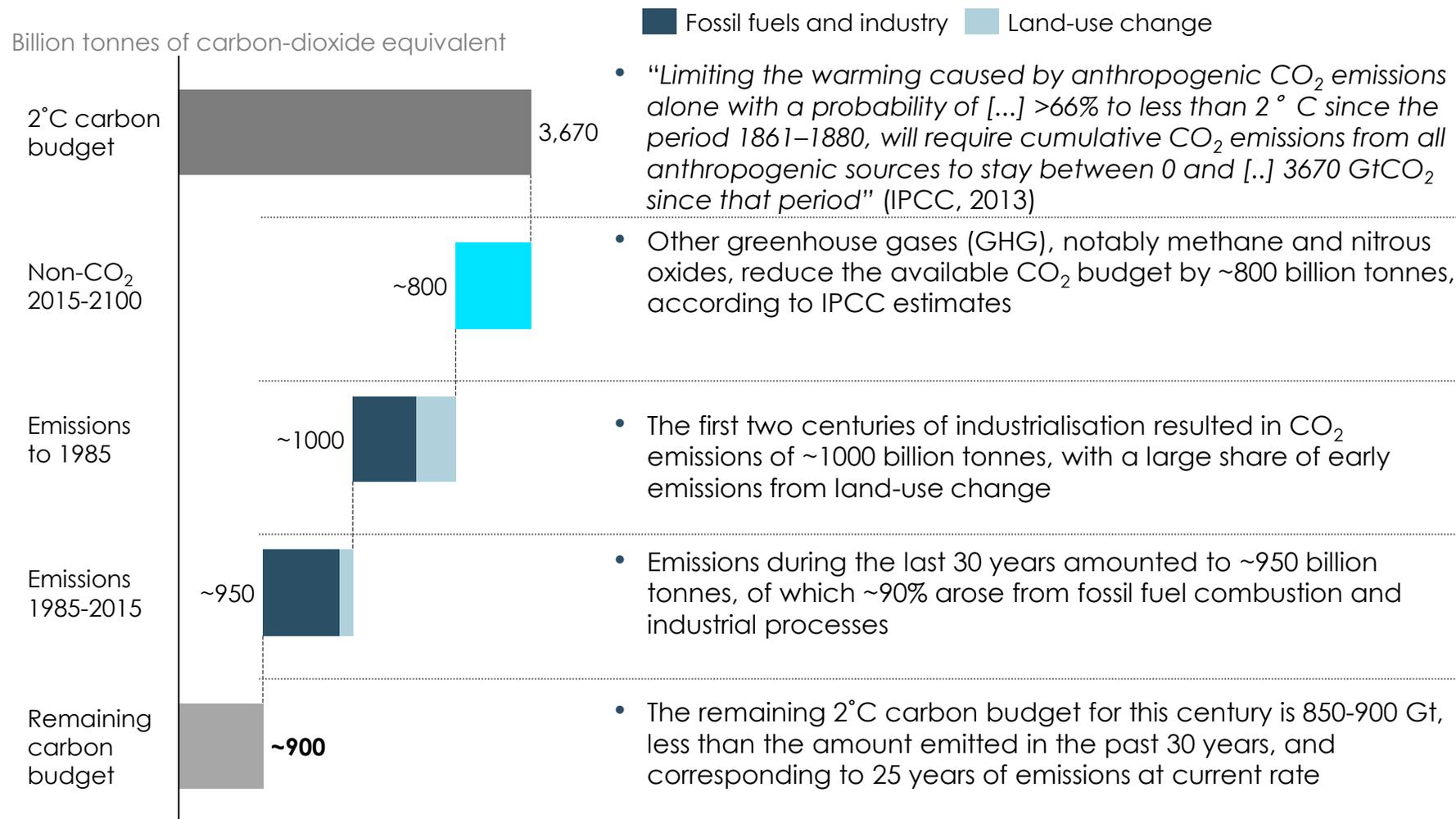
3. Fossil fuel use would fall by one-third to 2040 to meet 2°C objectives

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

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

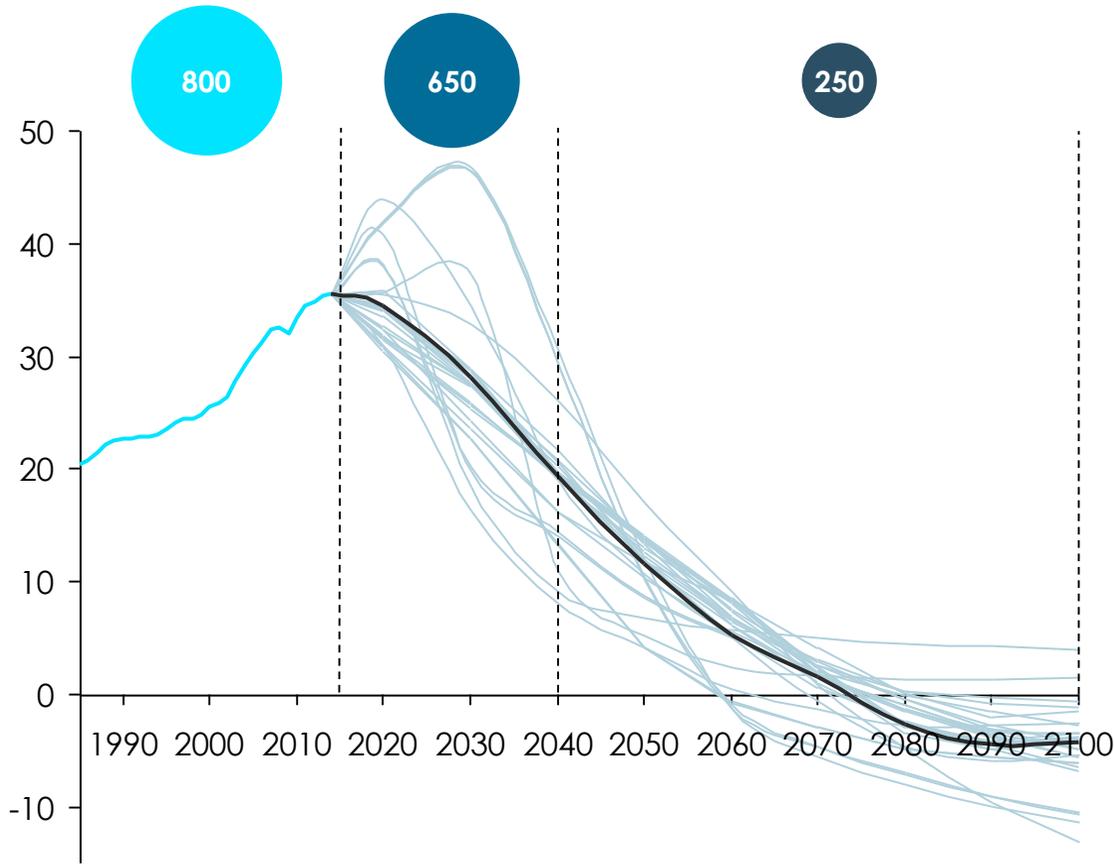


Source: Copenhagen Economics analysis based on IPCC (2013) WGI Summary for Policy Makers (quote from p. 27 of Summary); La Quéré (2014) Global carbon budget 2014

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

Emissions pathways for scenarios limiting warming to 2°C*

Billion tonnes CO₂



— Central scenario (median) **X** 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 to 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

