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).

The paper has contributed to the ETC's report Better Energy, Greater Prosperity available on the ETC website.

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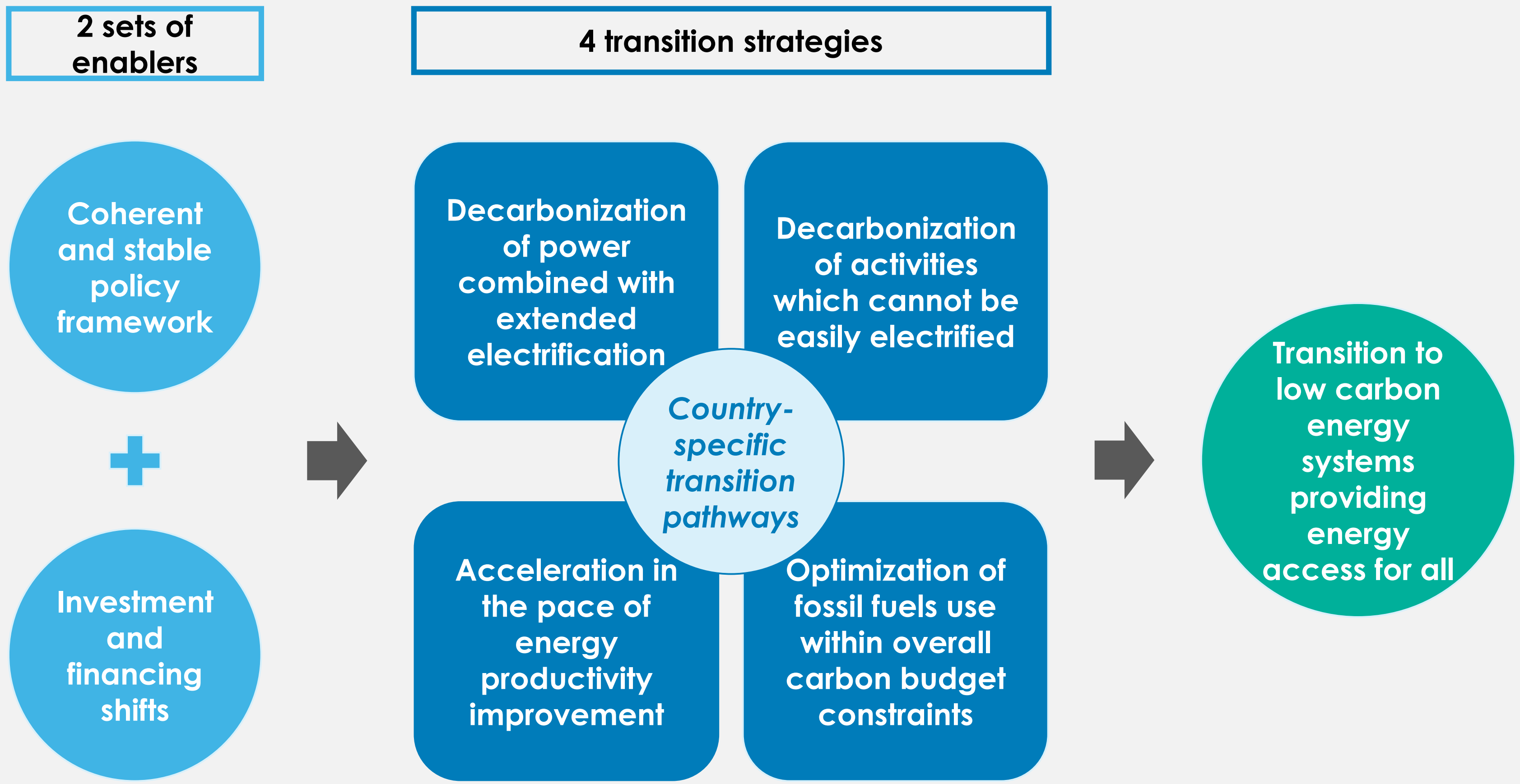
This research paper supports the work of the ETC by analyzing fossil fuels trajectories in low carbon scenarios

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

Summary report

January 2017

Content

Executive summary (1/3)

1. Energy needs are growing fast. Absent a profound energy transition, CO_2 emissions would increase by 50-70% by 2040, to 50-60 billion tonnes CO_2 per year.

- Population and GDP are likely to grow by ~20% and ~90%, respectively by 2040.
- 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 therefore 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 CO_2) until 2100. Achieving this requires that current emissions of 36 Gt CO_2 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 CO_2 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 CO_2 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 and sequestration through storage or transformation into CO_2-based products (CCS*); we define three CCS 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 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.

* For simplicity, CCS is used to capture CO_2 capture and sequestration through storage or through transformation into CO_2-based products.

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 due to natural decline of existing production.

- For oil, prices may fall from USD 90-120/bbl in a reference case, to 50-80/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 and sequestration of CO_2 (CCS) plays a major role in pathways to limit warming to 2°C, with eventual volumes of 10 or even 20 Gt CO_2 per year. This would require a step-change even as other options also are pursued: bioenergy, process change, and hydrogen in industry; renewable energy in power; and alternative forms of "negative emissions" technologies.

- In many pathways, CCS volumes reach 10 Gt/year by 2040, and approach 20+ Gt thereafter.
- We base our analyses of future fossil fuel use on a lower 7 Gt by 2040 and 11 Gt thereafter, but also analyse the implications of no CCS, or of still higher volumes.
- Achieving 7 Gt requires urgent development across scale, infrastructure, and cost:
  - Scale: more than two new plants each week to 2040.
  - Infrastructure: CO_2 volumes similar to current total oil and natural gas production.
  - Cost: a strong and predictable carbon price to overcome higher costs
- CCS is integral to most visions for "net zero" emissions in the long run, with "negative emissions" (often, CCS with bioenergy) offsetting residual emissions from fossil fuel use.

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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

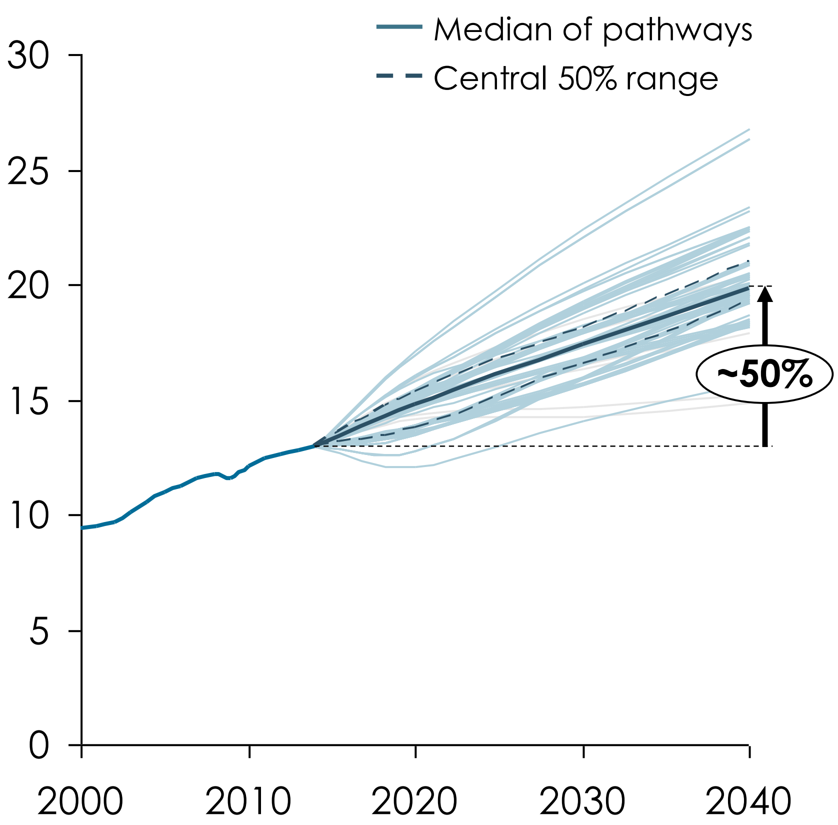
5. A 2°C energy transition has profound impacts on fossil fuel markets

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.

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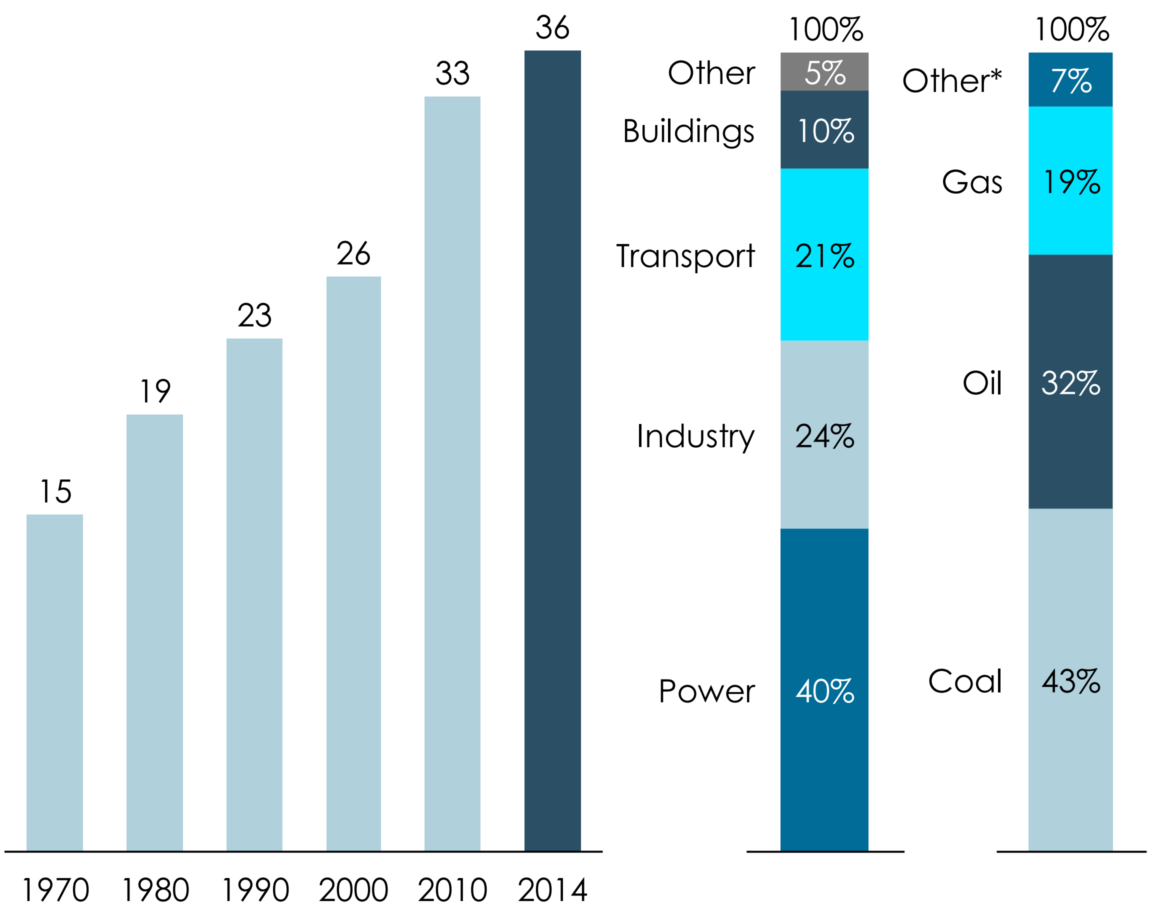
Today's energy system is based on fossil fuels and therefore carbon intensive, producing 36 billion tonnes CO_2 per year

