Low Carbon Energy Technologies – FactBook Update

Carbon Capture and Storage at a Crossroads

A.T. Kearney Energy Transition Institute
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Compiled by the A.T. Kearney Energy Transition Institute

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About the FactBook – Carbon Capture and Storage

This FactBook released in 2016 reflects the latest changes in the carbon capture and storage landscape. It summarizes the main research and development priorities in carbon capture and storage, analyzes the economics of the technology and presents the status and future of large-scale integrated projects.

About the A.T. Kearney Energy Transition Institute

The A.T. Kearney Energy Transition Institute is a nonprofit organization. It provides leading insights on global trends in energy transition, technologies, and strategic implications for private sector businesses and public sector institutions. The Institute is dedicated to combining objective technological insights with economical perspectives to define the consequences and opportunities for decision makers in a rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas with interested sponsors and relevant stakeholders.

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Executive summary (1/2)

CCS is a necessary and viable technology for limiting carbon dioxide emissions

As CO2 emissions and the atmospheric concentration of CO2 reach record highs, room for maneuver in mitigating the adverse effects of climate change is becoming dangerously tight. In the lowest-cost pathway to limiting the global increase in temperature to no more than 2°C (2DS Scenario), the IEA estimates that CCS will contribute to 13% of cumulative emission reductions by 2050. The IPCC, meanwhile, estimates that attempting to achieve the 2°C target without CCS would more than double mitigation costs, and may not be feasible at all.

CCS is technically viable: it is already a reality in power generation, natural gas processing and industrial hydrogen plants, where 15 large-scale integrated projects are capturing 28.5 MtCO2 per year in order to store it in deep saline aquifers or in oil reservoirs as part of enhanced oil recovery (EOR) operations. Industry players are adamant that the individual components of CCS have been proved to be technically feasible and are ready to be demonstrated on a large scale in other industrial sectors, such as cement, steel, and pulp and paper production. Globally, CCS currently abates emissions equivalent to the CO2 output of 9 GW of coal-fired power capacity.

R&D investments in CCS are substantial (~$1.6 billion in 2013, equivalent to that in wind or biofuels). Public laboratories and corporate players – chemicals companies, utilities, and oil and gas firms – are focusing on developing efficient capture processes that would reduce CCS energy and water penalties. Innovation needs in CO2 transport are less obvious, and field demonstrations rather than lab tests are most needed to improve scientists' understanding of how CO2 behaves when injected underground.

CCS can be a very competitive mitigation option, but its high up-front costs demand strong political will

CCS is seen as a costly technology because its high up-front costs for the project owner only bring long-term, shared climate benefits. The capture costs alone of a commercial-scale CCS project can amount to up to a billion dollars, although one such plant is capable of abating over 1 MtCO2 per year for several decades (the equivalent of taking over 200,000 cars off the roads during the lifecycle of the plant). First-of-a-kind projects incur high risk premiums, and, in the absence of robust carbon-pricing mechanisms (€7/tCO2 in Europe, $20/tCO2 tax credit in the US), direct public financial support is required to cover the up-front cost of large-scale CCS projects.

Yet CCS could be a cost effective way to curb CO2 emissions: in power generation, current abatement costs range from $48 to $114/tCO2 avoided in the US, which is no more expensive than installing offshore wind or solar plants, especially if the carbon-intensity of the electricity being displaced is significantly lower than that of coal (for instance, in case of high share of nuclear or hydropower capacities in the country's power fleet). Besides, costs are expected to decrease. With an estimated 8% CAPEX reduction for each doubling of CCS capacity installed, CCS power could be fully competitive with other clean electricity supply between 2030 and 2040 in Europe and in the U.S. under the IEA's 2DS Scenario. CCS is even cheaper (as low as $14/tCO2 today) when applied to industrial plants with CO2 separation already built into their processes, such as natural-gas processing or steam methane reforming. Perhaps more importantly, no alternative exists for cutting emissions from industrial applications such as chemicals, steel or cement production, a prerequisite for the construction of sustainable infrastructure. Finally, bioenergy such as woody biomass coupled with CCS (BECCS) could actively reduce atmospheric CO2 concentrations while producing renewable energy.

Executive summary (2/2)

The demonstration phase has stalled: only projects related to upstream oil and gas are moving forward

In 2009, CCS was on top of the political agenda: declared global public financial support exceeded $30 billion through various economic-stimulus packages; 70 integrated projects were in various stage of planning; and the IEA had recommended that 100 projects be storing 250 MtCO2/year by 2020. But, as of end-2015, the demonstration of large-scale CCS projects had progressed far more slowly than initially hoped. Final investment decisions taken since 2008 have amounted to less than $14 billion and involve only 13 new integrated projects. More worryingly, very few new projects have been identified since 2012, several promising ventures have been cancelled and almost no new firm investment decisions have been taken. As a result, committed public funding has decreased. Money spent or that remains committed to supporting CCS initiatives has been reduced from $30 billion to $10 billion.

In reality, the financial support required for each project has been so large that governments have rarely had the political will to subsidize CCS to the extent required: proposed grants have represented $4-$30 per tCO2 avoided over the lifetime of the plant, which is generally lower than required to pay for the installation costs of CCS. In addition, depressed carbon prices in Europe, public opposition to onshore storage, and the complexity of CCS projects have resulted in promising projects being cancelled in the advanced stages of planning. Furthermore, public funds allocated to cancelled projects have not been reallocated.

CCS has, so far, been advancing at two speeds: the only projects making headway are those related to the upstream oil and gas industry, in which CO2 is either captured at a low cost from natural-gas processing plants or is sold for use in enhanced oil recovery (EOR) operations. Globally, there are 28 integrated CCS projects operating or in the advanced planning stage: only one is not related to the upstream industry (a power plant without EOR), but has not reached final investment decision yet. This trend is likely to continue until 2020, as non-EOR storage projects are more complex to coordinate, depend on benign climate policies, and raise public-acceptance issues and reservoir discovery costs that can be avoided in EOR storage projects. By the end of the decade, operating CCS capacity should reach 57 MtCO2/year, 90% of which will be related to the production of oil or gas, and less than 20% to power generation.

CCS might only play a significant role beyond the most obvious projects if ambitious climate policies are pursued

Growing demand for the beneficial reuse of CO2 for EOR could drive CCS forwards during the present decade in the US and China. Although weak oil prices may have some negative impacts on CO2 demand for EOR, it could also accelerate CCS projects in the North Sea that are viewed as opportunities to postpone the decommissioning of unprofitable offshore infrastructure. China is now engaged in CCS demonstration, and is the only country where the number of projects in the pipeline is actually growing. It is also rapidly driving down the cost of capture, having openly expressed an ambition to become an exporter of capture-ready plants.

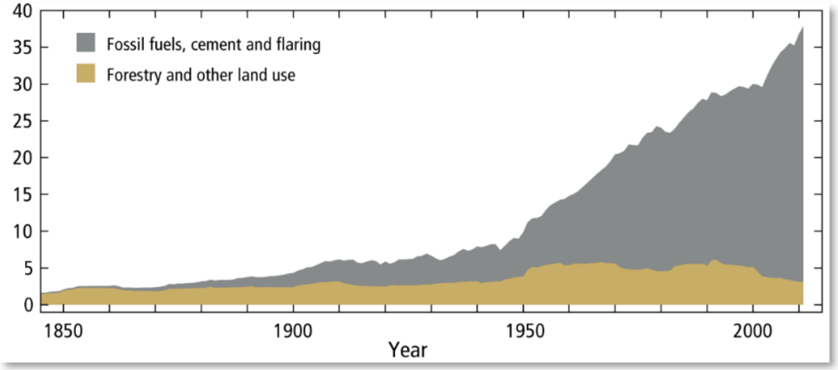
In the long term, the IEA estimates that the contribution of CCS to climate mitigation is likely to remain marginal if only energy policies adopted and proposed as of mid-2015 are considered. CCS will only play a significant role in climate-change mitigation if there is genuine determination to pay for decarbonization. Stricter carbon policies will be required to develop CCS beyond upstream oil and gas, and the enforcement of the 2°C agreement reached in Paris will be critical to the long-term success of CCS.

1. Rationale for CCS

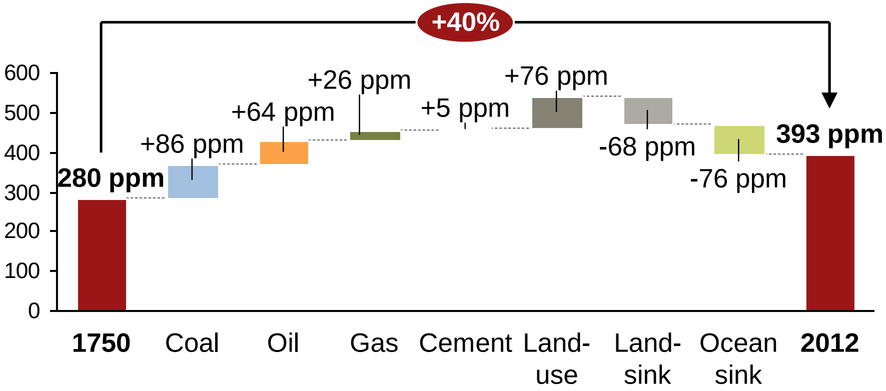
- An indispensable GHG mitigation option

Fossil-fuel use is responsible for the majority of manmade CO_2 emissions and atmospheric concentrations have been increasing since the Industrial Revolution

Global anthropogenic CO_2 emissions (1850-2011)



Global CO_2 atmospheric concentration Increase (1750-2012)