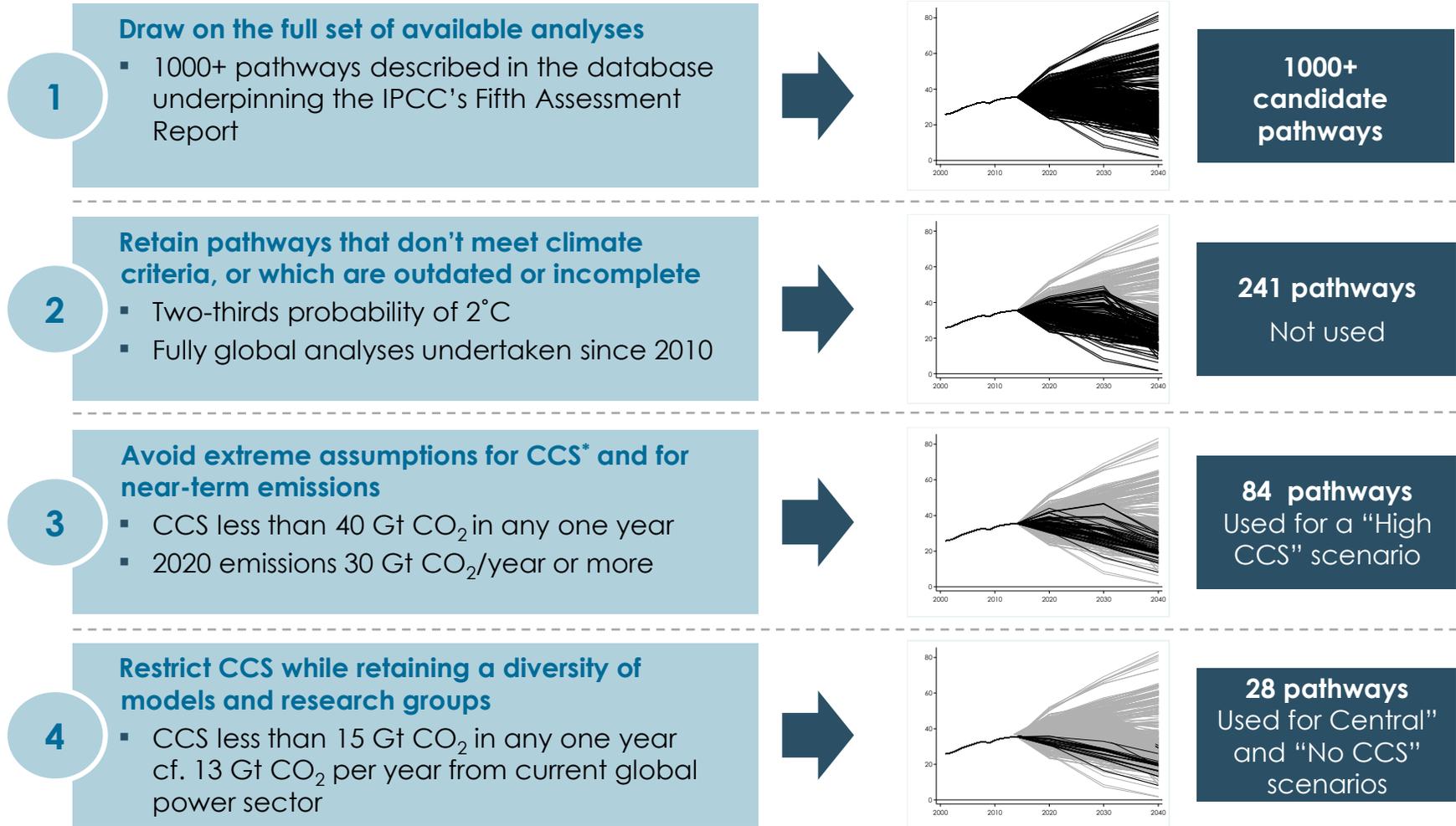
Note: * The figure shows 28 pathways consistent with limiting warming to 2°C, as well as other criteria.

Source: Copenhagen Economics analysis of data from AR5 database

Executive summary

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 to 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

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.

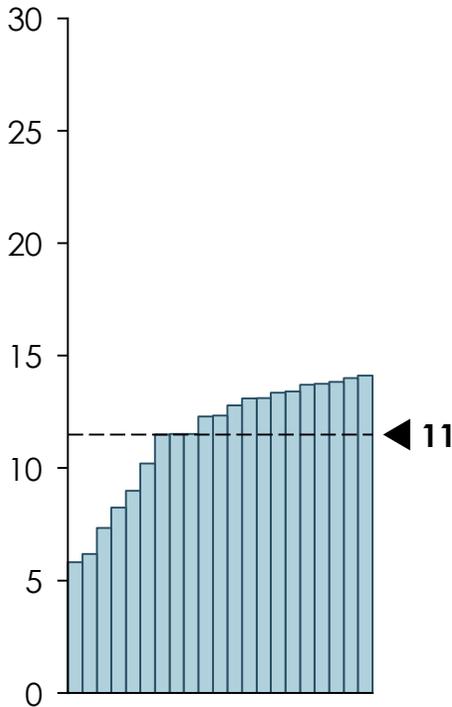
Notes: *Analyses of carbon capture in the scenarios used here refer to CCS – carbon capture and storage – and we therefore follow this nomenclature. It is in principle possible also to sequester carbon removed from the atmosphere through various forms of carbon utilisation.

We define three scenarios for fossil fuel use based on the maximum level of CCS used

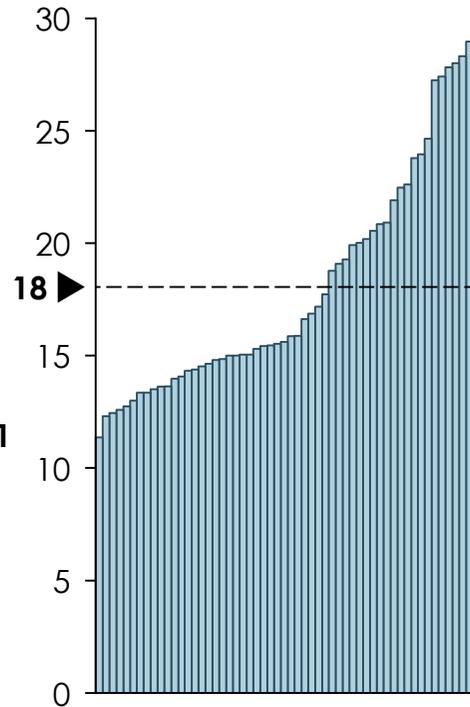
Average CO₂ capture from CCS on fossil fuels and bioenergy 2040-2100 in 2°C pathways

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 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. We avoid using these to analyse the future of fossil fuels in a 2°C scenario

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. 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.