CO_2 emissions from fossil fuel combustion and industrial processes

Billion tonnes per year; % of total



- Emissions today are 36 Gt CO_2, 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 CO_2.
- 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) CO_2 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 CO_2 emissions: 2015 report.

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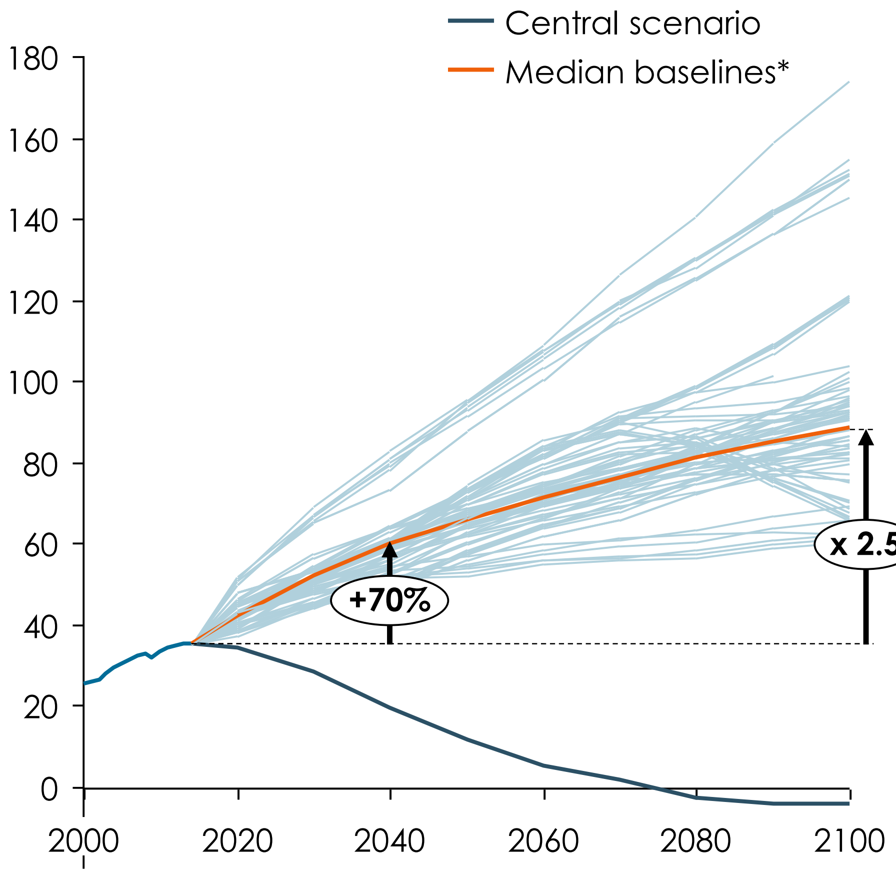
Without an energy transition, CO_2 emissions could eventually rise to 2-3 times current levels

Carbon dioxide emissions, baseline scenarios

Billion tonnes CO_2 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 CO_2 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 CO_2 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

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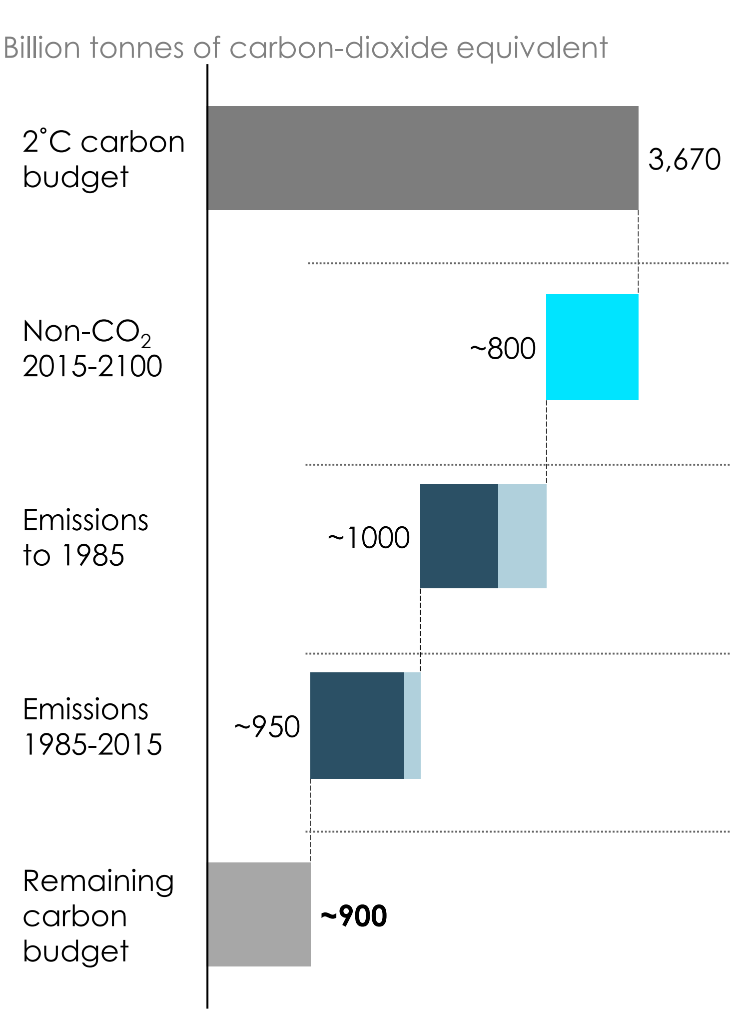
The remaining "carbon budget" for 2˚C warming is less than 900 Gt CO_2, similar to emissions in the past three decades



- *"Limiting the warming caused by anthropogenic CO_2 emissions alone with a probability of [...] >66% to less than 2 ˚ C since the period 1861–1880, will require cumulative CO_2 emissions from all anthropogenic sources to stay between 0 and [..] 3670 $GtCO_2$ since that period"* (IPCC, 2013)
- Other greenhouse gases (GHG), notably methane and nitrous oxides, reduce the available CO_2 budget by ~800 billion tonnes, according to IPCC estimates
- The first two centuries of industrialisation resulted in CO_2 emissions of ~1000 billion tonnes, with a large share of early emissions from land-use change
- Emissions during the last 30 years amounted to ~950 billion tonnes, of which ~90% arose from fossil fuel combustion and industrial processes
- The remaining 2˚C carbon budget for this century is 850-900 Gt, less than the amount emitted in the past 30 years, and corresponding to 25 years of emissions at current rate

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

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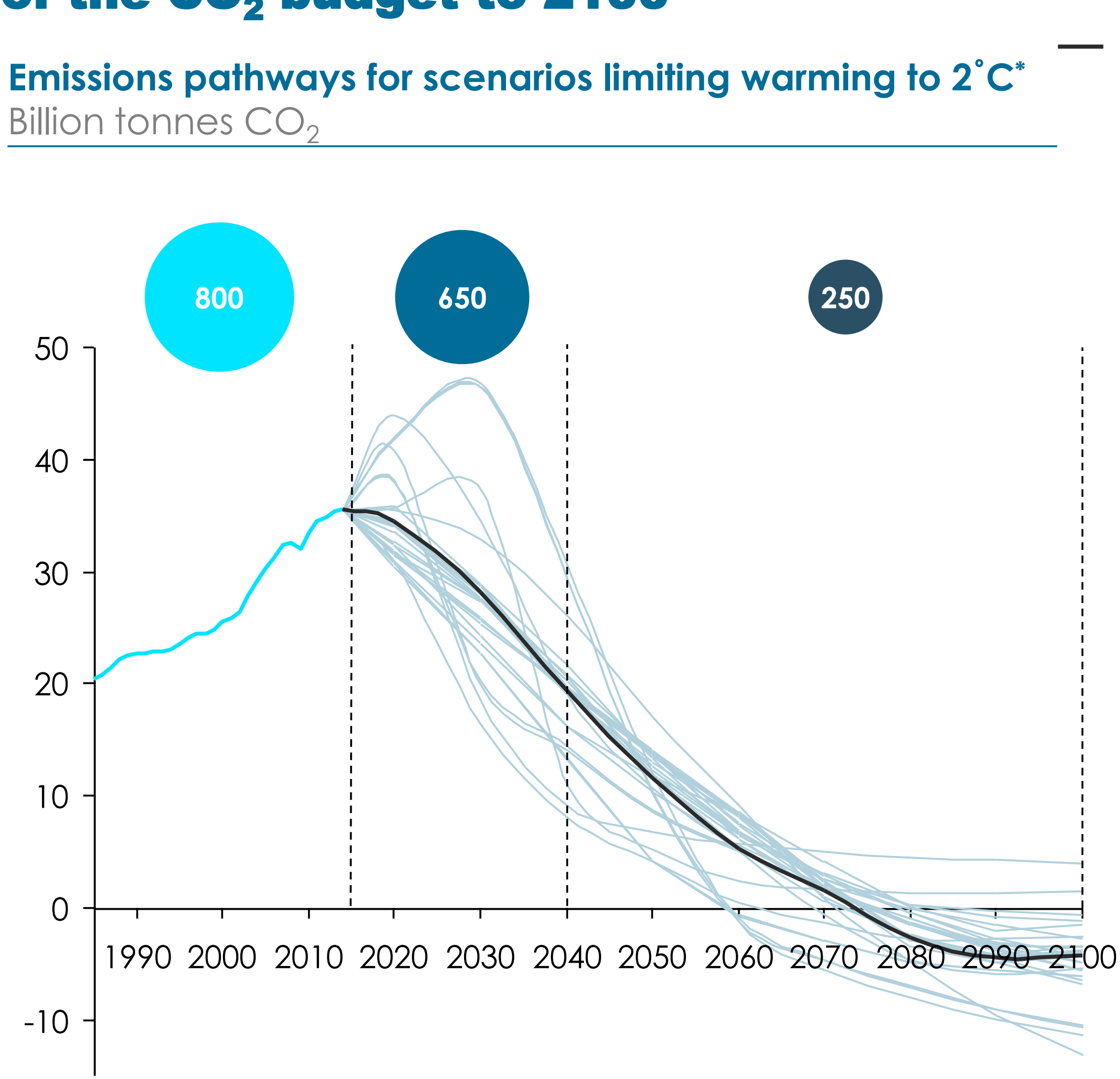
Even in a 2° C scenario, 650 Gt CO_2 could be emitted to 2040, ~75% of the CO_2 budget to 2100