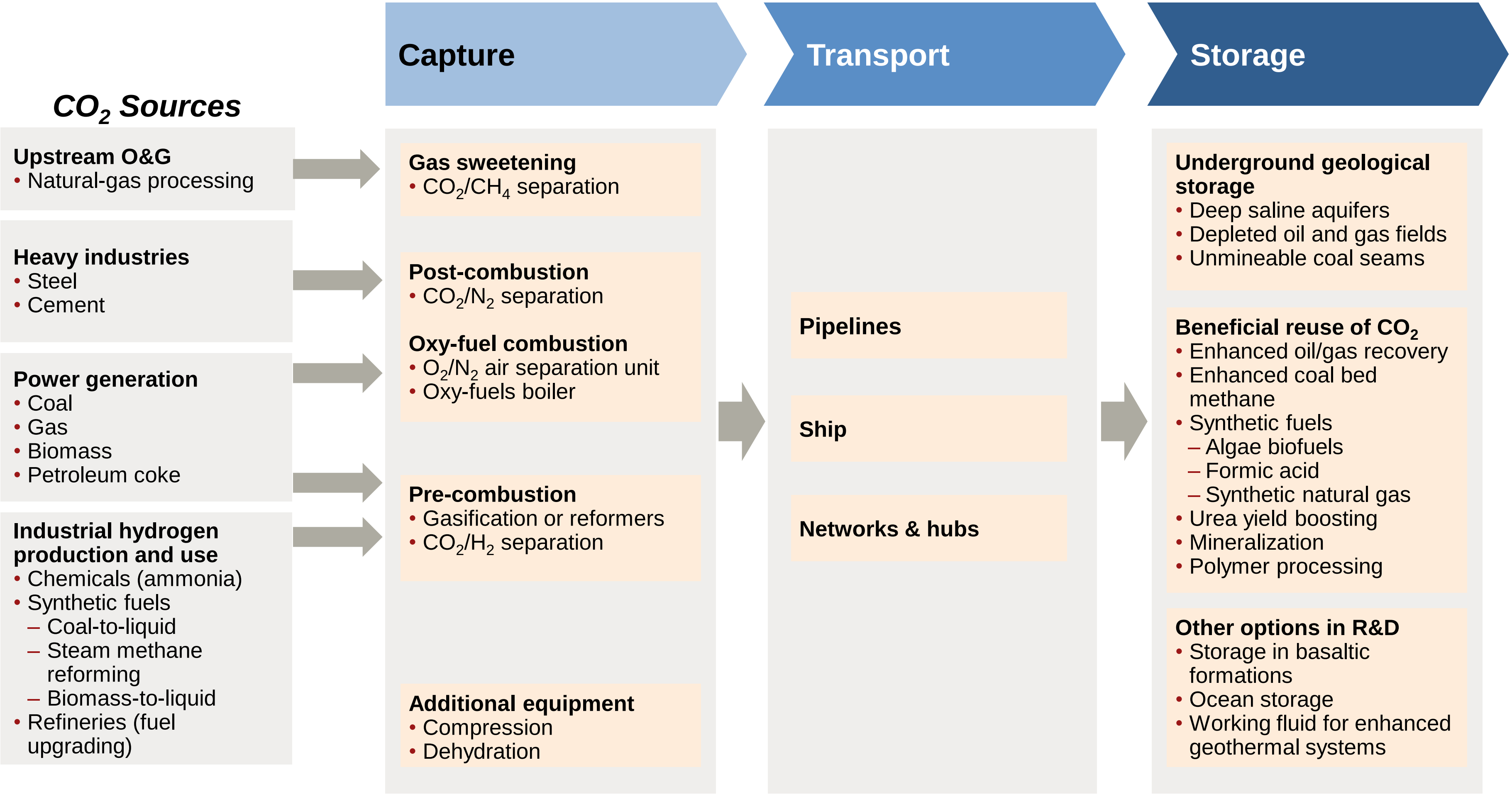


- Fossil-fuel consumption has increased exponentially since the beginning of the Industrial Revolution. These carbon-intensive primary energy sources are the main component of anthropogenic CO_2 emissions.
- About 40% of anthropogenic CO_2 emissions have remained in the atmosphere since 1750, the rest was removed by land and ocean sinks. This has led to increasing atmospheric concentrations of CO_2, which reached the 400 ppm threshold in 2015.
- As a consequence, the Earth's greenhouse effect is reinforcing and oceans are acidifying worldwide. This phenomenon is called anthropogenic climate change, and has various negative consequences.
- There are three complementary options for mitigating CO_2-induced climate change: limiting fossil-fuel consumption, enhancing CO_2 sinks (e.g. forestry), and cleaning fossil-fuel combustion emissions before they enter into the atmosphere in a process called CCS.

1. ppm: parts per million; 1 Coal also include solid fuels derived from biomass such as wood
Source: IPCC (2014), "Climate Change 2014: Synthesis Report"; http://shrinkthatfootprint.com/carbon-emissions-and-sinks; A.T. Kearney Energy Transition Institute analysis

CCS refers to a set of CO_2 capture, transport and storage technologies that are put together to abate emissions from various stationary CO_2 sources

Ccs value chain



CO_2 Sources

Upstream O&G
- Natural-gas processing

Heavy industries
- Steel
- Cement

Power generation
- Coal
- Gas
- Biomass
- Petroleum coke

Industrial hydrogen production and use
- Chemicals (ammonia)
- Synthetic fuels
  - Coal-to-liquid
  - Steam methane reforming
  - Biomass-to-liquid
- Refineries (fuel upgrading)

Capture

Gas sweetening
- CO_2/CH_4 separation

Post-combustion
- CO_2/N_2 separation

Oxy-fuel combustion
- O_2/N_2 air separation unit
- Oxy-fuels boiler

Pre-combustion
- Gasification or reformers
- CO_2/H_2 separation

Additional equipment
- Compression
- Dehydration

Transport

Pipelines

Ship

Networks & hubs

Storage

Underground geological storage
- Deep saline aquifers
- Depleted oil and gas fields
- Unmineable coal seams

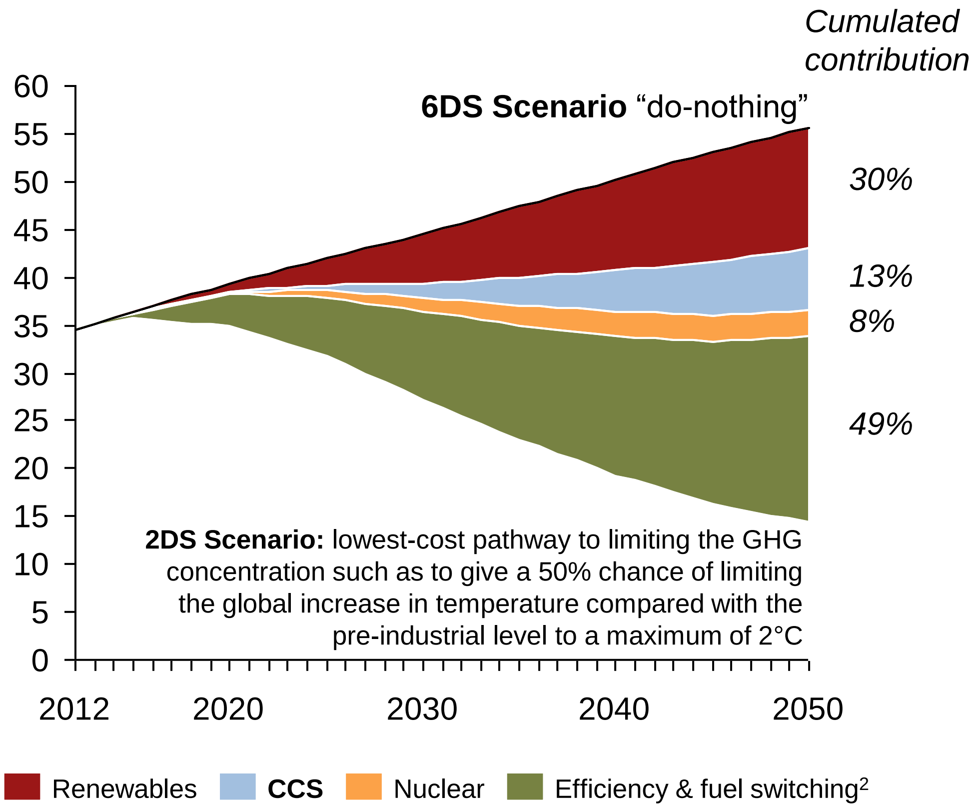
Beneficial reuse of CO_2
- Enhanced oil/gas recovery
- Enhanced coal bed methane
- Synthetic fuels
  - Algae biofuels
  - Formic acid
  - Synthetic natural gas
- Urea yield boosting
- Mineralization
- Polymer processing

Other options in R&D
- Storage in basaltic formations
- Ocean storage
- Working fluid for enhanced geothermal systems

Source: A.T. Kearney Energy Transition Institute analysis

CCS is expected to play an important role in achieving least-cost portfolio approaches to mitigating CO_2 emissions

CO_2 abatement levers in IEA 2DS scenario relative to 6DS Scenario Annual energy-related CO_2 emissions (Gt)



- According to the IEA (2014), the world would be heading towards long-term global warming of 6°C if no climate mitigation measures were implemented (6DS scenario). In the least-cost mitigation scenario, to limit the increase in temperature to below 2°C, the IEA estimates that CCS would need to contribute to 13% of cumulative CO_2 emission abatement between 2011 and 2050.
- According to the Intergovernmental Panel on Climate Change (IPCC, 2014), mitigating climate change without CCS will be difficult: the majority of economic models assessed could not achieve GHG-concentration stabilization around 450ppm without CCS, and those that could showed a 138% average increase in total discounted mitigation costs [29%-237% range][1].