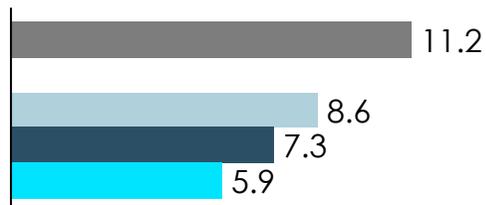
The level of fossil fuel use compatible with a 2°C scenario depends strongly on the level of feasible CCS assumed

Fossil fuel consumption in 2040, total and by fuel



Total fossil fuels

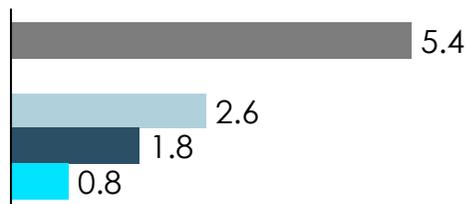
Billion tonnes oil eq. per year



- 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

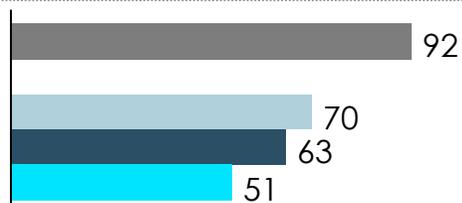
Billion tonnes coal eq. per year



- Coal use falls by two-thirds to 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

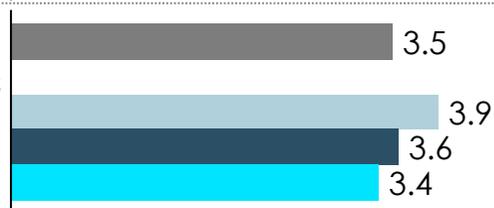
Million barrels per day



- 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



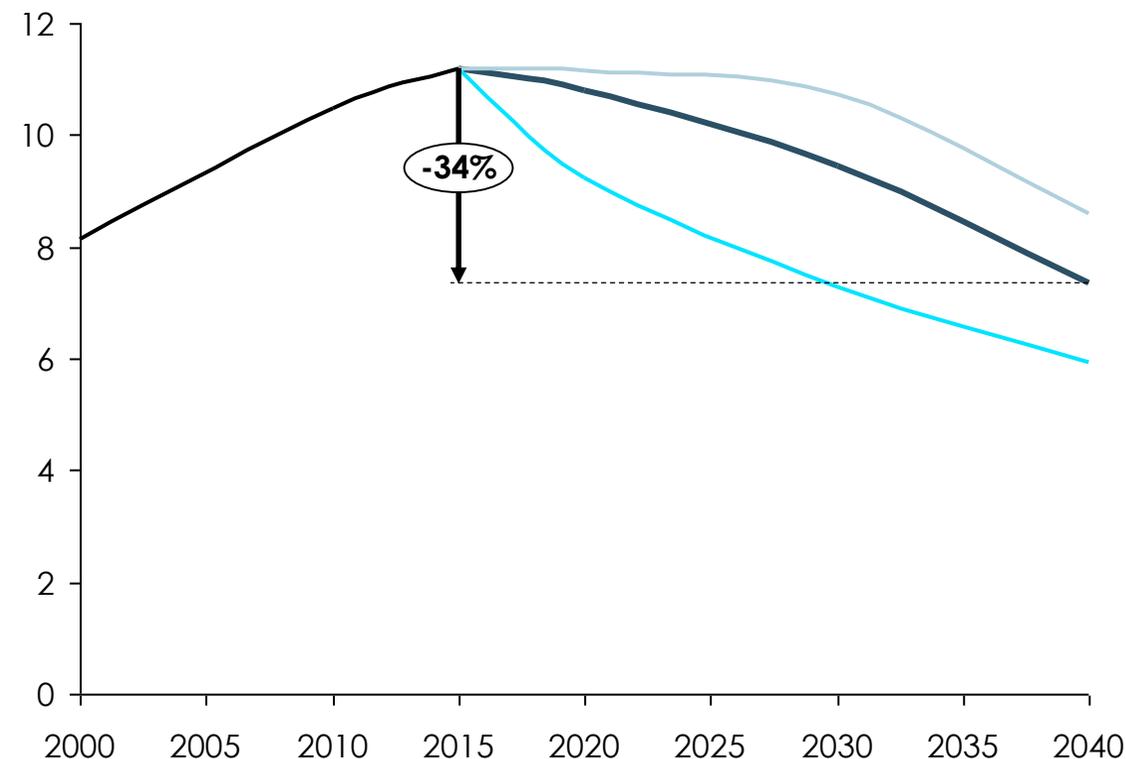
- Natural gas use to 2040 is not much affected by the level of CCS, but depends more on other factors.
- Effects are greater after 2040, where some pathways see continued natural gas consumption at ~3.5 tcm per year, supported by >10 Gt CCS/year.

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.

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 current levels

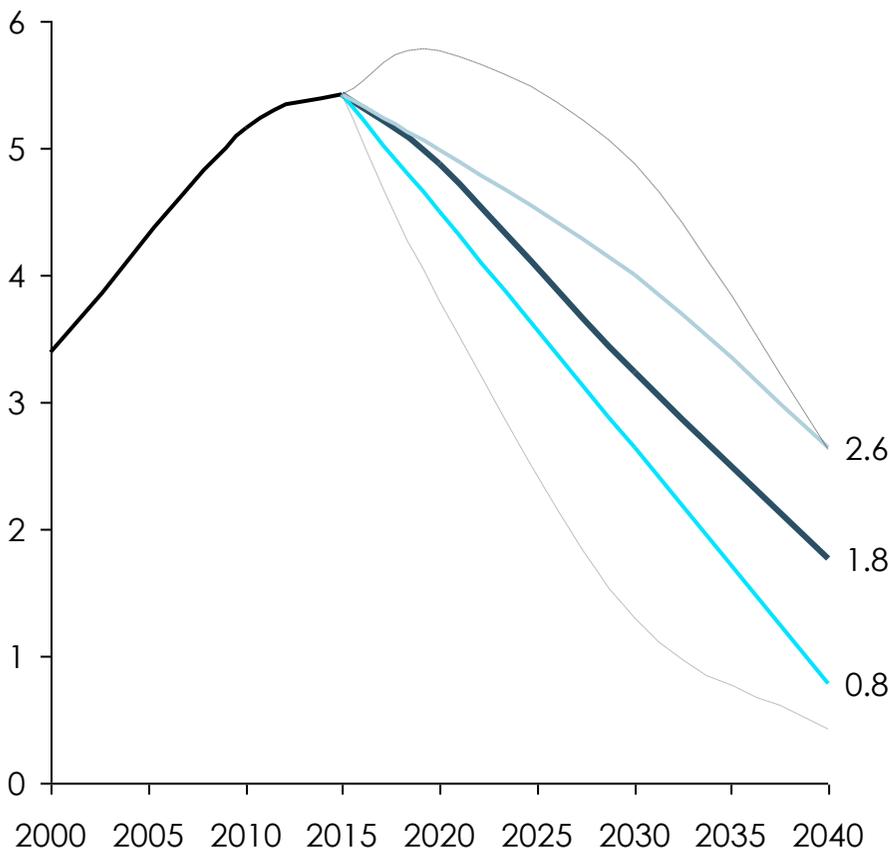
Notes: *In the central and high CCS scenarios, CO₂ removal needs increase significantly beyond 2040 to remain within 2°C. The “Central CCS” scenario is based on scenarios limiting the risk of a global temperature rise of more than 2 degrees to less than one third, with 2020 emissions of at least 30 GtCO₂ and with no more than 15 Gt CO₂ 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