Emissions pathways for scenarios limiting warming to 2˚C*

Billion tonnes CO_2



- 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 CO_2, 2016-2040, corresponding to ~75% of the total remaining carbon budget
- The remaining ~250 Gt CO_2 available to 2100 imply annual average emissions of 4 Gt CO_2 per year, one-tenth of current levels
- Keeping emissions to these levels may require emissions to become "net negative" through technologies that remove CO_2 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

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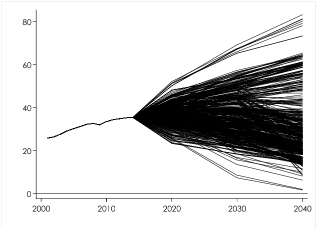
We limit our analysis to scenarios that meet climate objectives and avoid aggressive levels of carbon capture

1

Draw on the full set of available analyses

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

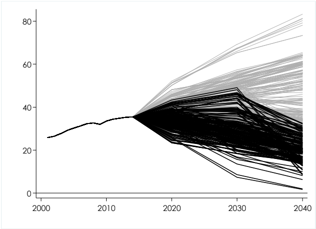


1000+ candidate pathways

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



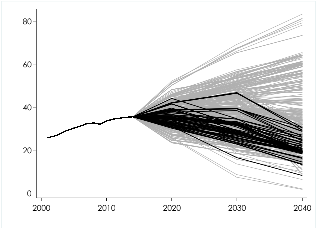
241 pathways

Not used

3

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

- CCS less than 40 Gt CO_2 in any one year
- 2020 emissions 30 Gt CO_2/year or more



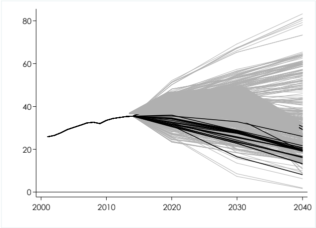
84 pathways

Used for a "High CCS" scenario

4

Restrict CCS while retaining a diversity of models and research groups

- CCS less than 15 Gt CO_2 in any one year cf. 13 Gt CO_2 per year from current global power sector



28 pathways

Used for Central" and "No CCS" scenarios

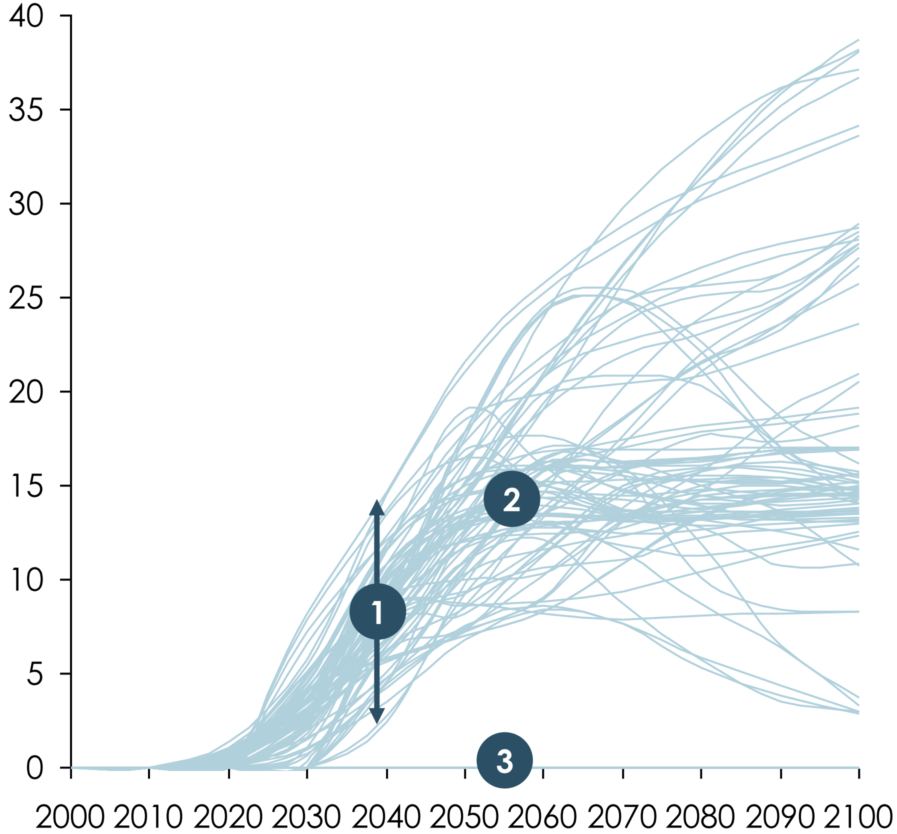
Source: Copenhagen Economics analysis of data from AR5 database.

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*.

CO_2 capture and sequestration (CCS) is a key factor already by 2040, with continued growth to balance the carbon budget

CO_2 capture through CCS in 2˚C scenarios

Gt CO_2 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 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
  2. CCS grows still larger thereafter. Scenarios cluster around 12-15 Gt CO_2, and very few scenarios foresee less than 10 Gt CO_2 per year. Although scenarios differ, most of this is for BECCS.
  3. Only 7 out of 84 pathways meet energy and climate needs entirely without CCS

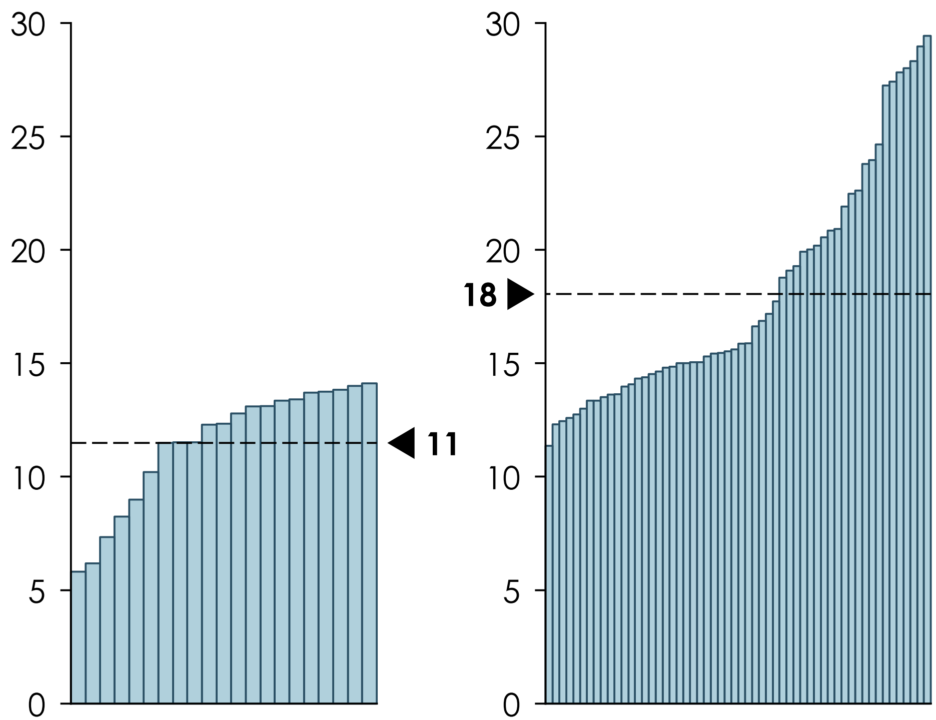
Notes: Total CO_2 captured per year through CCS in 84 AR5 scenarios.
Source: Copenhagen Economics analysis of data from AR5 database.

We define three scenarios for fossil fuel use based on the maximum level of CO_2 capture and sequestration used

Average CO_2 capture from CCS on fossil fuels and bioenergy 2040-2100 in 2˚C pathways

Gt CO_2 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 CO_2. Most see high CCS deployment, with an average across pathways of 11 Gt CO_2 per year, 2040-2100
- **High CCS:** 56 scenarios where CCS eventually reaches levels between 15-40 Gt CO_2 per year, with an average value of 18 Gt CO_2 per year, 2040-2100.