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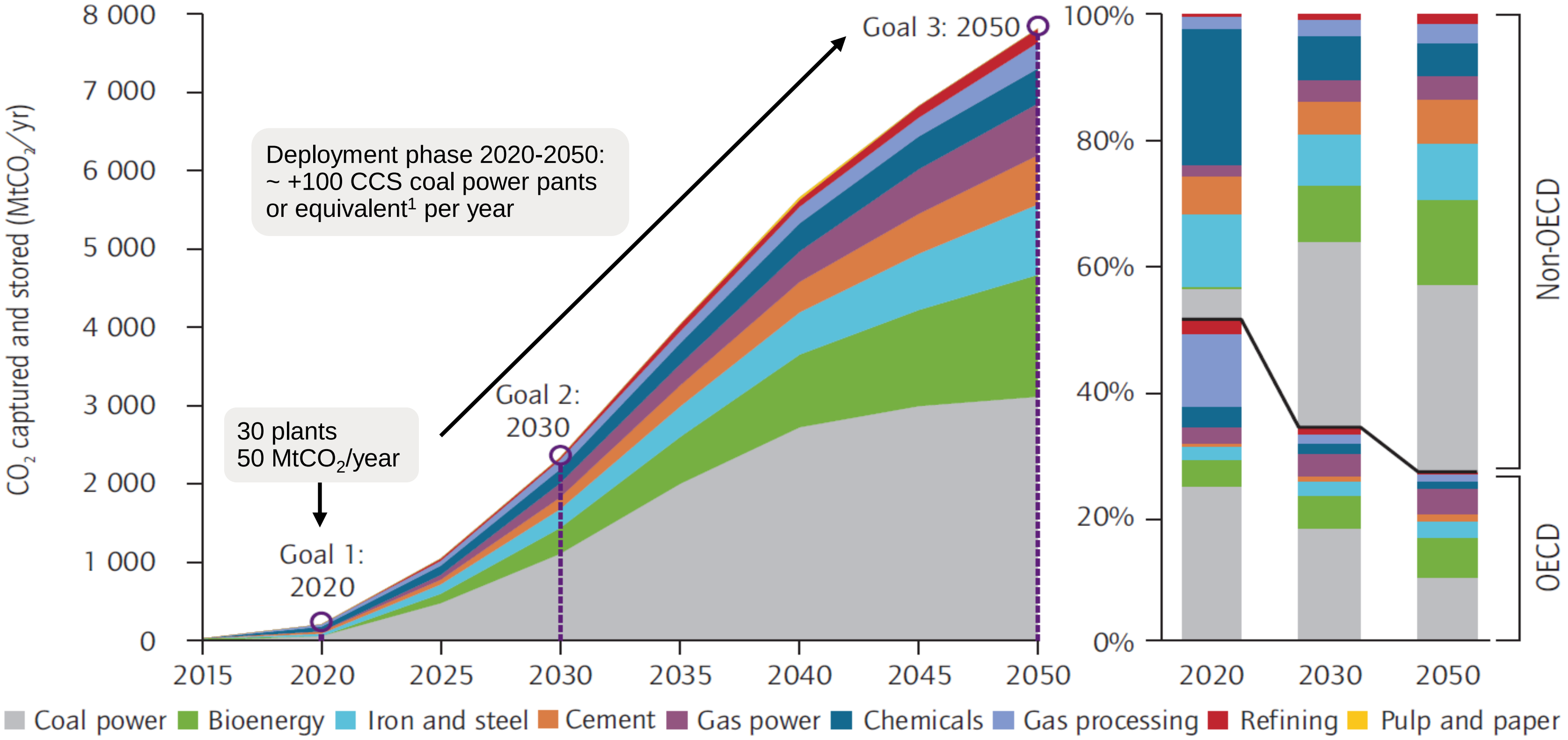
1. Out of 10 models assessed, only four have succeeded in limiting the concentration of greenhouse gases to between 430 and 480 ppm without CCS; 2. Fuel switching between fossil-fuels only (e.g., from coal to gas). It excludes switching to renewables or nuclear.

Source: IEA (2015) "Energy Technology Perspective"; IPCC (2014), "AR5-WGIII, section 6.3.6.3"

CCS is mainly expected to address coal-power emissions in developing economies, yet it is also the only available method of decarbonizing heavy industry

Annual CO_2 captured and stored in IEA 2DS scenario



Deployment phase 2020-2050: ~ +100 CCS coal power pants or equivalent[1] per year

30 plants
50 $MtCO_2$/year

Combined with bioenergy, CCS results in negative CO_2 emissions

CCS is the only method of decarbonizing cement and steel plants, an essential aspect of building renewable energy infrastructure

CO2 separation is already part of some industrial processes, creating low-cost opportunities for CCS

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1. Equivalent to a 500MW pulverized coal power plant with post-combustion CCS, abating 2.6 MtCO2/year.

Source: Adapted from IEA (2013), “Technology Roadmap for CCS”

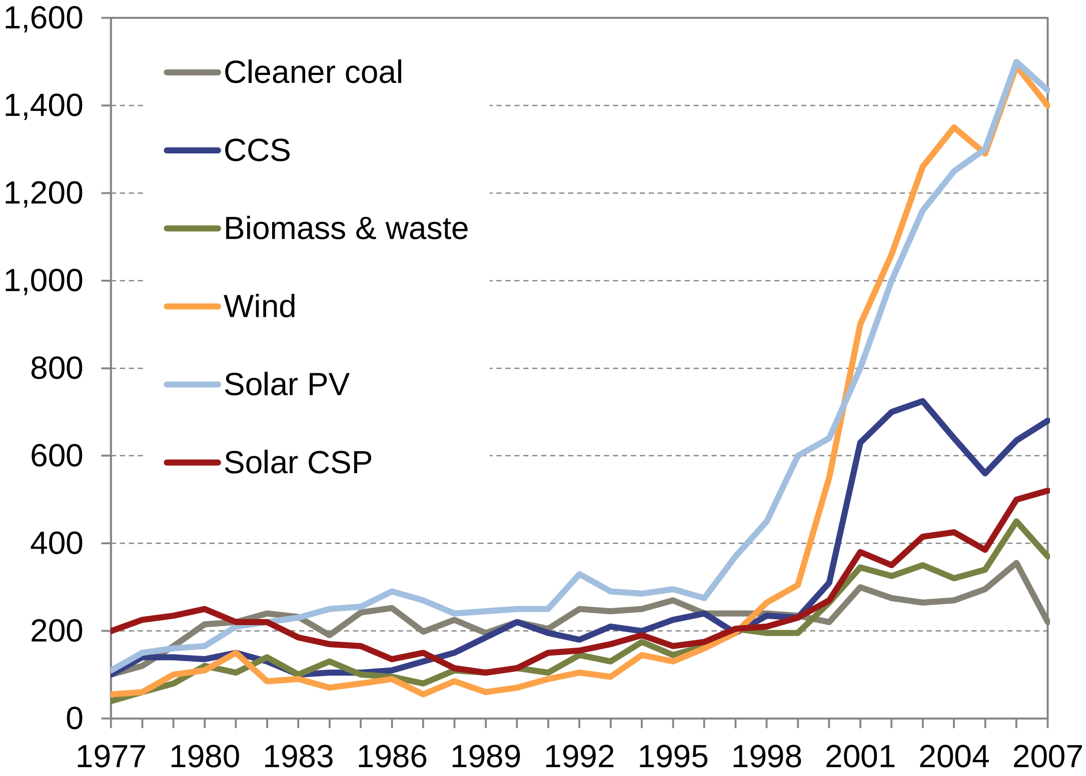
2. Research & Development

- CCS technologies are now proven

R&D efforts in CCS accelerated in the early 2000s

Annual Number of patents filed for various low-carbon technologies

1977-2007, in absolute numbers of patents



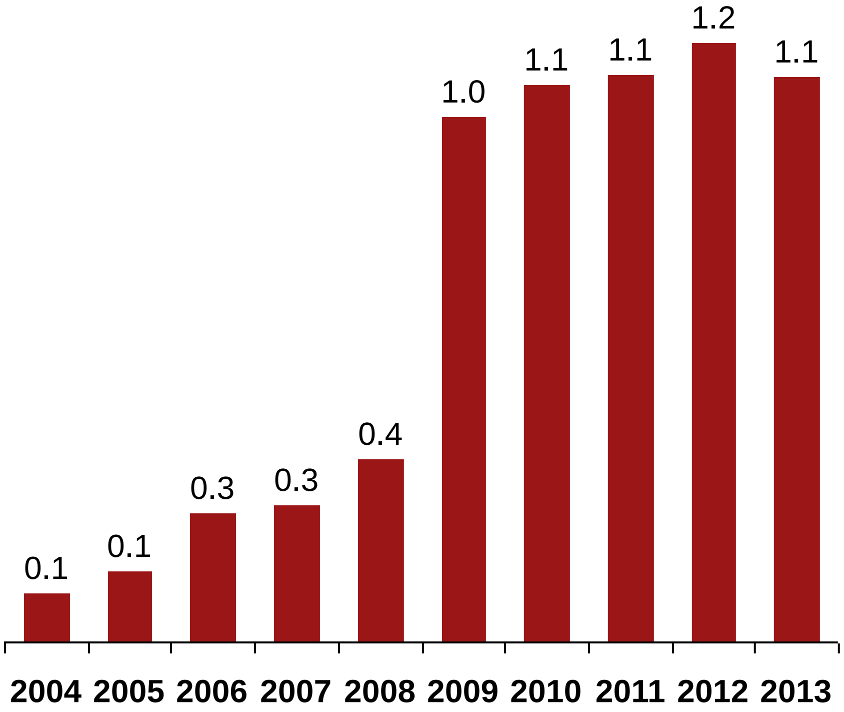
- The capture, transport and storage parts of the value chain have been proved for various commercial purposes during the past 20 years. But individual technologies, especially in capture, are far from optimized for integrated CCS application.
- Industrial companies, laboratories and start-ups are actively developing second-generation technologies for CCS, reflected by a surge in numbers of patents filed relating to carbon capture since 2000.