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

Coal consumption, all sectors

Billion tonnes coal equivalent



— Central scenario — High CCS
— No CCS scenario - - - Central 50% of pathways

- 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

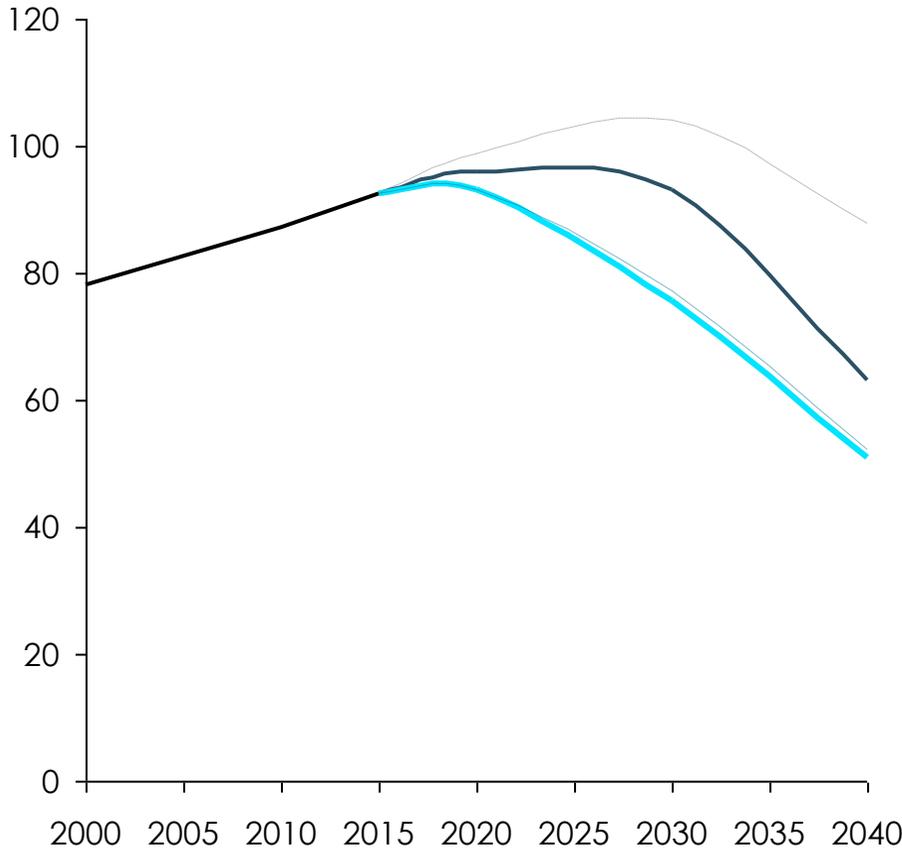
Note: Percentiles (dashed lines) are 25th and 75th percentile values in analysed set of AR5 database scenarios.
 Source: Historic data from BP; future scenarios from Copenhagen Economics analysis of AR5 database as described in appendix

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

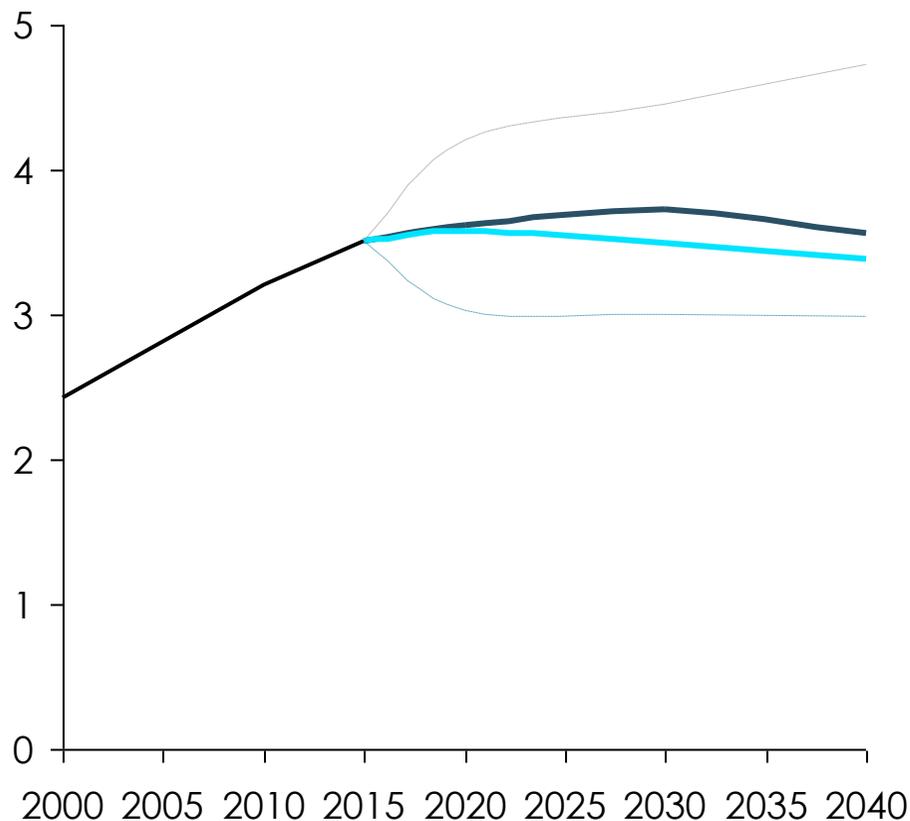
Note: Percentiles (dashed lines) are 25th and 75th percentile values in analysed set of AR5 database scenarios.
 Source: Historic data from BP; future scenarios from Copenhagen Economics analysis of AR5 database as described in appendix

Natural gas consumption stays roughly level to 2040 and is relatively unaffected by CCS/U 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