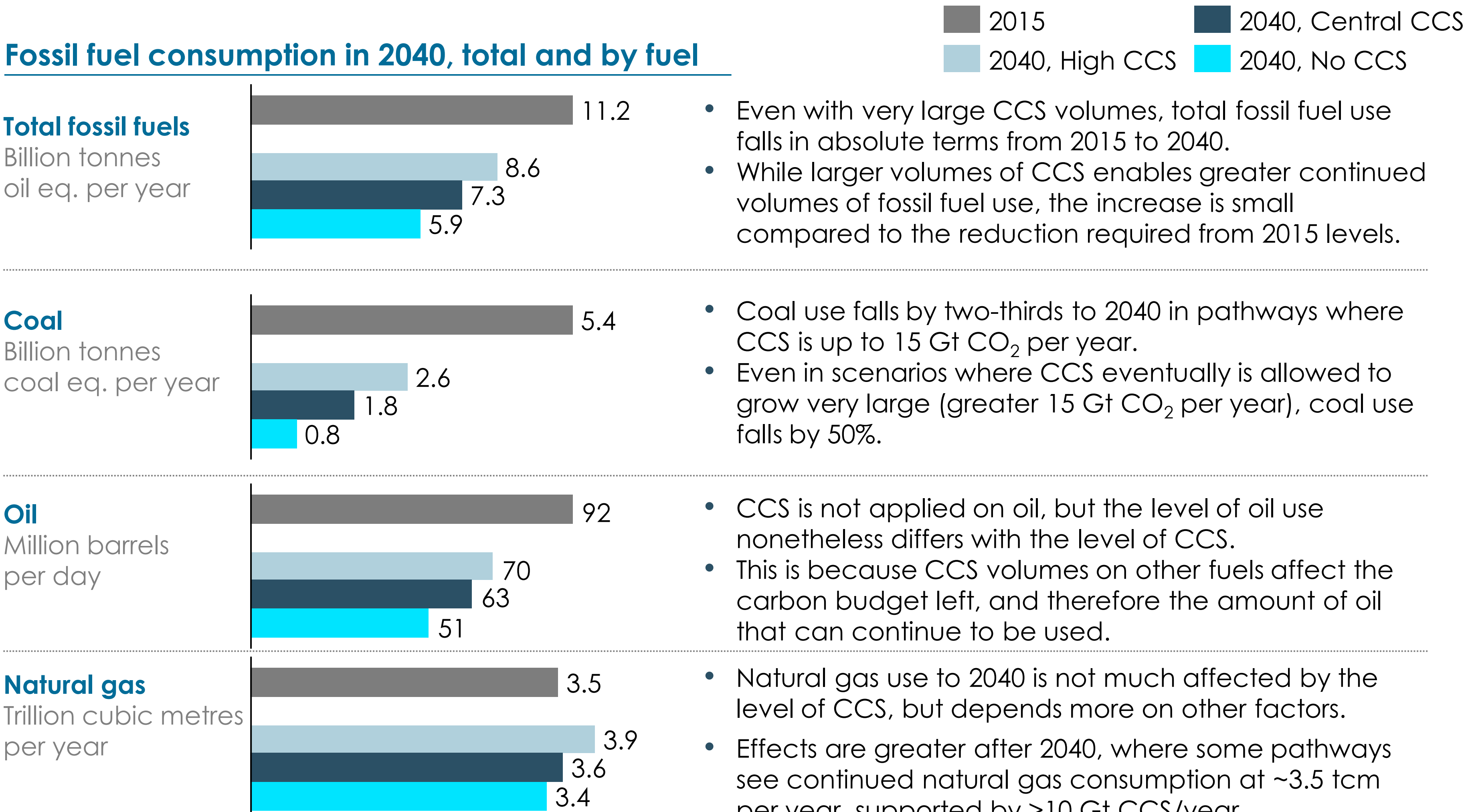
The future fossil fuels use trajectories presented later on are based on the central CCS scenarios.

Note: We restrict analyses to scenarios with no more than 40 Gt CO_2 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 CO_2 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



- 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 use falls by two-thirds to 2040 in pathways where CCS is up to 15 Gt CO_2 per year.
- Even in scenarios where CCS eventually is allowed to grow very large (greater 15 Gt CO_2 per year), coal use falls by 50%.

- 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 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.

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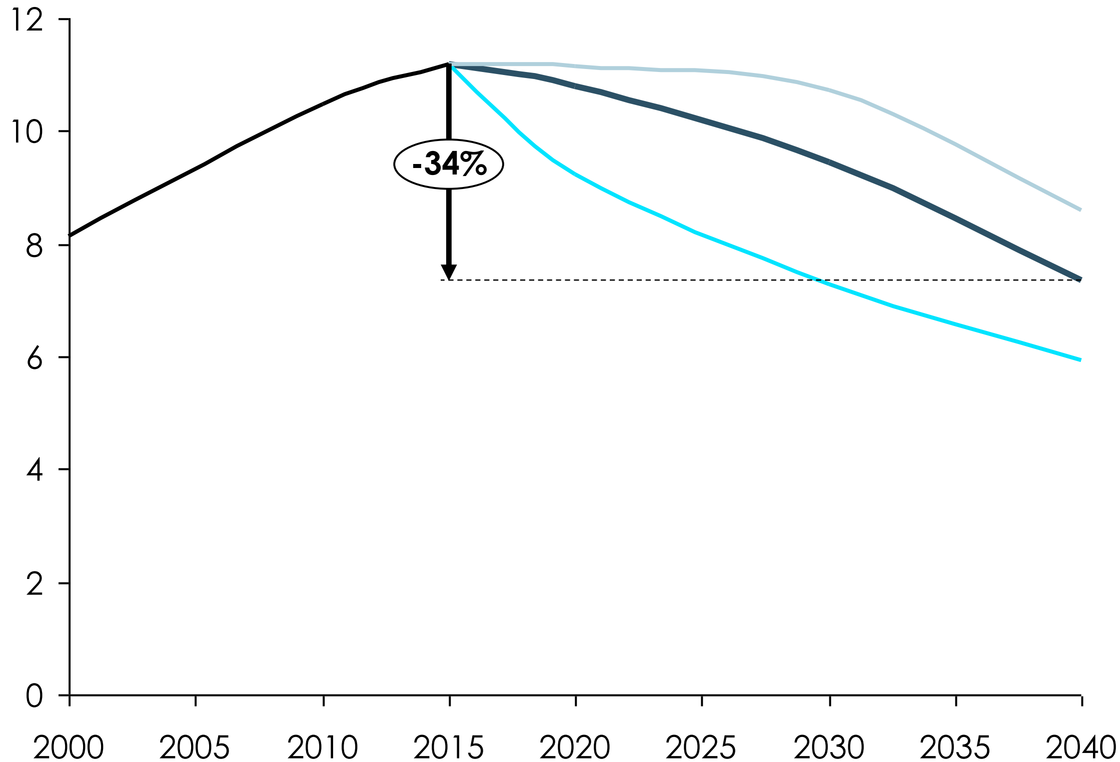
* For simplicity, CCS is used to capture CO_2 capture and sequestration through storage or through transformation into CO_2-based products.

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 CO_2 capture, 2040 and 2040-2100

Billion tonnes CO_2 per year

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

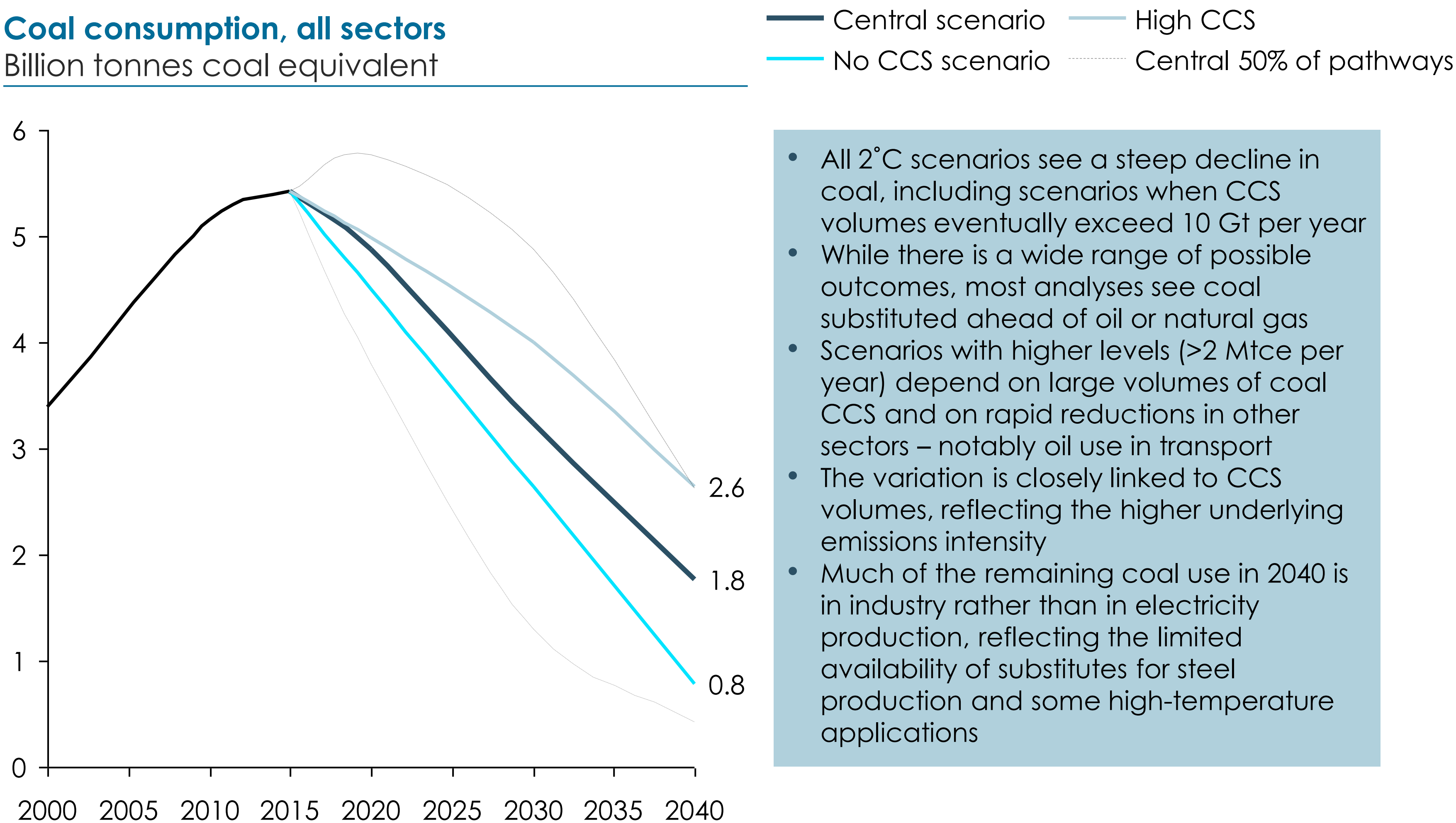
- "Central CCS" implies large future capture volumes, similar to the emissions from current global power production (13 Gt CO_2)
- "No CCS" requires 2040 fossil fuel use to fall to half current levels