1. The number of patents related to carbon capture boomed after the beginning of the century, reaching 9,160 at the end 2007. Of these, 68% were filed in the US and 80% were filed by national or multinational corporations. Around 20% of patents for clean coal are connected with integrated gasification combined cycle (IGCC) plants – so-called “capture ready” for pre-combustion; CSP: Concentrated Solar Power.

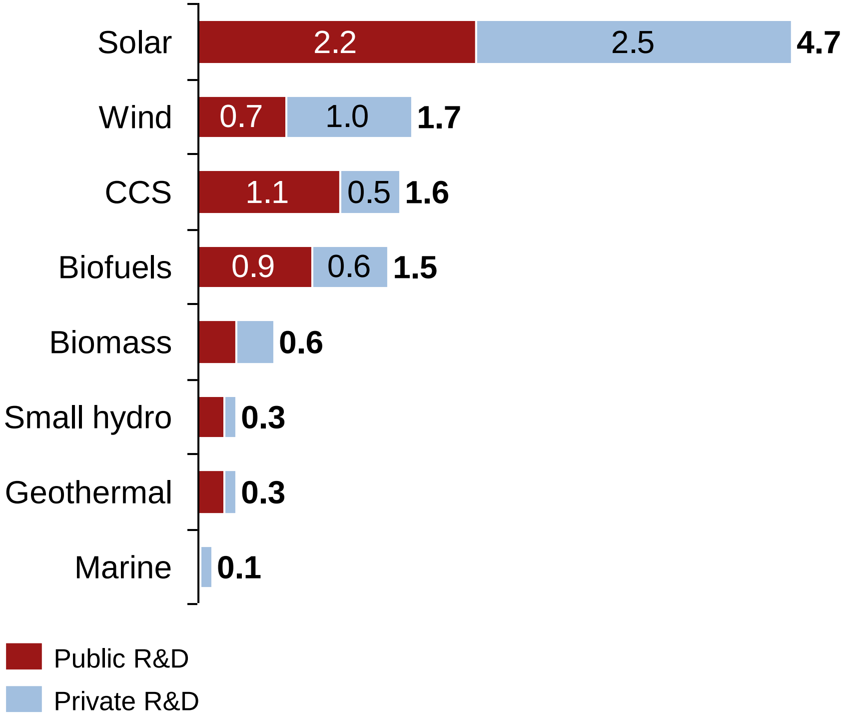
Source: Chatham House (2009), “Who Owns Our Low Carbon Future?”

R&D budgets allocated to CCS have risen to levels equivalent to those allocated to other renewable technologies

Annual public R&D spending in CCS
$ billion



2013 R&D spending in CCS and renewables $ billion



1. Public R&D refers to IEA member country only. CCS R&D is defined in this report as all CCS investments except those for Large Projects (integrated projects above 0.6 MtCO2/year).
Source: IEA (2015), "Energy Technology Perspective"; UNEP (2014), "Global Trend in Renewable Energy Investment"

The main corporate players conducting R&D in CCS are specialty chemicals producers, utilities, and oil and gas companies

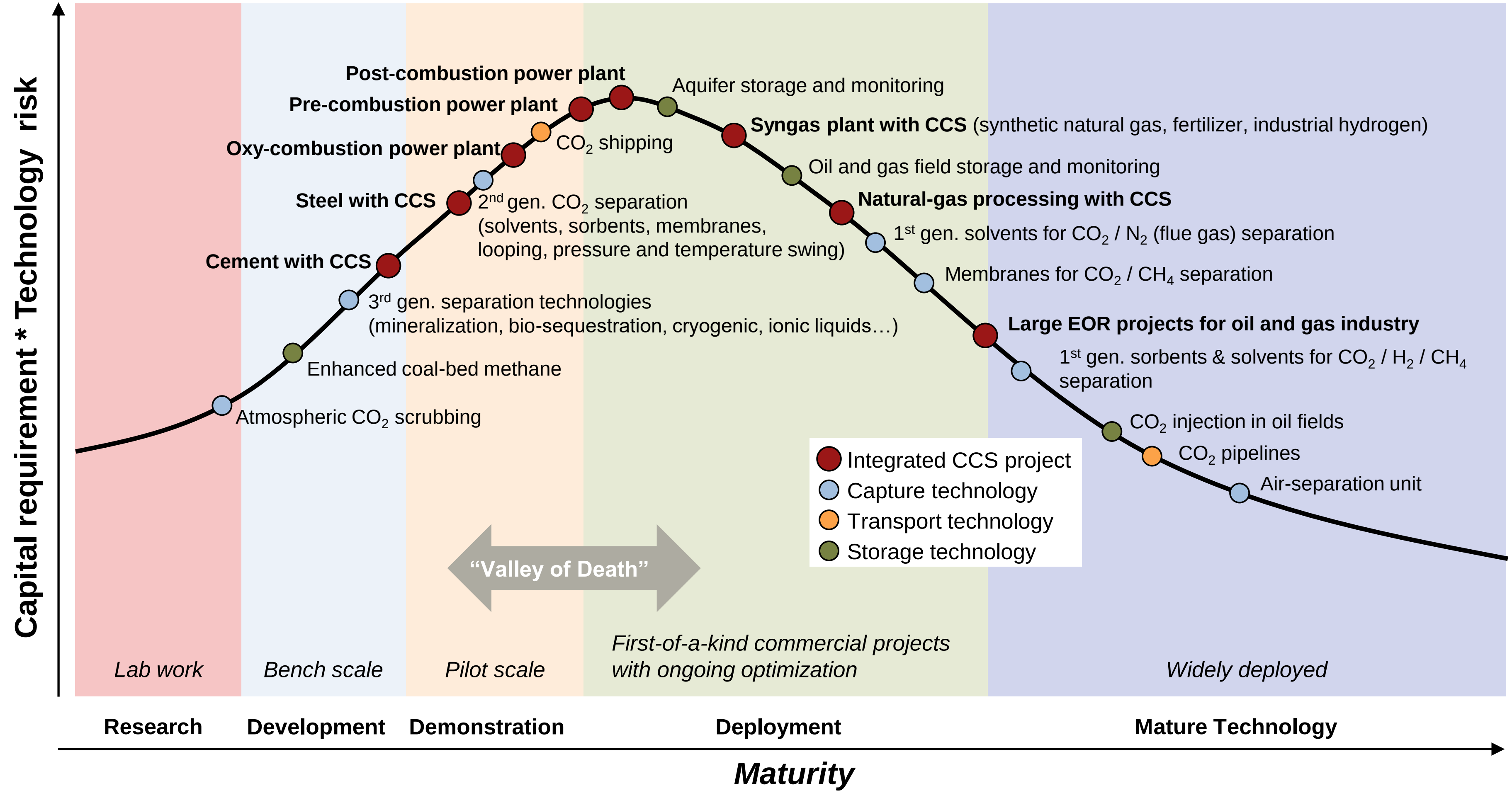
Top R&D players in terms of patents filed in 2010

	Capture	Transport	Storage
Key R&D players	• Praxair • Air Liquide • Air Products • Linde • Shell • Mitsubishi • ExxonMobil • Arkema • General electric • IFPEN	• GDF Suez • Maersk • Wartsila	• Shell • IFPEN • Terralog • ExxonMobil • Schlumberger • CDX gas • Air Products • Diamond QC technologies • Dropscone • BHP Billiton

Source: A.T. Kearney Energy Transition Institute, based on UNEP, EPO and ICTSD (2010)

Individual technologies are now sufficiently proven to enable large-scale integrated demonstration projects

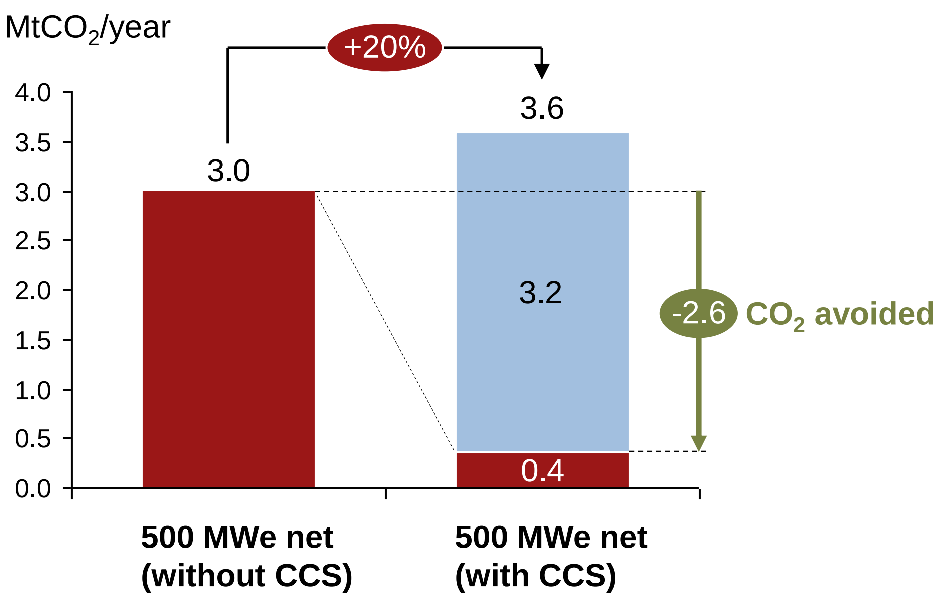
Investment-risk curve of CCS technologies and integrated plants



Source: A.T. Kearney Energy Transition Institute

R&D efforts are currently focused on carbon capture, which incurs a sizeable energy and water penalty