Executive summary

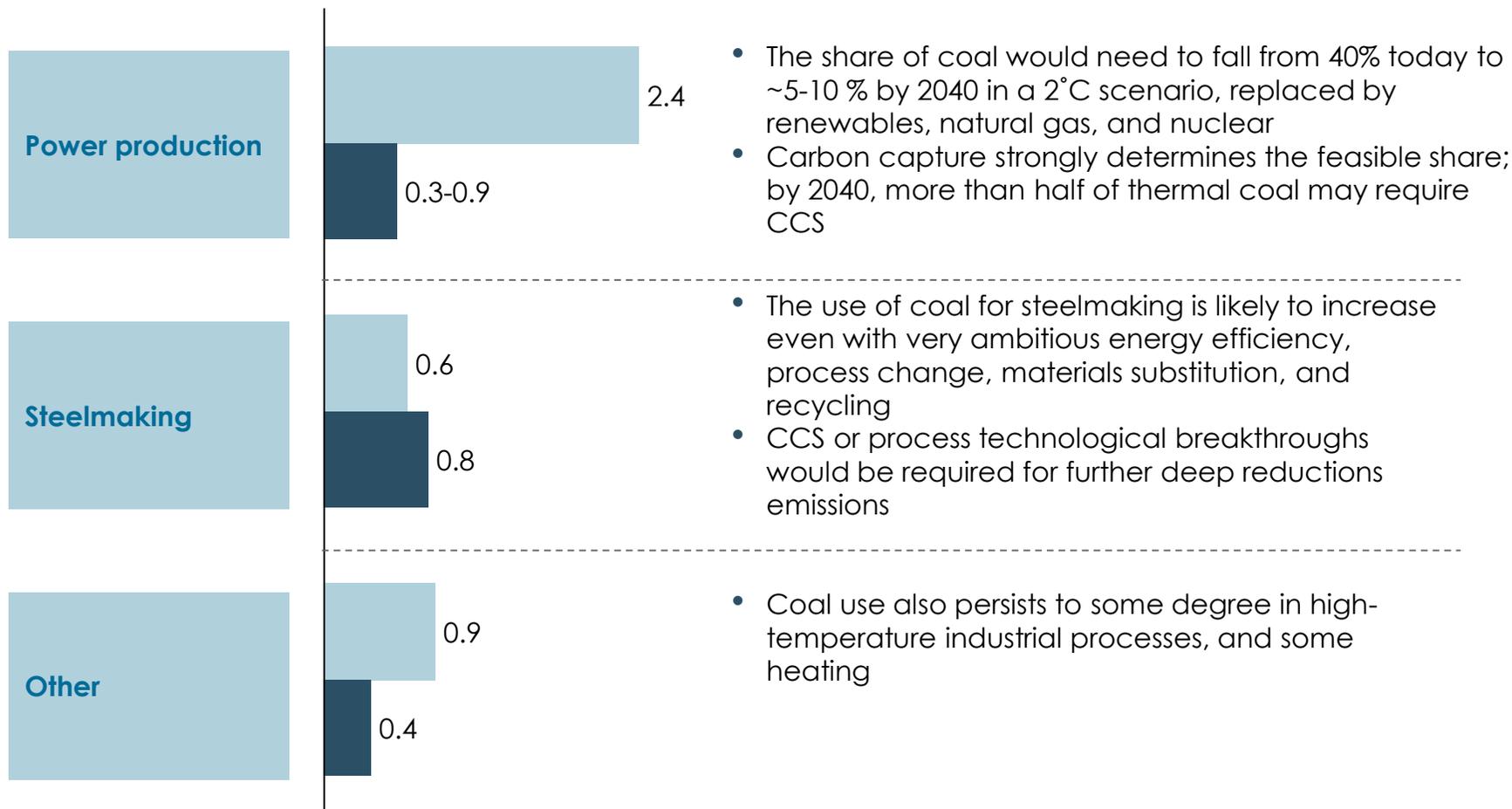
1. Rapidly growing energy needs set the scene for an energy transition
2. A 2°C objective implies a strict carbon budget
3. Fossil fuel use would fall by one-third to 2040 to meet 2°C objectives
- 4. The role of fossil fuels changes by 2040 in a 2°C energy system**
5. A 2°C energy transition has profound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

Coal is still used as a feedstock in industry; its use as a fuel in power production falls significantly