Notes: *In the central and high CCS scenarios, CO_2 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 $GtCO_2$ and with no more than 15 Gt CO_2 removal from CCS in any given year. The "No CCS" scenario fulfils the same criteria as the Central scenario but has no CO_2 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/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

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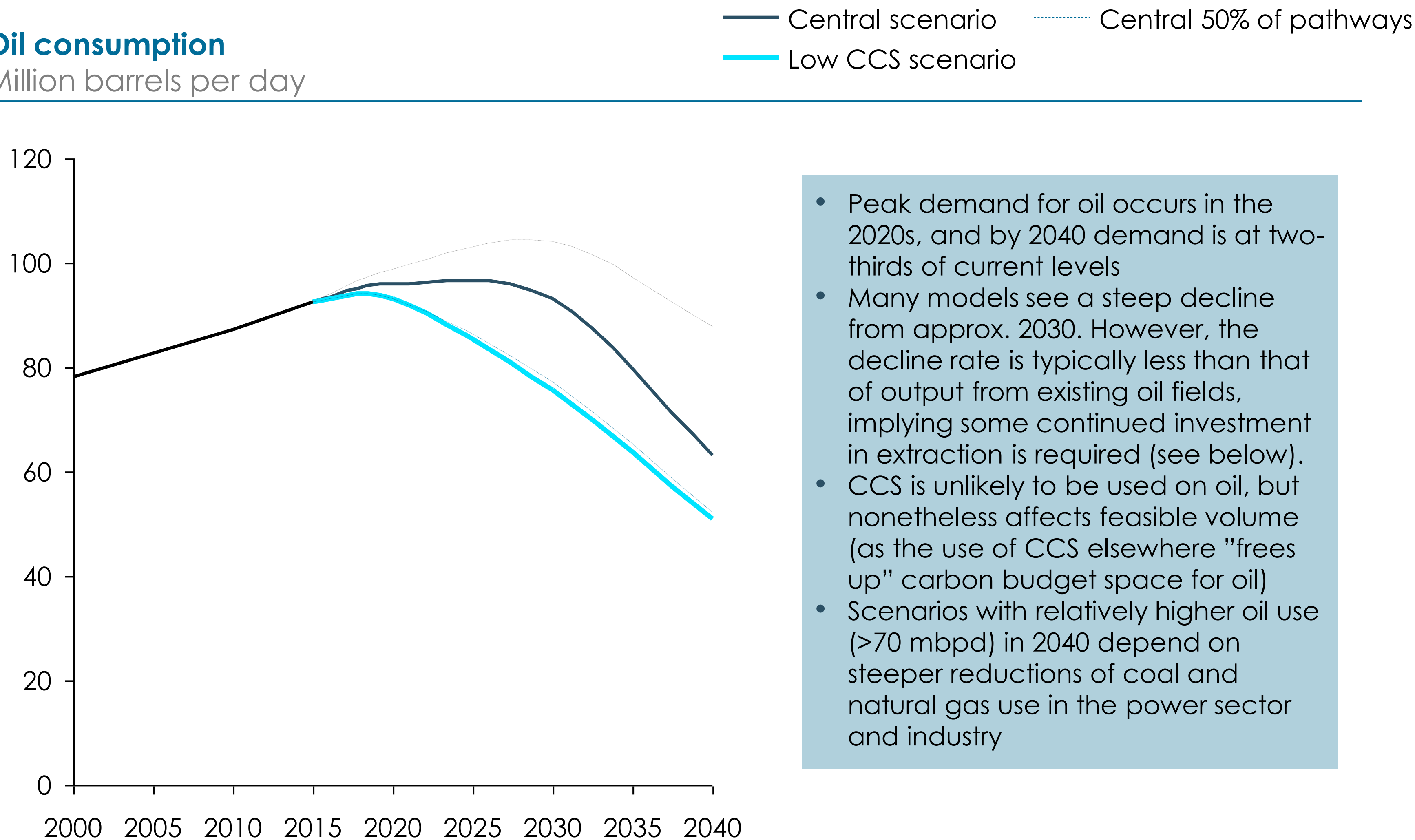
Oil may keep rising into the 2020s before falling by >30% below today's level in 2040; without CCS/CCU, demand must fall by 45%

Oil consumption
Million barrels per day

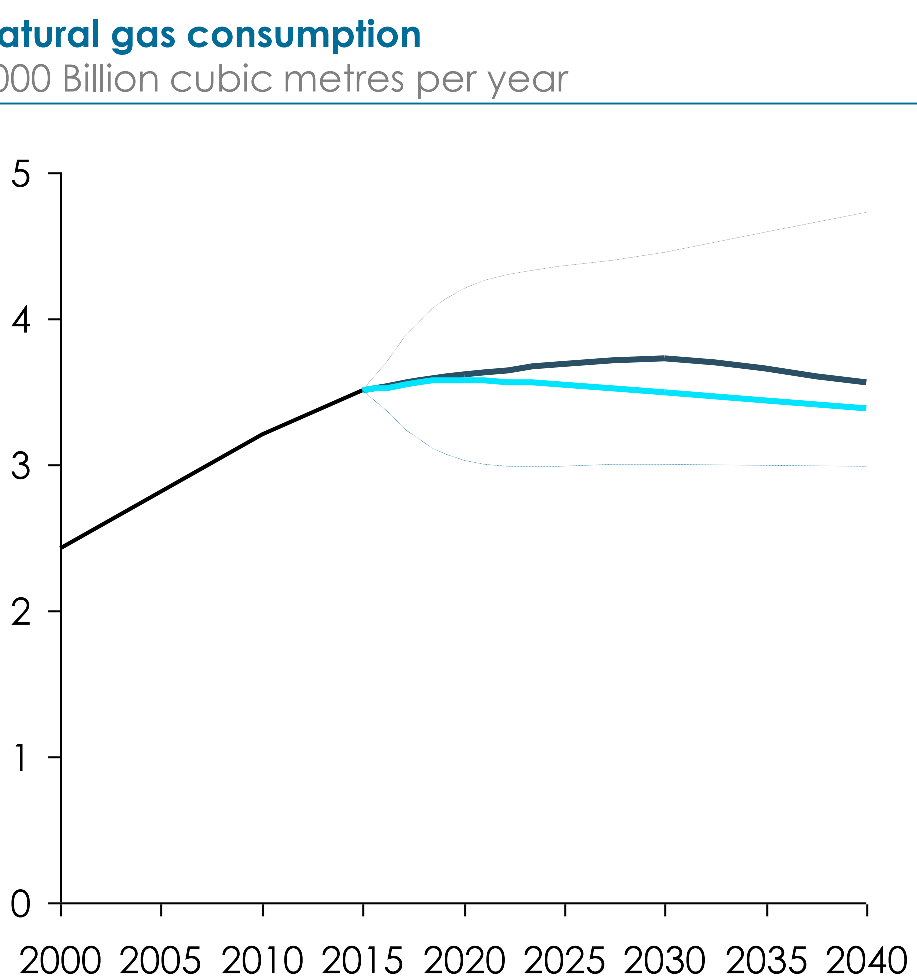


- Peak demand for oil occurs in the 2020s, and by 2040 demand is at two-thirds of current levels
- Many models see a steep decline from approx. 2030. However, the decline rate is typically less than that of output from existing oil fields, implying some continued investment in extraction is required (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/CCU levels

Natural gas consumption
1000 Billion cubic metres per year



- 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

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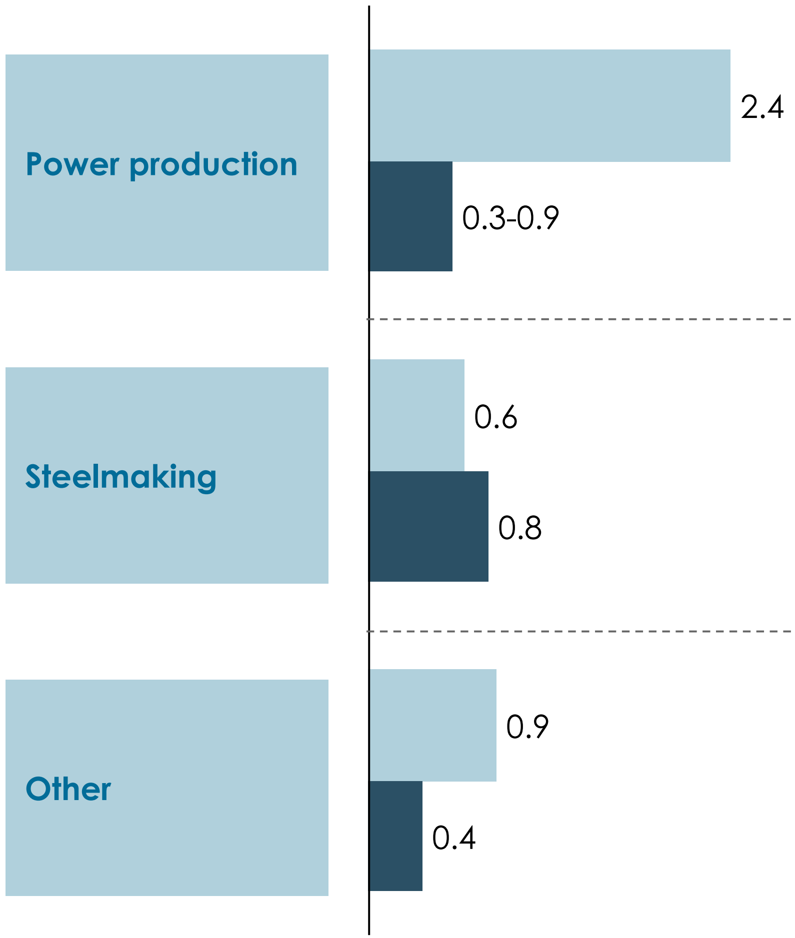
Coal will be needed as a feedstock in industry; its use as a fuel in power production is likely to fall significantly