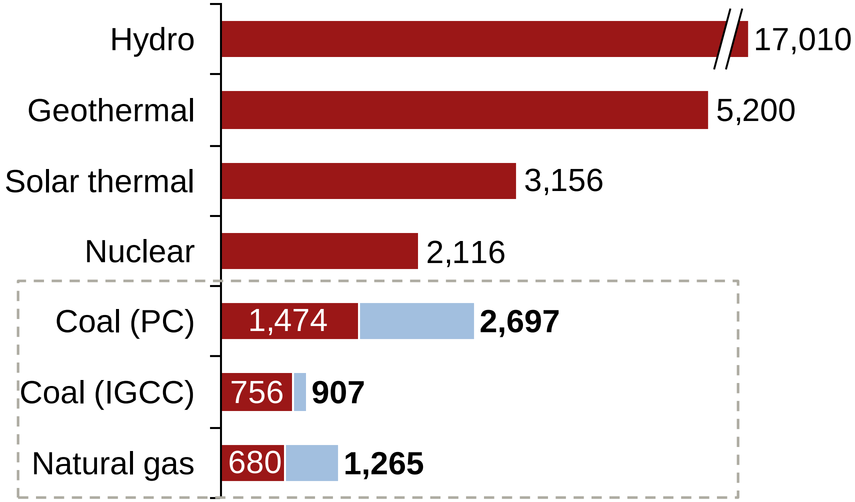
Illustration of a 20% energy Penalty on a 500 MWe coal plant



- Energy penalty currently ranges between 16% and 43%, depending on the capture process.

🟦 CO_2 stored 🟥 CO_2 emitted

Water consumption of various plant types L/MWh



- Water penalty currently ranges between 10% and 80%, depending on the capture process.

🟥 Base plant water consumption 🟦 With CCS

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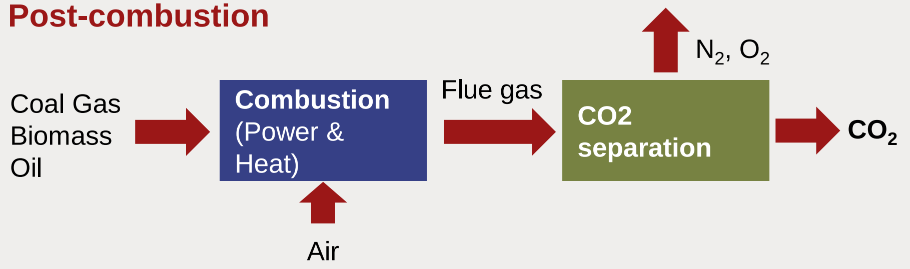
1. PC: pulverized Coal; IGCC: Integrated Gasification Combined Cycle.

Source: World Policy Institute (2011), “The Water-Energy Nexus”; NETL (2010), ”Cost and Performance Baseline for Fossil Energy Power Plants”.

Three main carbon capture process are being demonstrated in power generation

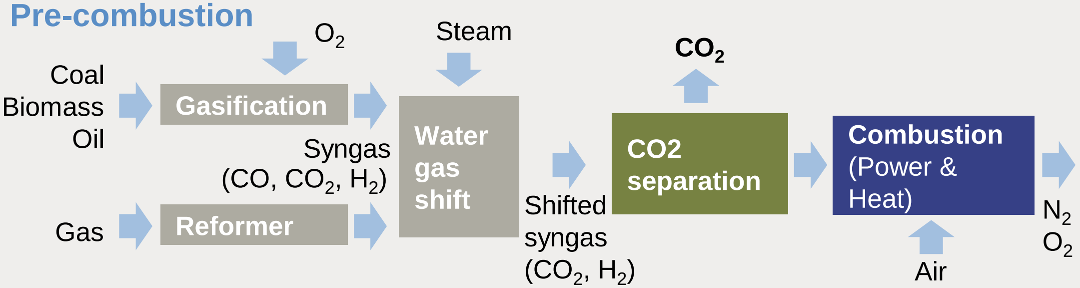
Main carbon capture processes

Post-combustion



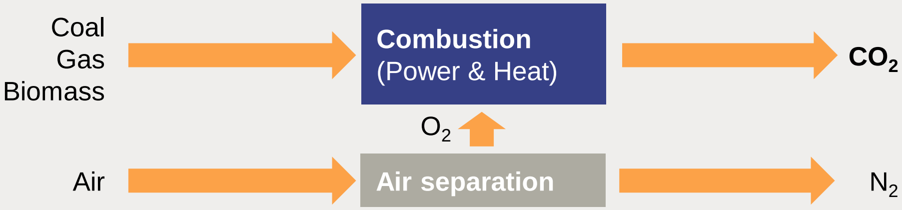
- Post-combustion systems are the most mature capture technology (late demonstration stage), and are expected to be retrofitted to modern and efficient thermal power plants: SPC and NGCC. But post-combustion capture can be retrofitted to almost any existing plant with a large and steady source of CO_2 by adding the capture process to the exhaust-gas circuit. Post-combustion is the only system that does not require an additional oxygen-production plant. However, the process is still highly inefficient, given the low partial pressure of CO_2 in the flue gas.

Pre-combustion



- Shifted syngas (CO2 and H2 mix) production from hydrocarbon fuel is a mature process. Further separation of CO2 from H2 prior to clean combustion in IGCC plants is in the demonstration stage. Advantages are the relative ease with which CO2 can be separated from H2, compared with flue gases, and the versatility of potential end-products from hydrogen beyond electricity. Drawbacks lie mostly in the high capital cost and complexity of the IGCC plant.

Oxy-combustion



- Burning fuel in pure oxygen instead of air produces a pure stream of CO2 and avoids the difficult process of CO2/N2 separation. Another benefit is greater energy efficiency than in post-combustion. However, oxy-combustion technology is in the early demonstration phase. The main hurdle is the very large stream of oxygen required, and extremely high temperature reached in the oxy-combustion chamber. Another important issue is the insufficient purity of CO2 in flue gases, which was problematic in early demonstration projects.

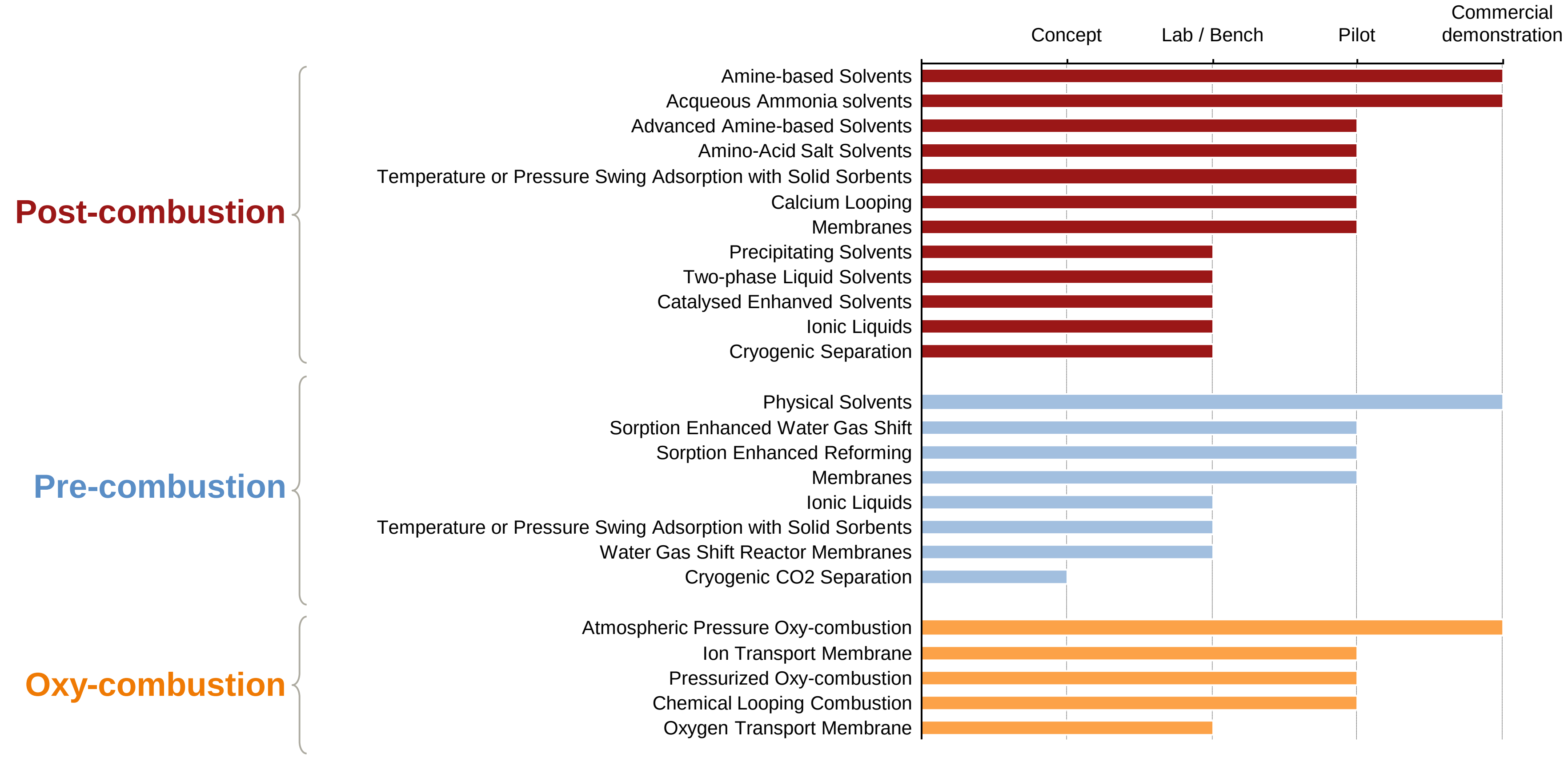
1. SPC: supercritical pulverized coal; NGCC: natural gas combined-cycle; IGCC: Integrated gasification combined cycle.