2013 2040

Coal consumption, illustrative scenario

Billion tonnes of oil equivalent



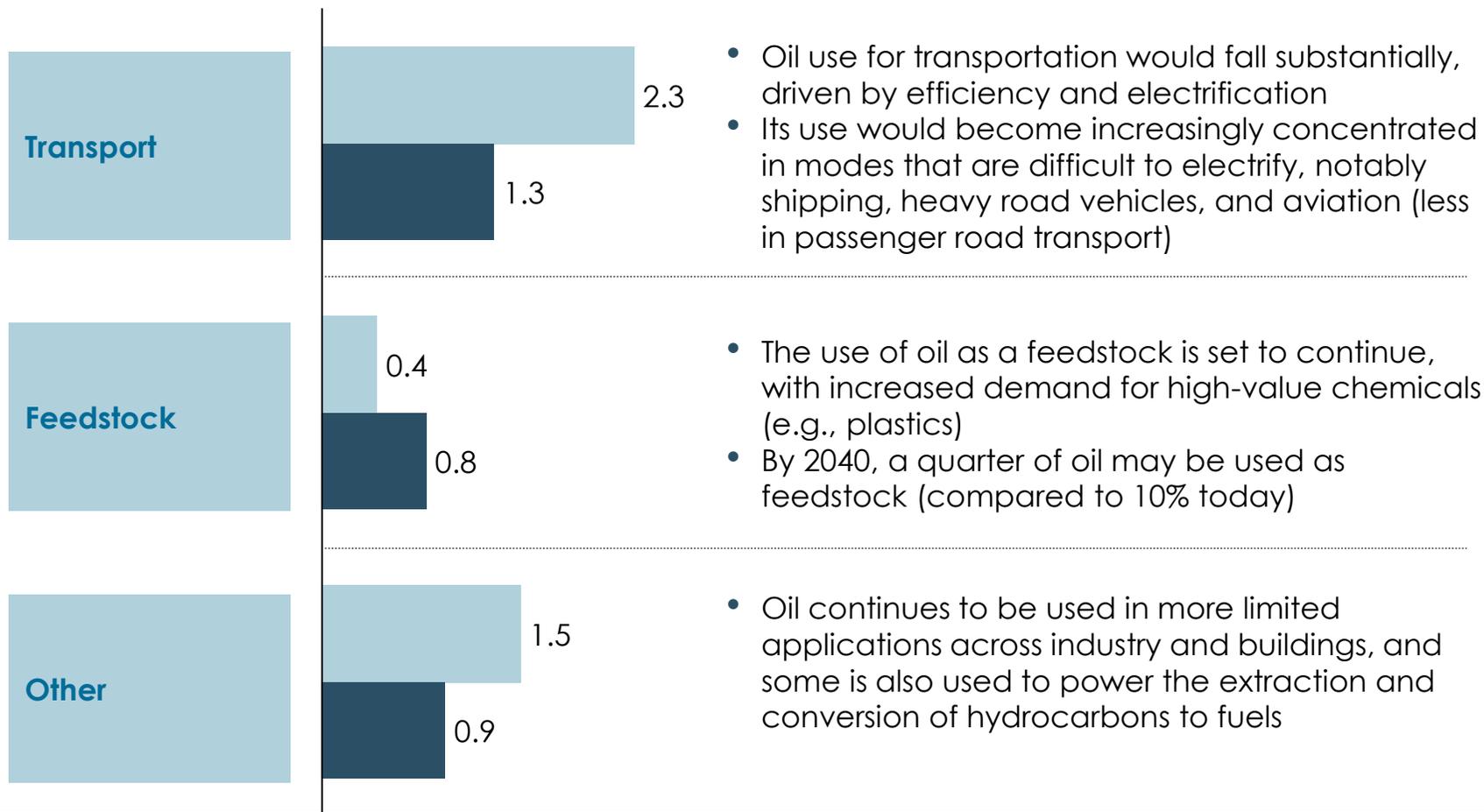
Source: Copenhagen Economics analysis

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

2013 2040

Oil consumption, illustrative scenario

Billion tonnes of oil equivalent



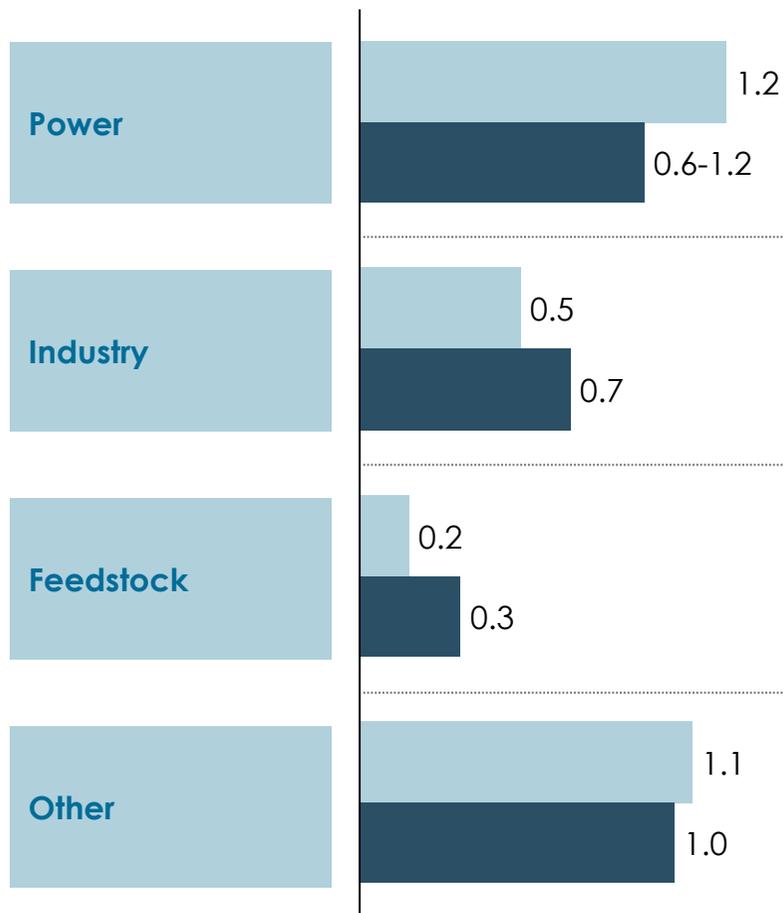
Source: Copenhagen Economics analysis

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



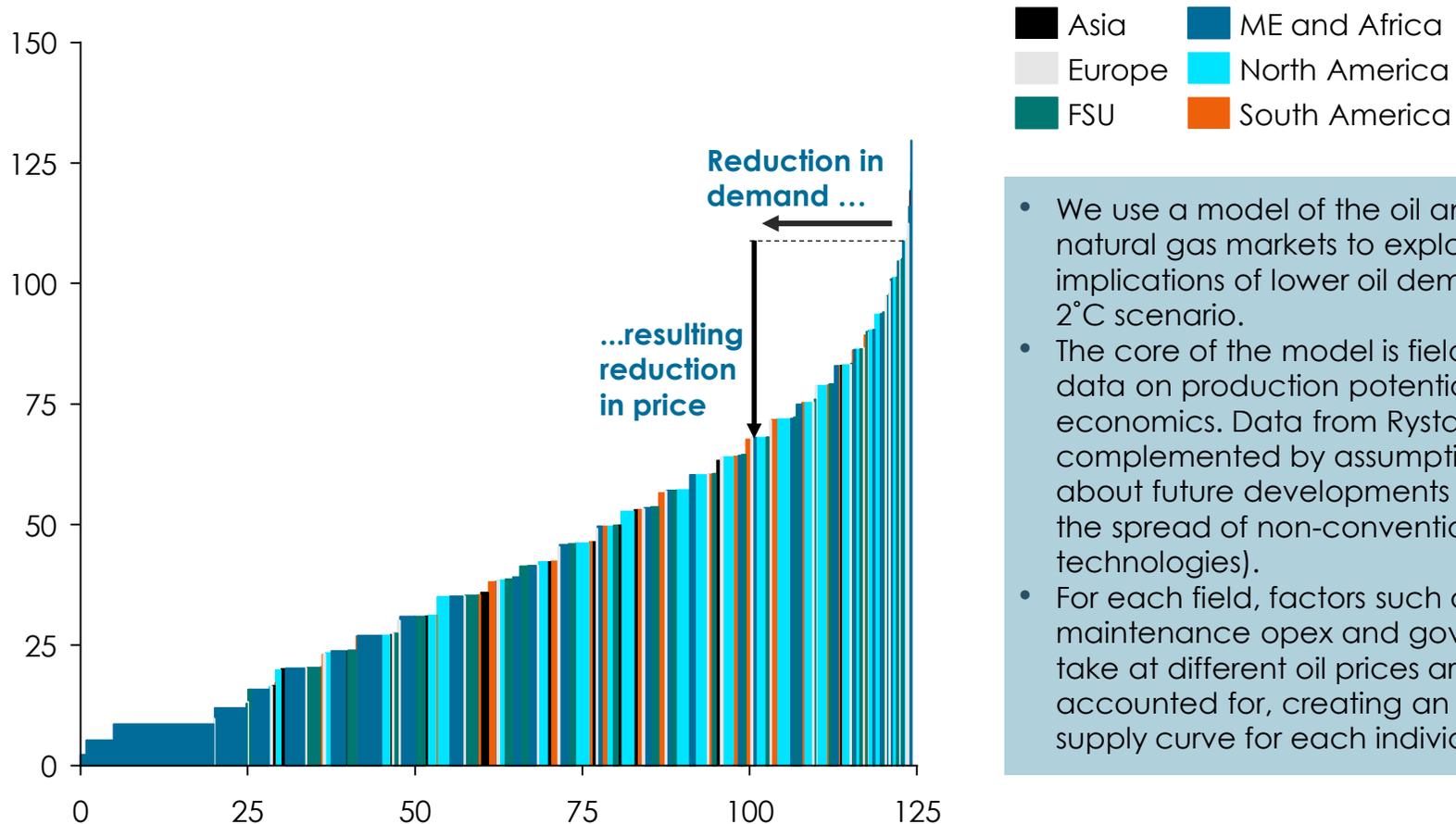
- Power generation from natural gas may be 10-15% of power generation in 2040
- Carbon capture may lead to a lower gas share, by enabling a higher share of coal; however, 40-50% of natural gas plants may also need to use CCS
- Much of the remaining gas is used in industry, where it may increase in absolute terms as a clean fuel and substitute for coal in high-temperature applications
- The use of gas as a feedstock will increase, driven by increasing demand for chemicals (e.g., fertilisers)
- 10% of natural gas may be used as feedstock by 2040, as compared to around 5% today
- Gas use in buildings depends on the feasibility of energy efficiency improvements, renewables, and electrification
- Gas use could also increase in transport, but emissions gains depend on low end-to-end methane leakage

Source: Copenhagen Economics analysis

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



- 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)