Coal consumption, illustrative scenario

Billion tonnes of oil equivalent



- The share of coal would need to fall from 40% today to ~5-10 % by 2040 in a 2°C scenario, replaced by renewables, natural gas, and nuclear
- Carbon capture strongly determines the feasible share; by 2040, more than half of thermal coal may require CCS/CCU

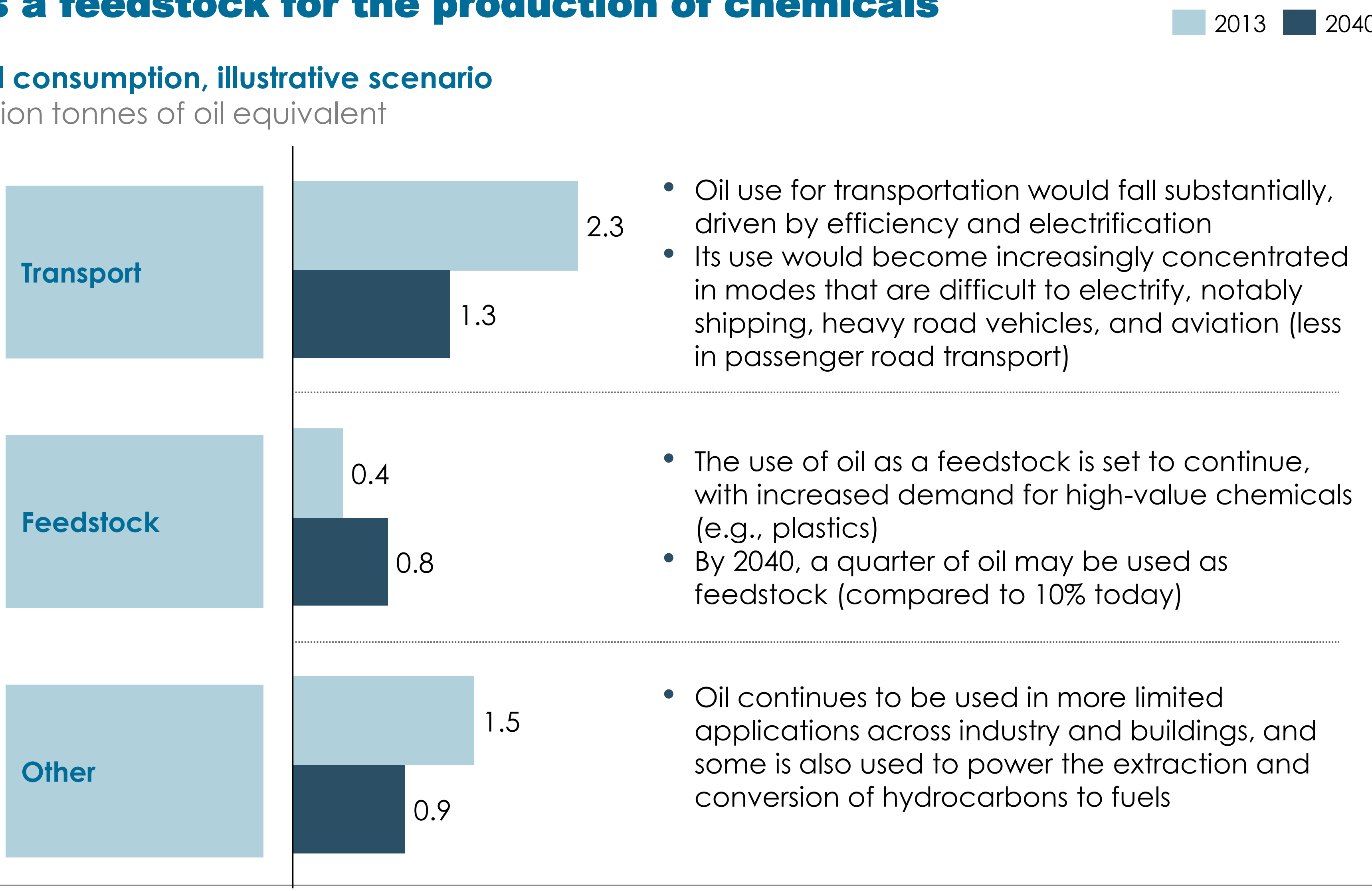
- The use of coal for steelmaking is likely to increase even with very ambitious energy efficiency, process change, materials substitution, and recycling
- CCS or process technological breakthroughs would be required for further deep reductions emissions

- Coal use also persists to some degree in high-temperature industrial processes, and some heating

Source: Copenhagen Economics analysis

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

Oil consumption, illustrative scenario
Billion tonnes of oil equivalent



- Oil use for transportation would fall substantially, driven by efficiency and electrification
- Its use would become increasingly concentrated in modes that are difficult to electrify, notably shipping, heavy road vehicles, and aviation (less in passenger road transport)

- The use of oil as a feedstock is set to continue, with increased demand for high-value chemicals (e.g., plastics)
- By 2040, a quarter of oil may be used as feedstock (compared to 10% today)

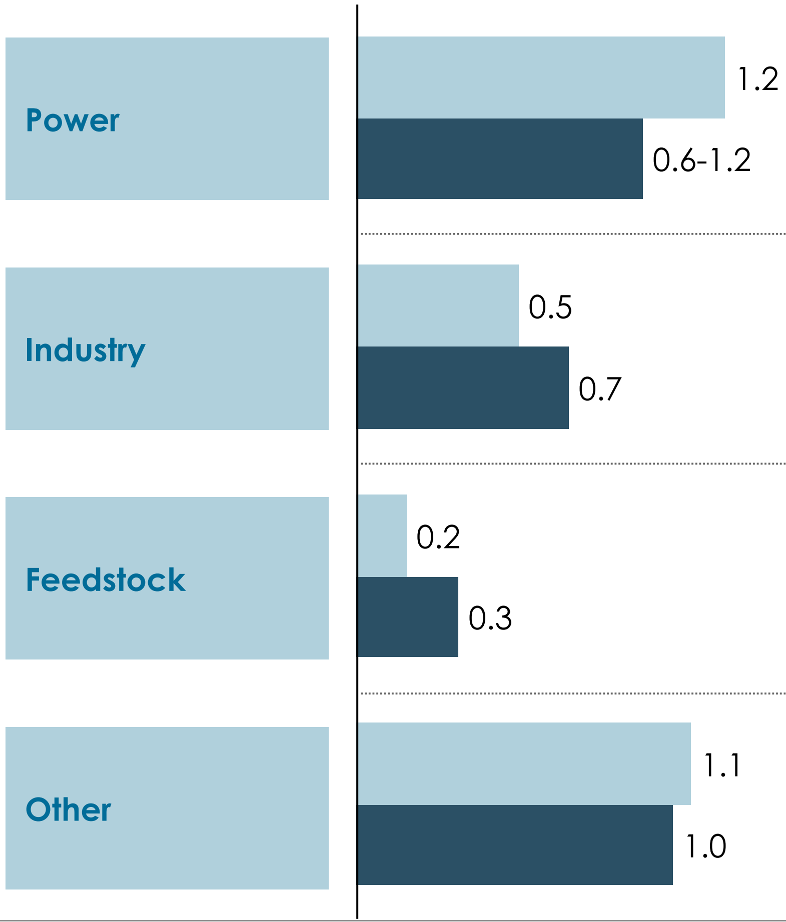
- Oil continues to be used in more limited applications across industry and buildings, and some is also used to power the extraction and conversion of hydrocarbons to fuels

Source: Copenhagen Economics analysis

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

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

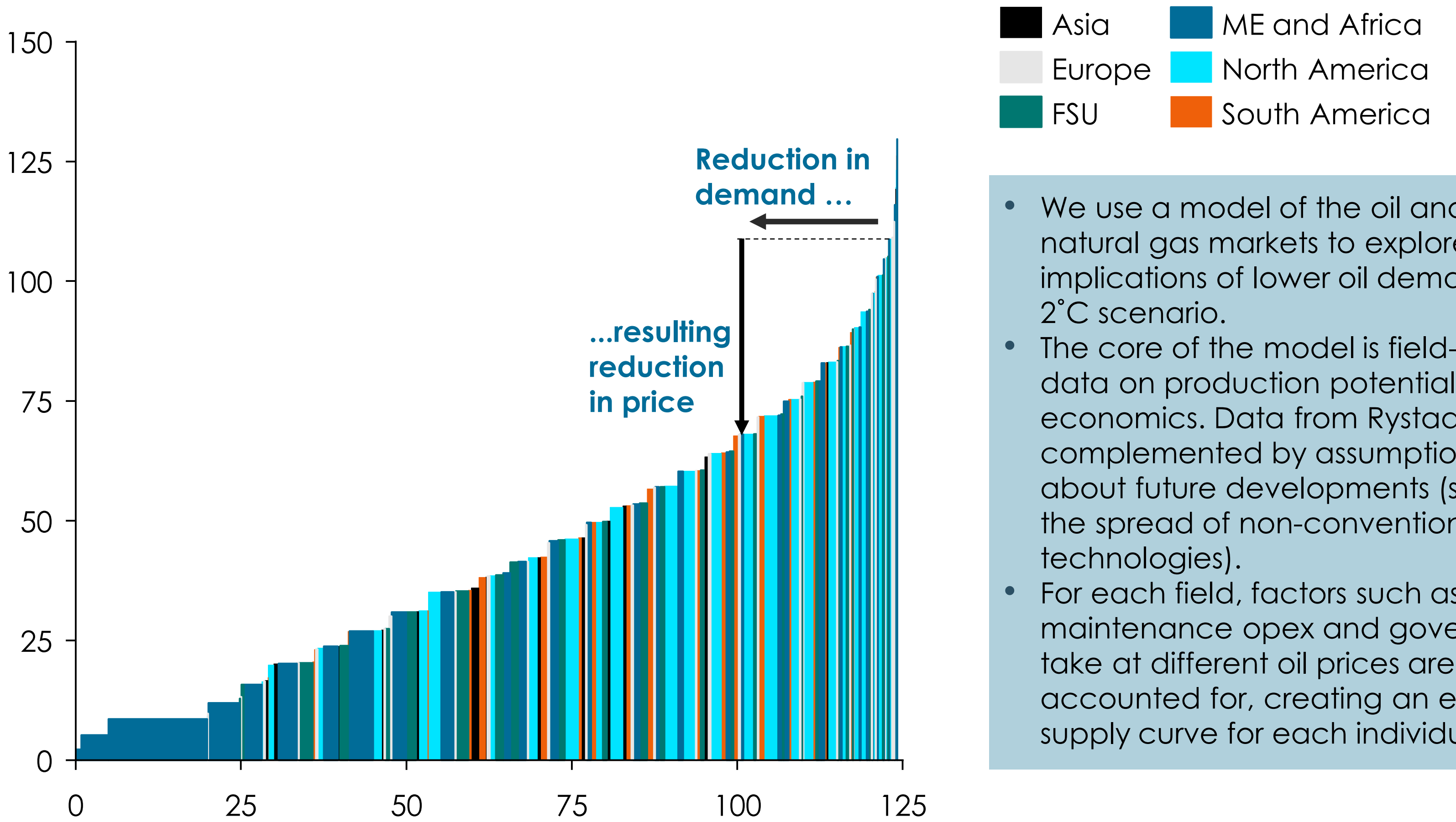
- Gas use in buildings depends on the feasibility of energy efficiency improvements, renewables, and electrification
- Gas use could also increase in transport, but emissions gains depend on low end-to-end methane leakage