Source: A.T. Kearney Energy Transition Institute

Specific CO_2-separation technologies are being developed for each capture process

Technological maturity of CO_2 separation technologies

Capture Process **Separation Technology** **Technological Maturity**



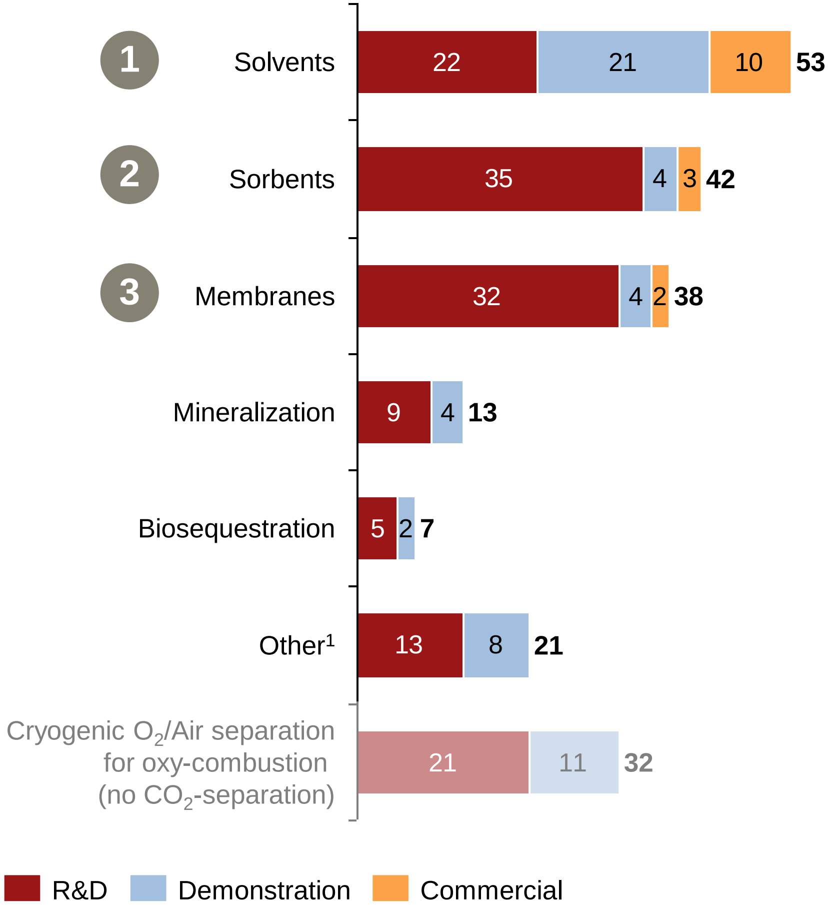
Post-combustion	Amine-based Solvents	Commercial demonstration
	Acqueous Ammonia solvents	Commercial demonstration
	Advanced Amine-based Solvents	Pilot
	Amino-Acid Salt Solvents	Pilot
	Temperature or Pressure Swing Adsorption with Solid Sorbents	Pilot
	Calcium Looping	Pilot
	Membranes	Pilot
	Precipitating Solvents	Lab / Bench
	Two-phase Liquid Solvents	Lab / Bench
	Catalysed Enhanved Solvents	Lab / Bench
	Ionic Liquids	Lab / Bench
	Cryogenic Separation	Lab / Bench
Pre-combustion	Physical Solvents	Commercial demonstration
	Sorption Enhanced Water Gas Shift	Pilot
	Sorption Enhanced Reforming	Pilot
	Membranes	Pilot
	Ionic Liquids	Lab / Bench
	Temperature or Pressure Swing Adsorption with Solid Sorbents	Lab / Bench
	Water Gas Shift Reactor Membranes	Lab / Bench
	Cryogenic CO2 Separation	Concept
Oxy-combustion	Atmospheric Pressure Oxy-combustion	Commercial demonstration
	Ion Transport Membrane	Pilot
	Pressurized Oxy-combustion	Pilot
	Chemical Looping Combustion	Pilot
	Oxygen Transport Membrane	Lab / Bench

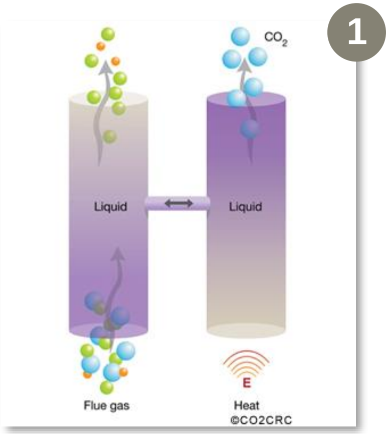
1. Refer to the appendix for a description of some of these processes and technologies.

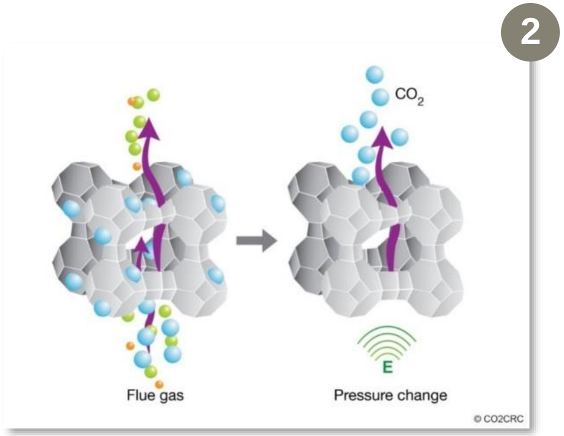
Source: GCCSI (2014), "Global Status of CCS"

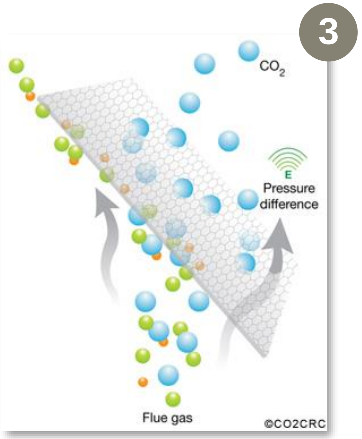
Solvent, sorbent and membranes are the most advanced separation methods, but competition to be the most efficient technology is intense

Number of CO_2 separation technologies being developed







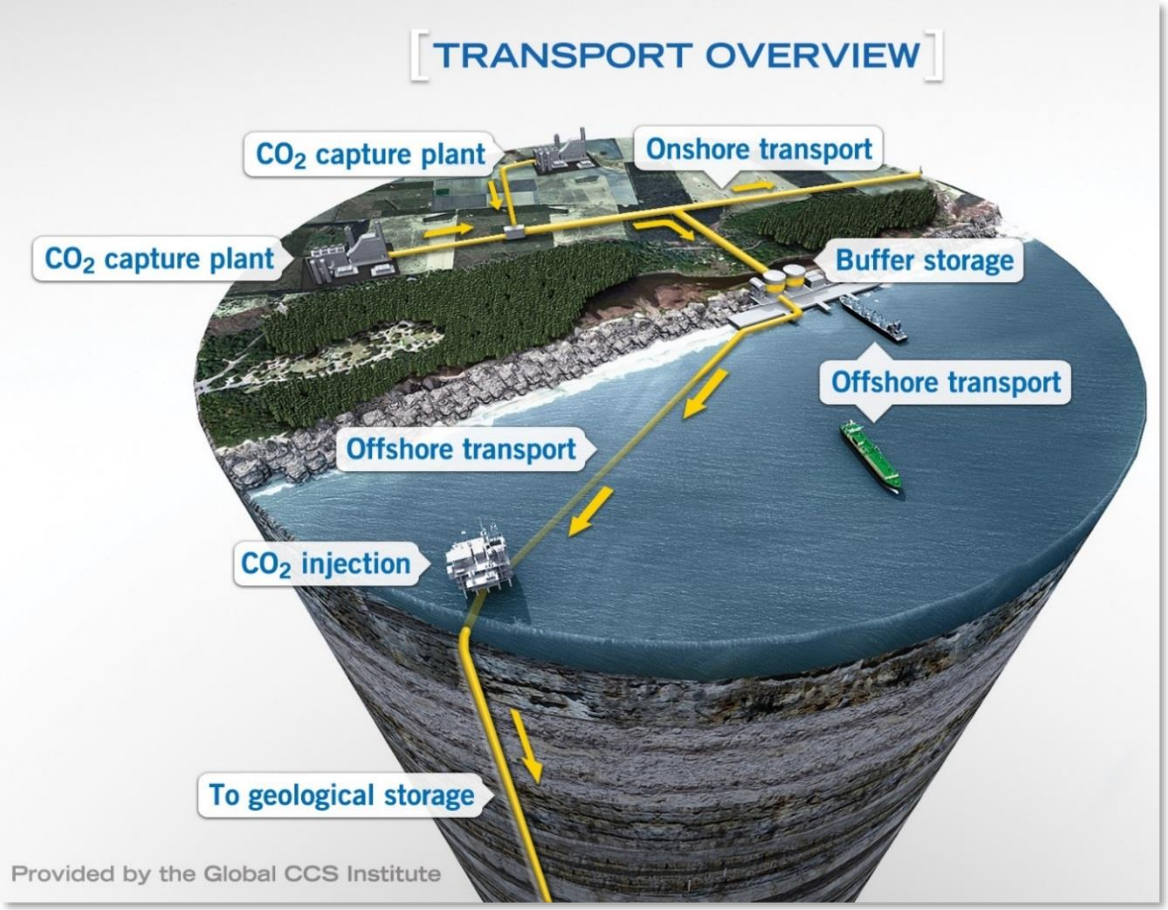


1. Other includes electro-chemical separation, hydrates, etc…

Source: A.T. Kearney Energy Transition Institute analysis, BNEF database accessed in May 2015; Picture credits: CO2CRC, online public library

The innovation needed in CO_2 transportation is less obvious

Transport Overview



- CO2 transportation is already well established, and poses no greater risk than natural gas transportation, which is already well managed.
- 50 CO2 pipelines, with a combined length of 6,600km, already operate in North America, transporting over 60 MtCO2 annually, mostly for enhanced oil recovery (EOR) purposes. The technical challenges presented by CO2 pipelines differ from those associated with natural gas, and include impurities in the CO2 stream, and managing corrosion and pressure (both much higher than in natural gas pipelines).
- Maritime transportation of CO2 is already in use at a small scale in the drinks industry, and could be a promising and flexible transport option for the bulk transportation of CO2 in CCS, in large vessels similar to those used to transport liquefied petroleum gas.
- Truck and rail transport are unlikely to play a significant role in CCS deployment.