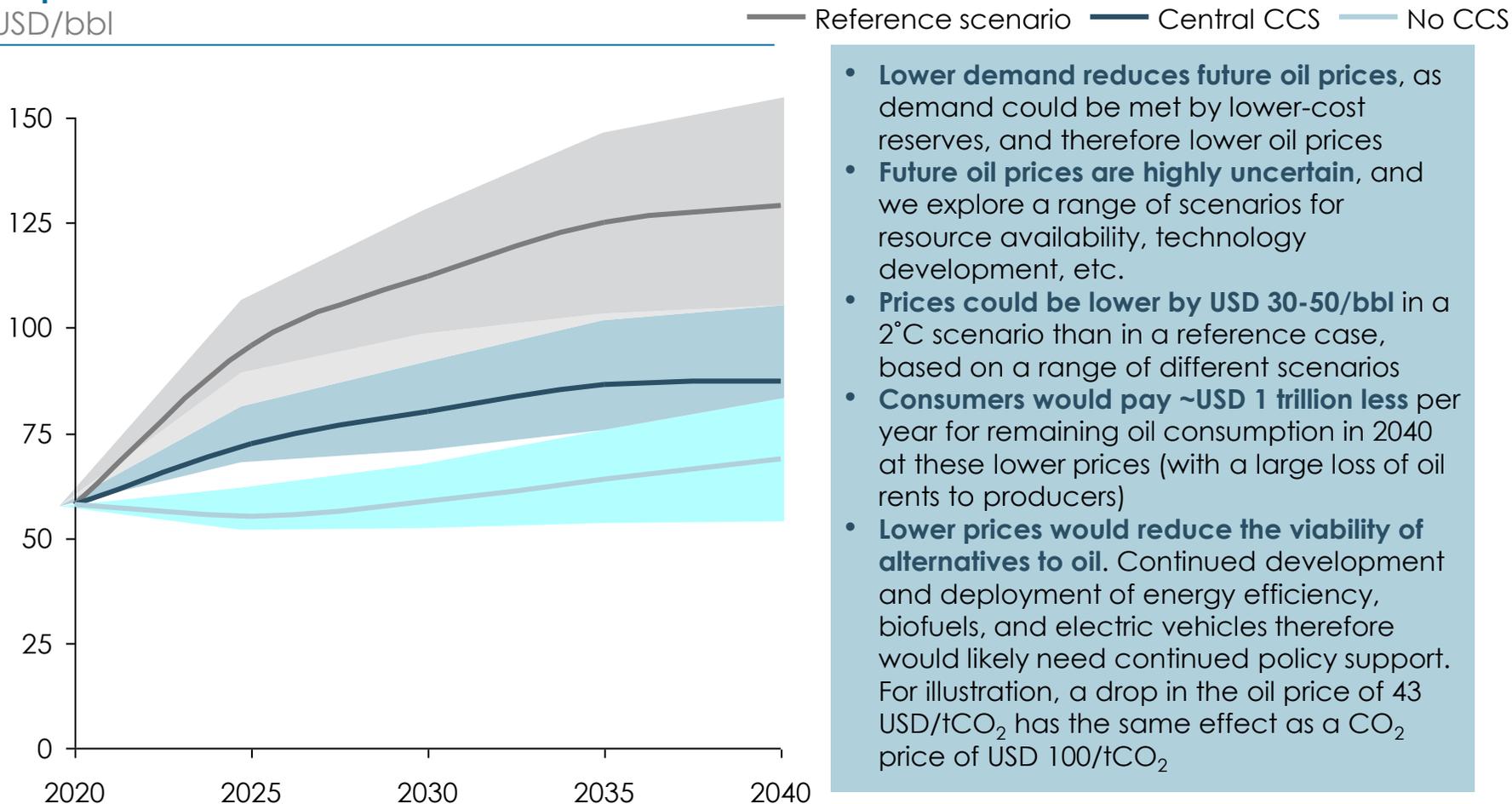
Executive summary

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 to 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

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



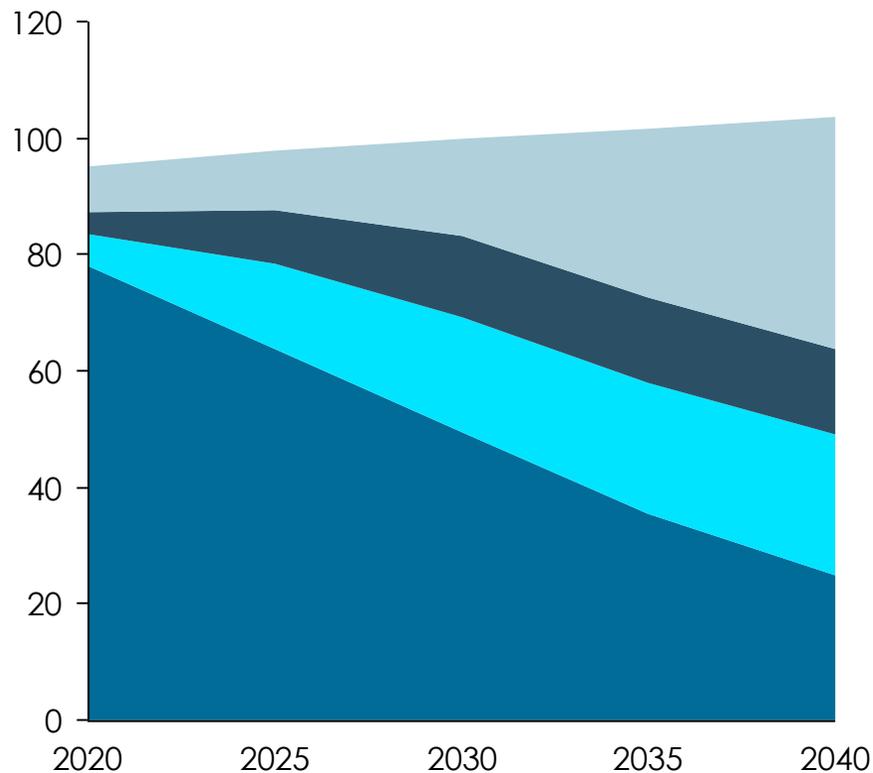
- **Lower demand reduces future oil prices**, as demand could be met by lower-cost reserves, and therefore lower oil prices
- **Future oil prices are highly uncertain**, and we explore a range of scenarios for resource availability, technology development, etc.
- **Prices could be lower by USD 30-50/bbl** 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 c. 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

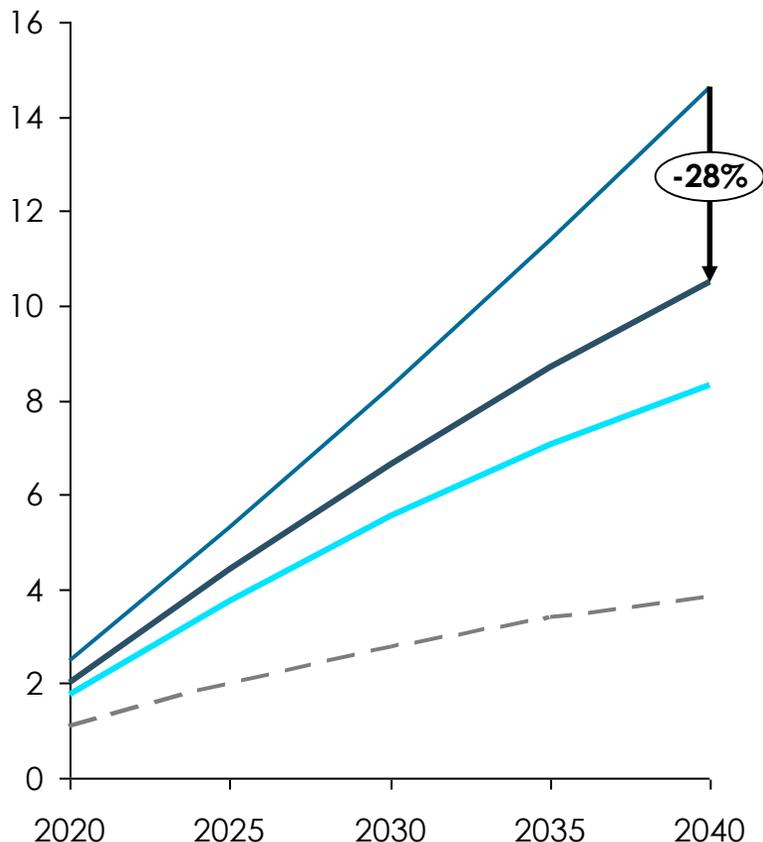
Note: “Existing fields” include fields currently producing and under development. Decline rates are calculated for the rate of investment that can be supported by prevailing oil prices as estimated by the model.