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

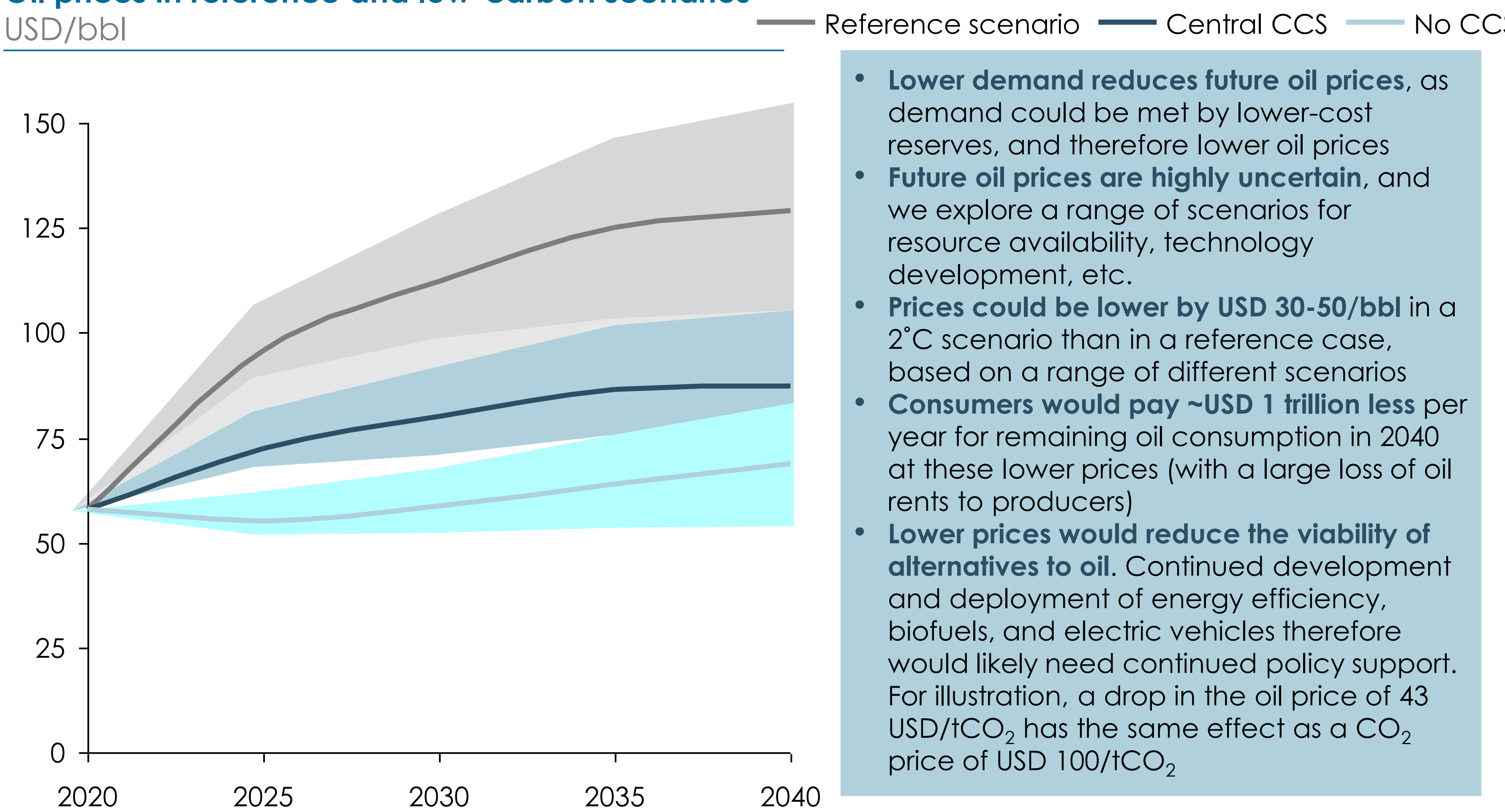
5. A 2°C energy transition has profound impacts on fossil fuel markets

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



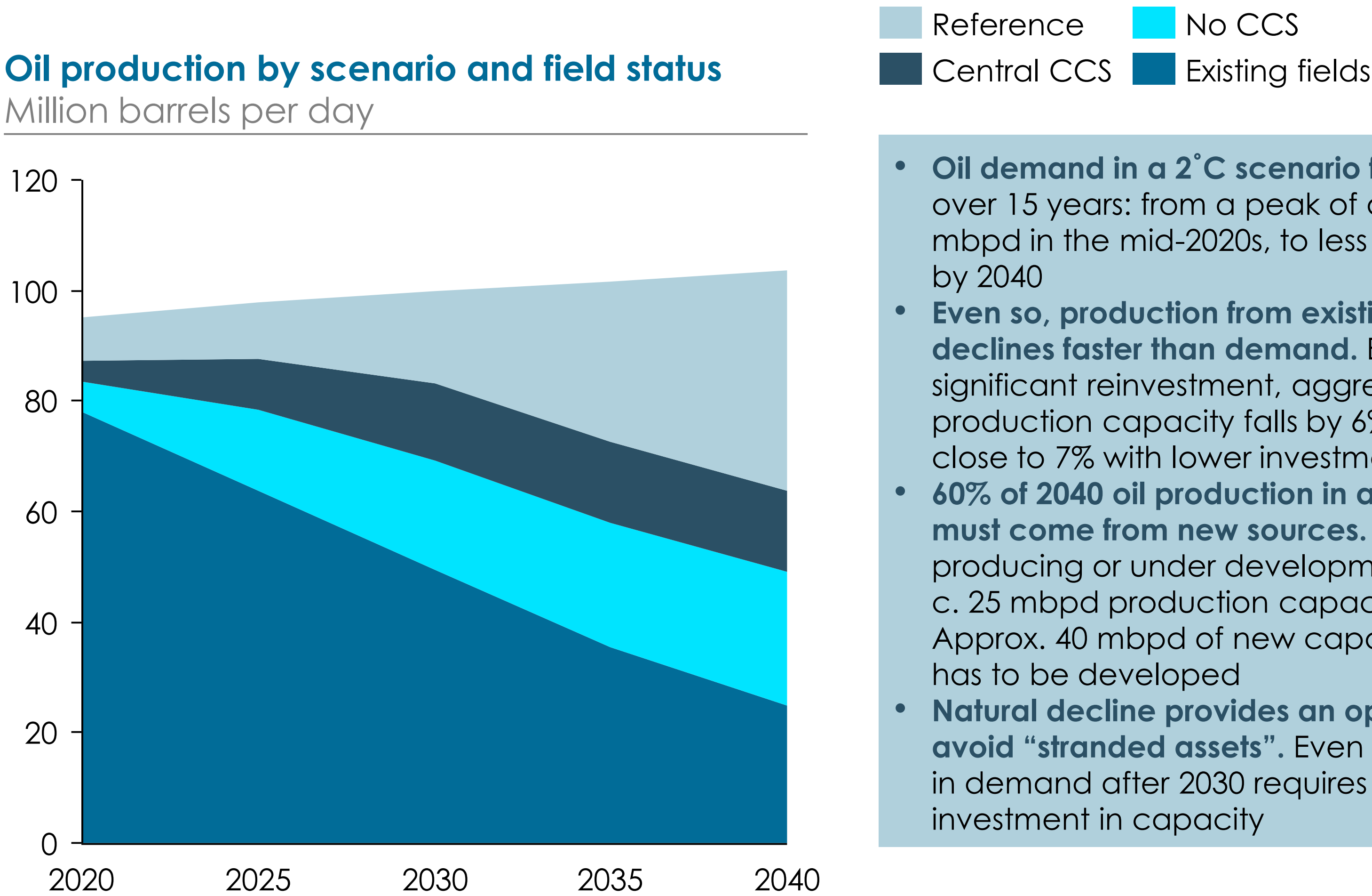
- **Lower demand reduces future oil prices**, as demand could be met by lower-cost reserves, and therefore lower oil prices
- **Future oil prices are highly uncertain**, and we explore a range of scenarios for resource availability, technology development, etc.
- **Prices could be lower by USD 30-50/bbl** 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/tCO_2 has the same effect as a CO_2 price of USD 100/tCO_2