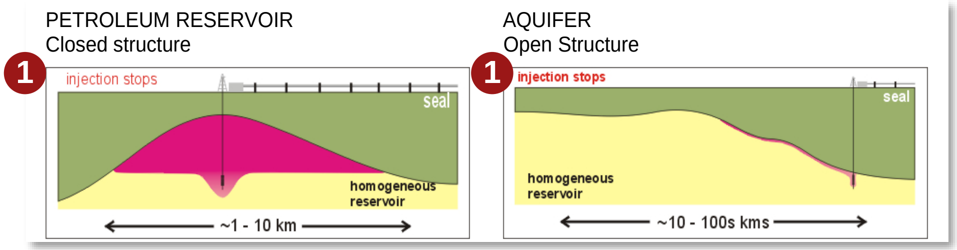
Source: Picture credit: NETL (2014), “Near term projection for CO2 EOR”: Picture credit: The Global CCS Institute

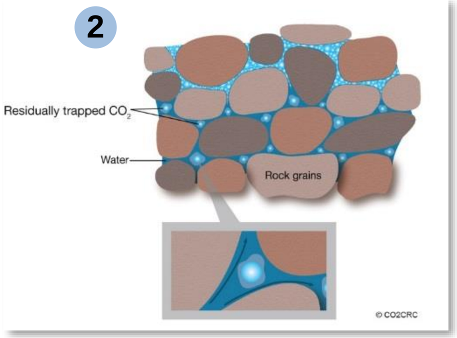
The aims of R&D in storage are to find suitable reservoirs and understand the behavior of CO_2 underground, for which field demonstration are indispensable

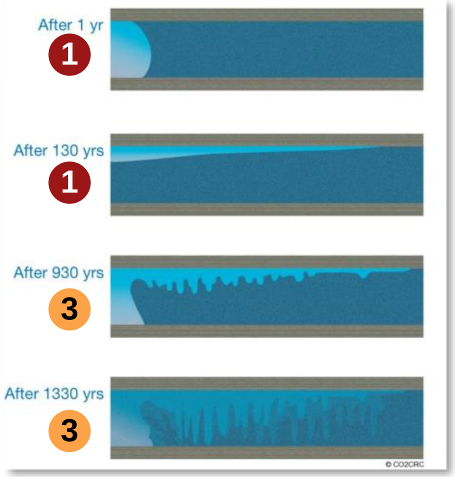
Main storage R&D axis

1. Assess country-wide storage space:
   - Early results seem to indicate massive theoretical storage potential globally;
   - most of the potential lies within deep saline aquifers, which are geographically widespread;
   - Pore space in depleted oil and gas reservoirs is suitable but has limited availability;
   - According to the GCCSI, “the importance of undertaking storage-related actions this decade to prepare for widespread CCS deployment post-2020 cannot be overstated”.
2. Understand CO_2 behavior, through:
   - Large-scale field demonstrations in aquifers;
   - Software modeling tools of key trapping mechanisms:
     ① Physical trapping of mobile CO_2 plume
     ② Residual trapping of immobile CO_2 bubbles
     ③ Solubility trapping of dissolved immobile CO_2
   - Reservoir engineering to manage risk of leakage;
   - Monitoring, verification and accounting (MVA);
   - International standards for MVA and risk assessments;

Simplified behavior of CO_2 after injection







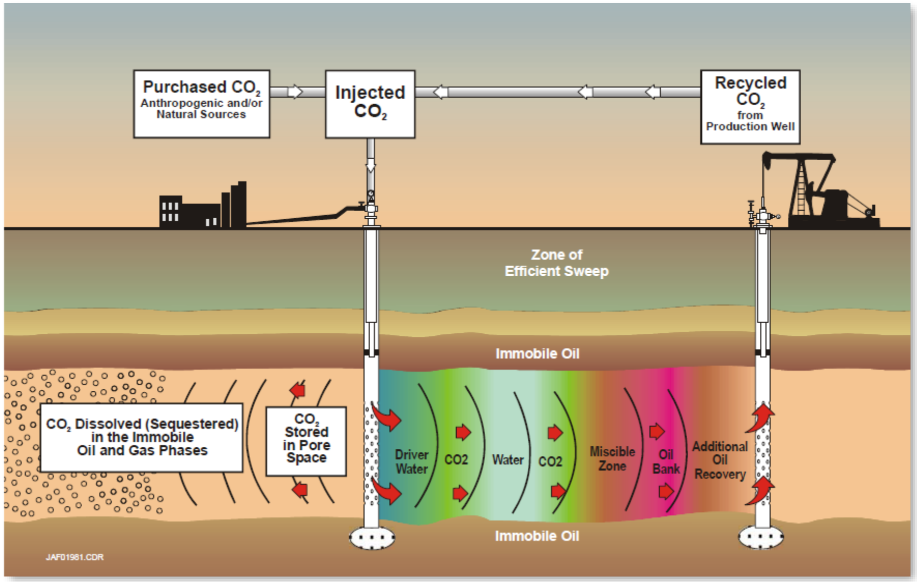
Source: GCCSI (2014), “Global Status of CCS”; Picture credits: CO2CRC; CAGS

Beyond geological storage, CO_2 could also be reused for various revenue-generating purposes

Options for carbon capture and use

- **CO2-EOR**: injection of CO2 into nearly depleted petroleum reservoirs acts as a solvent that reduces the viscosity of the oil and allows enhanced oil recovery of the reservoir. Once the field is depleted, it can be utilized to store additional CO2 permanently.
- **ECBM (Enhanced Coal Bed Methane):** injection of CO2 in coal seams adsorbs and captures CO2 while releasing methane. This process is unproved on a commercial scale but has the potential to utilize diluted CO2 in flue gas and avoids capture and compression costs.
- **Urea yield boosting**: production of urea (a fertilizer) through the reforming of natural gas requires more CO2 than obtained in the reforming process. It is a proven technology.
- **Algae fixation**: the engineered capture of CO2 by photosynthesis, where algae are fed with a pure stream of CO2 to convert them directly into liquid fuels is still in the early stage of demonstration.
- **Mineralization**: CO2 is stored in the form of limestone or other calcium carbonates and integrated within concretes and cements.
- **CO2-EGS**: this alternative to enhanced geothermal systems uses CO2 as working fluid in place of water.

Enhanced Oil Recovery (EOR) principles



Source: A.T. Kearney Energy Transition Institute. Picture credit: IEA Greenhouse Gas R&D Program (IEA GHG), “CO2 Storage in Depleted Oilfields: Global Application Criteria for Carbon Dioxide Enhanced Oil Recovery”