Source: Copenhagen Economics oil market model; Rystad data

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 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 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)

Executive summary

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 to 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**

Carbon capture affects the carbon budget in two ways

Effect on carbon budget

Key potential applications

Fossil fuels



- 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

- 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

Bioenergy



- 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

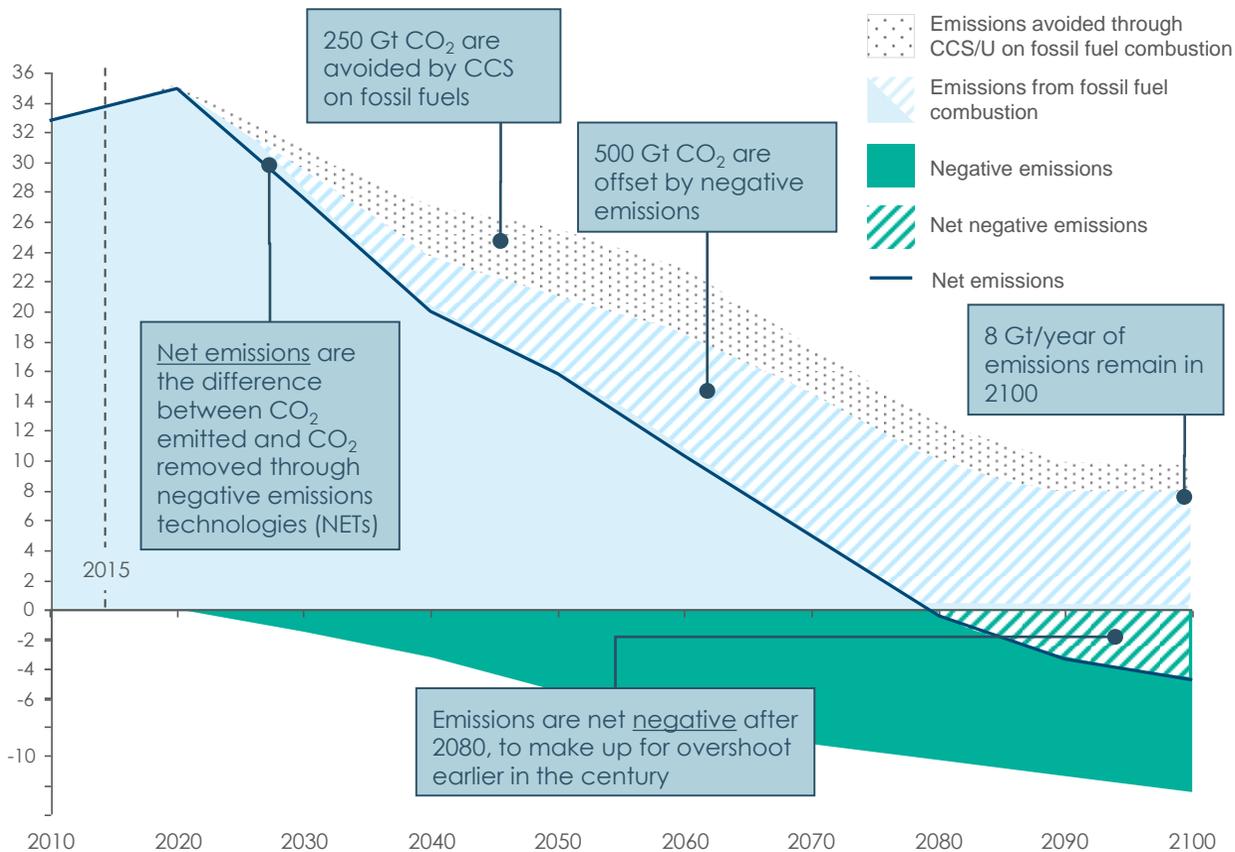
- Potential uses in power plants and other large point sources, such as industry.
- Largely speculative: one operational plant.

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

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 CCS/U 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

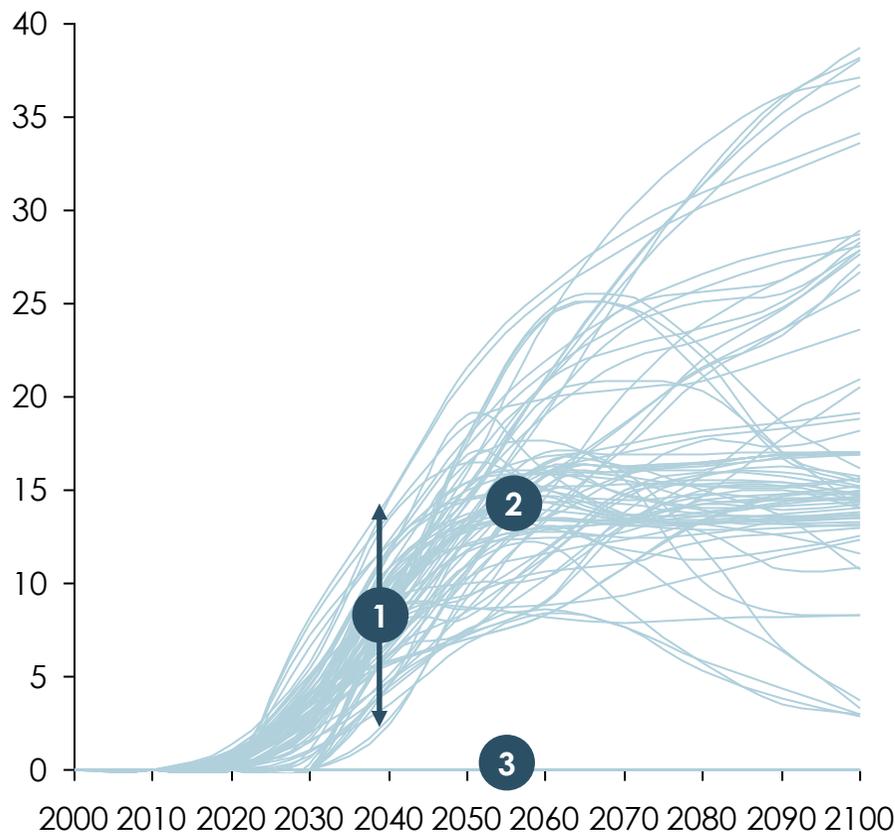
Notes: * The Central CCS scenario is the median of 28 scenarios which do not see CCS exceed 15 Gt CO₂ per year in any year up to 2100.

Source: Copenhagen Economics analysis of data from AR5 database.

CO₂ capture is a key factor already by 2040, and grows even larger thereafter 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
 - “negative emissions” help reduce the demands of a very stringent carbon budget, and
 - models tend to favour solutions in the far future (whose costs are “discounted”)
- The volume of CCS therefore quickly becomes very large:
 - In 2040, CCS volumes already are 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
 - CCS grows still larger thereafter. Scenarios cluster around 12-15 Gt CO₂, and very few scenarios meet foresee less than 10 Gt CO₂ per year. Although scenarios differ, most of this is for BECCS (see below)
 - 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.

CCS faces challenges of scale, infrastructure, and cost; the Central scenario with 7+ Gt CO₂ is therefore 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.