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



- **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

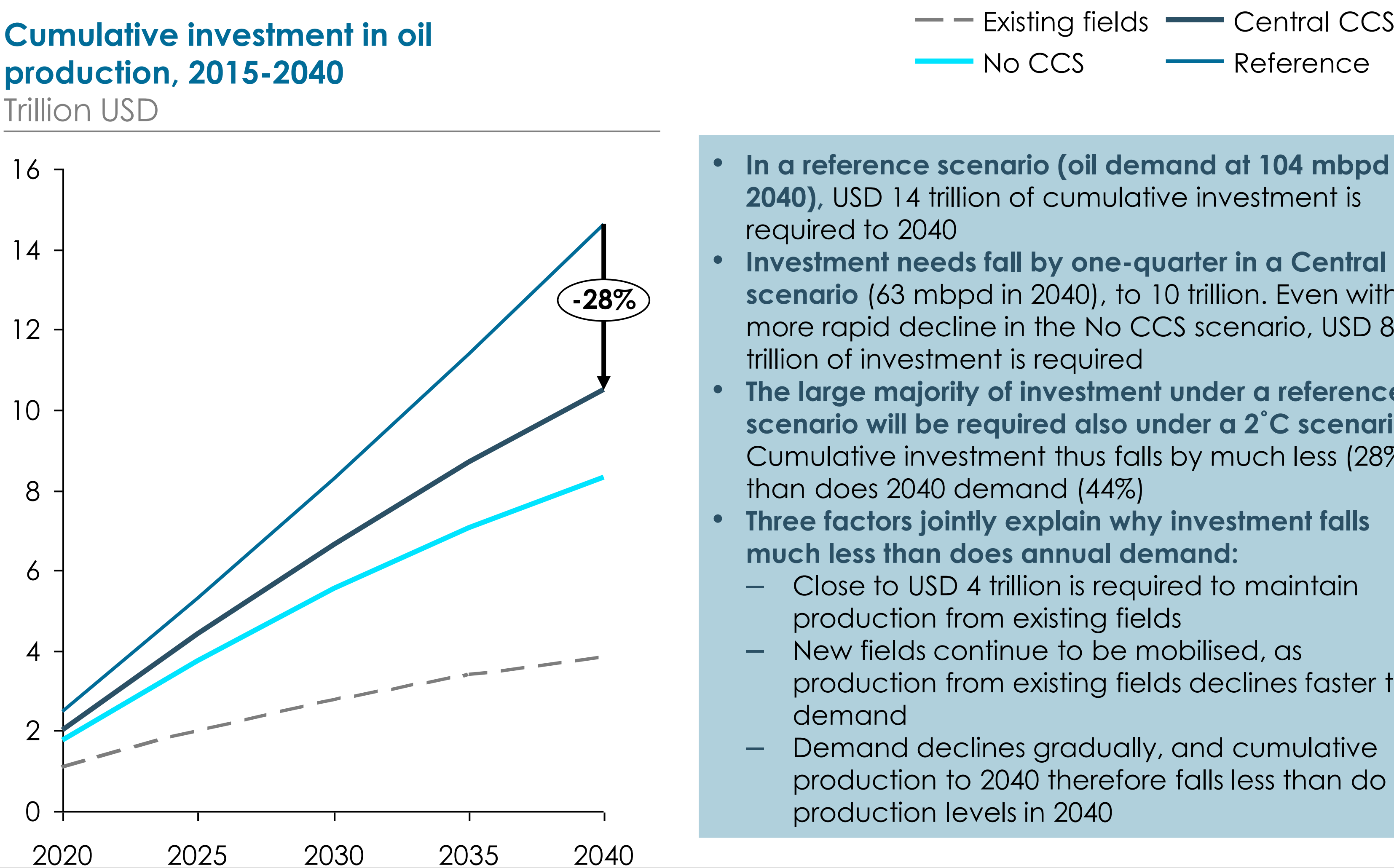
Note: "Existing fields" include fields currently producing and under development. Decline rates are calculated for the rate of investment that can be supported by prevailing oil prices as estimated by the model.

Source: Copenhagen Economics oil market model; Rystad data

Copenhagen Economics

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



- **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)

Copenhagen Economics

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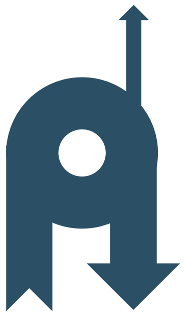
Carbon capture affects the carbon budget in two ways

Fossil fuels



Effect on carbon budget

- 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

Key potential 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

Effect on carbon budget

- Provides energy services (e.g., power) without net CO_2 emissions, thus freeing up carbon budget space
- Additionally, can potentially move CO_2 from the atmosphere to permanent stores (“negative emissions”), offsetting some remaining CO_2 emissions from other sources
- Extent of carbon budget gain depends critically on whether production of biofuels affects CO_2 levels, for example through land-use change

Key potential applications

- 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

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

CARBON CAPTURE

Separation, clean-up, and concentration *of CO_2 from other gases, as a precursor to sequestration*

Fossil fuel / industrial process CO_2

- Separation and clean-up of CO_2 from large point sources with high concentration
  - Post-process, Oxy-fuel, syngas/hydrogen, etc.

Atmospheric CO_2

- Capture of CO_2 at low concentrations, e.g., through:
  - Biomass, capturing CO_2 through photosynthesis
  - Weathering, speeding up formation of rock
  - Direct air capture, using chemical processes to concentrate CO_2

SEQUESTRATION

Permanent removal *of CO_2 from atmosphere, while avoiding negative side-effects or leakage*

UTILISATION - *EXAMPLES*

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

		Sequestration	Utilisation - examples
Storage		• CO_2 storage in geological formations	• Enhanced oil recovery (subject to monitoring)
Transfor-mation	Minerals	• Storage in rocks or minerals	• Replace conventional construction materials and aggregates
Transfor-mation	Products	• Bio/CO_2-based plastics, carbon fibre, etc.	• Replace conventional products based on fossil fuel feedstock
Uptake	Land	• Re- / afforestation • Soil carbon sequestration	• Increase soil quality, e.g. through mulching
Uptake	Ocean	• Ocean fertilisation • Increased alkalinity	• *N/A (high uncertainty about effects)*

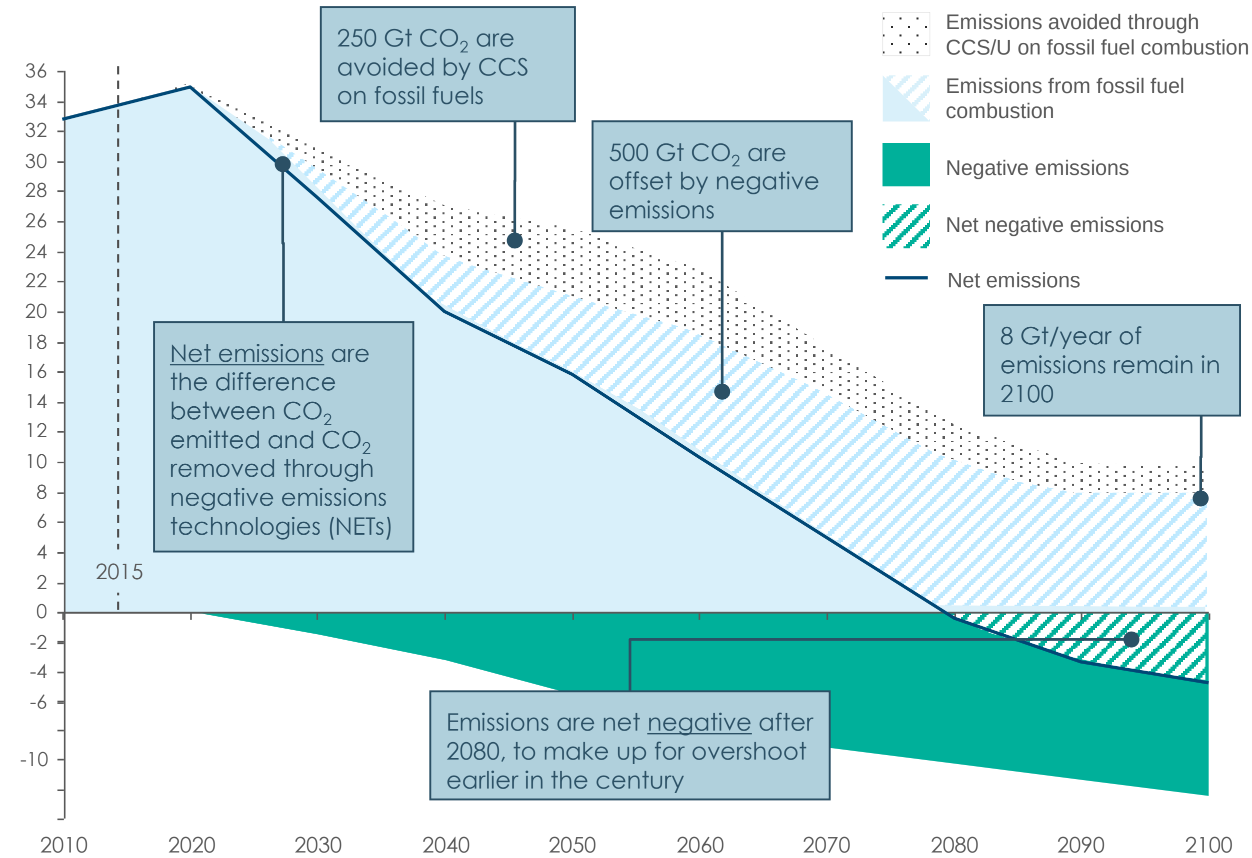
- **Capture technology maturity** differs. Capture of concentrated CO_2 is proven at demonstration/lab scale for a range of applications, but still modest. Weathering and direct air capture are at the concept stage, with high energy penalties. Biomass uptake is large.
- **Sequestration potential** also 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 CO_2 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 CO_2 uptake are highly uncertain.
- **Utilisation** also varies. Enhanced oil recovery is proven and has underpinned most sequestration to date. CO_2-based products are at R&D stage, with construction materials a large potential volume market. Agricultural / forestry practices have proven potential.

Sources: ...

In most pathways, "net zero" emissions result from low remaining CO_2 release combined with "negative emissions"

Balance of emissions in Central CCS scenario* 2010-2100

Gt CO_2 per year



- "Negative emissions" through CO_2 capture and sequestration on bioenergy (BECCS) and other negative emission technologies (NETs) remove ~3 Gt CO_2 of in 2040, and 12 Gt CO_2/year in 2100
- By 2080, emission are net negative, i.e. more emissions are removed from the atmosphere through NETs, than are emitted each year
- In 2100, CO_2 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 CO_2 by 2100, corresponding to 55% of the total carbon budget.
- ~250 Gt of CO_2 emissions are avoided through CCS on fossil fuel combustion. CCS 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 CO_2 per year in any year up to 2100.
Source: Copenhagen Economics analysis of data from AR5 database.

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 CO_2 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 CO_2 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.