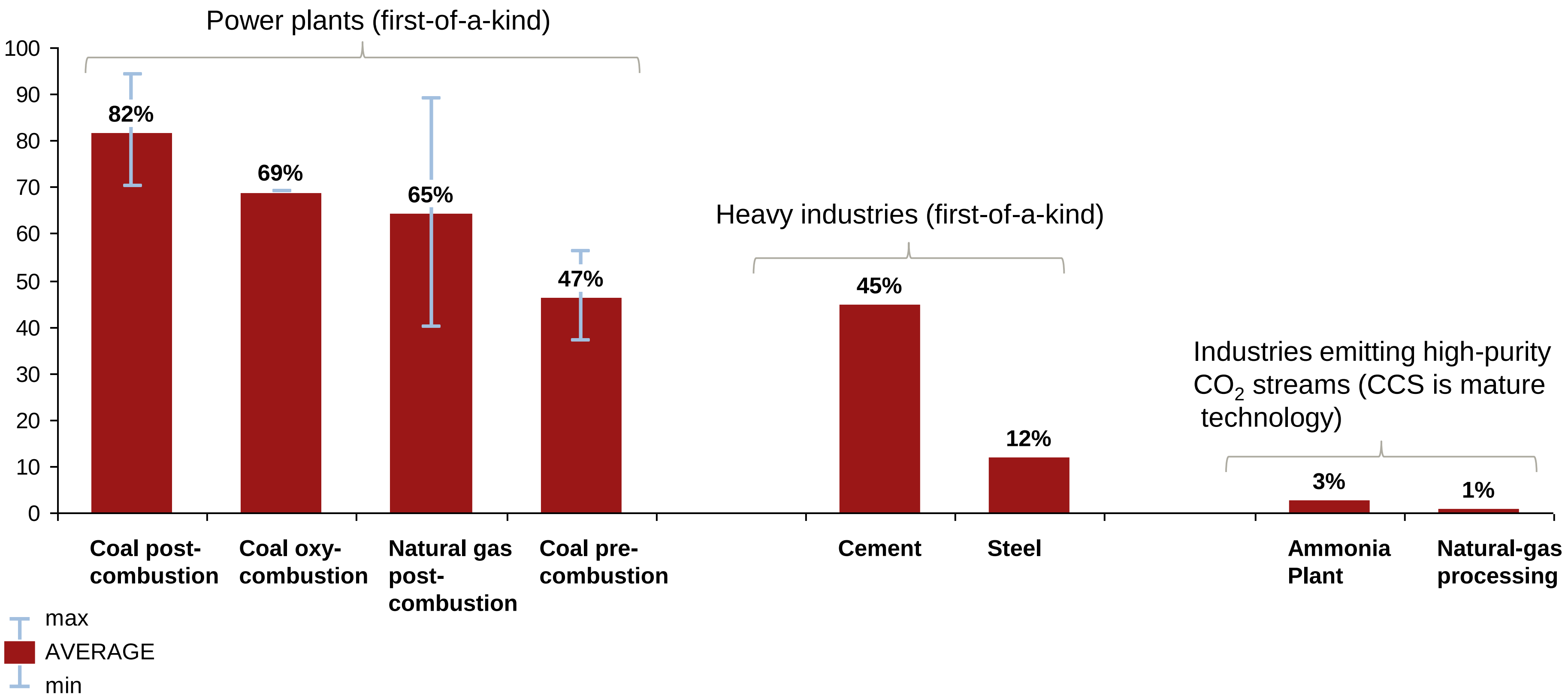
3. Economics

- CCS requires strong political support for decarbonization

Applying CCS to power plants greatly increases the levelized cost of production

Increase in levelized cost of production for CCS plants

Based on current technologies in the US, with storage site at 100 km by pipeline in an identified aquifer



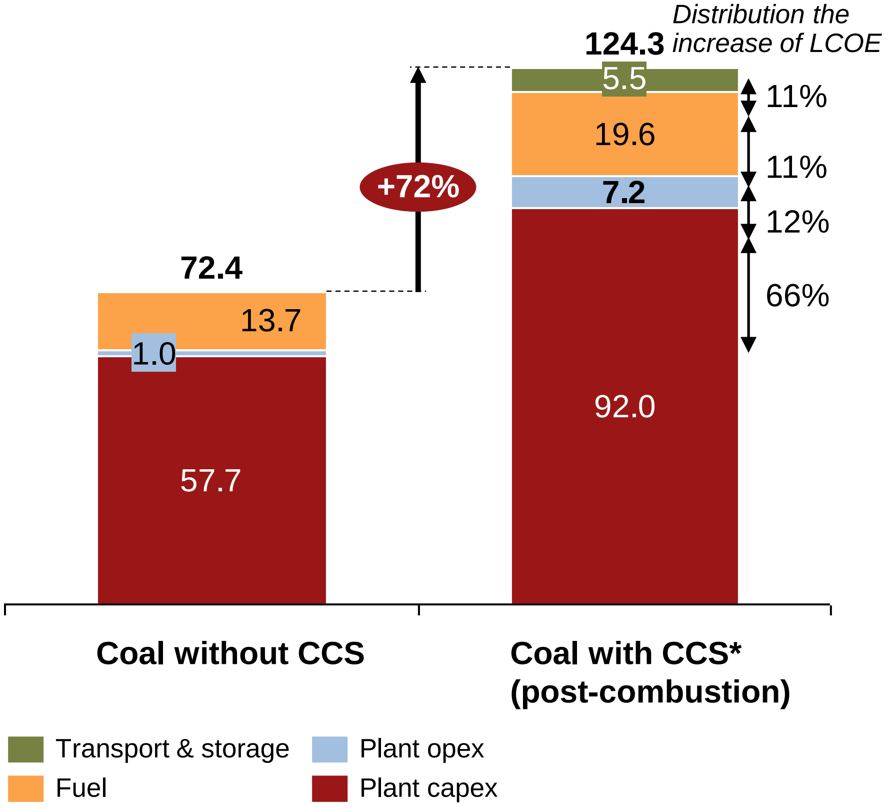
1. Natural gas plant uses combined cycle technology (NGCC). Post-combustion and oxy-combustion base plant are supercritical pulverized coal. Pre-combustion base plant is an integrated gasification combined-cycle unit.

Source: Global CCS Institute (2011), "Economic Assessment of Carbon Capture and Storage Technologies"; BNEF (2012), online

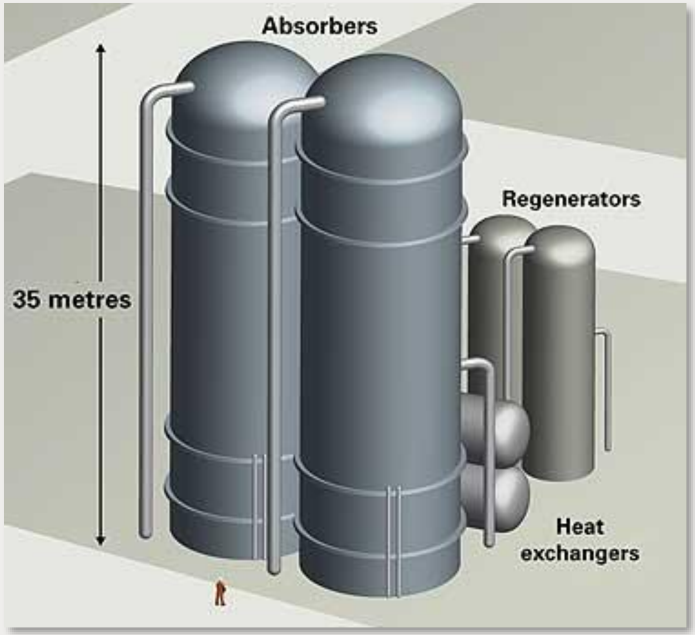
In power generation, the cost penalty is largely due to the capture process

Levelized Cost Of Electricity (LCOE)

$/MWh



Illustrative 500MW Post-combustion system



Whichever capture technology is used:

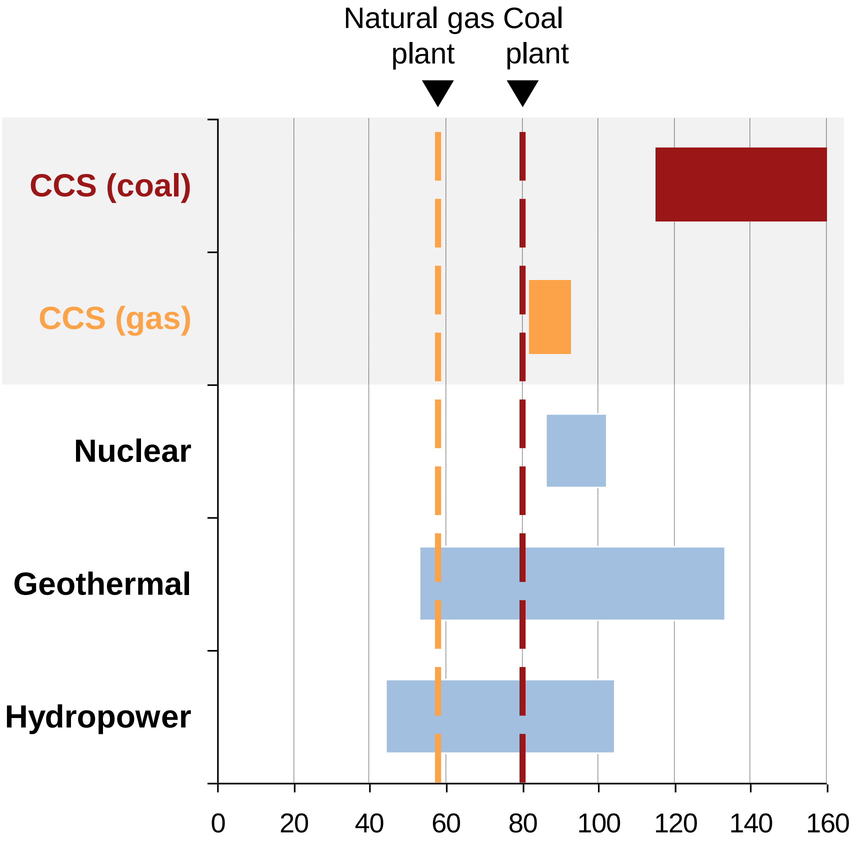
- Over two-third of the increase in LCOE comes from capture.
- An energy penalty of 16% to 43% is incurred by the capture system.

* First-of-a-kind supercritical pulverized coal power plant with amine-based post-combustion capture and onshore aquifer storage at 100 km by pipeline

Source: BNEF (2012), "Q4 2011 CCS Outlook."

In terms of levelized cost of electricity (LCOE), gas-fired CCS power plants are more attractive than their coal counterparts in the U.S. due to low natural gas prices

Range Of LCOE for non-intermittent[1] power plants in the US in 2014 - $/MWh



- Based on preliminary engineering studies, the LCOE of coal power plants with CCS is generally higher than the LCOE of other types of baseload plants in the U.S.
- Thanks to relatively cheap natural gas prices in the US ($5/mmbtu in this analysis), natural gas-fired CCS power plants are nearing competitiveness with nuclear.
- Nevertheless, LCOE alone is not a sufficient metric from which to draw conclusions:
  - **Costs decrease over time**: Costs of CCS power are difficult to estimate because of the lack of full-scale plants in operation: The largest plant has a capacity of 100MW, and total combined CCS power capacity only amounts to about 300MW. Cost reductions are expected the more new plants with similar designs are built (see next slide);
  - **Power plants have varying degrees of flexibility**: Although CCS power plants will never be able to ramp up and down faster than their non-CCS counterparts, ingenious capture design could limit the CCS flexibility penalty. However, this comes at a cost: for instance, amine-based post-combustion gas CCS plants can be made more flexible by storing spare, regenerated solvents for use in the case of a rapid ramp-up.

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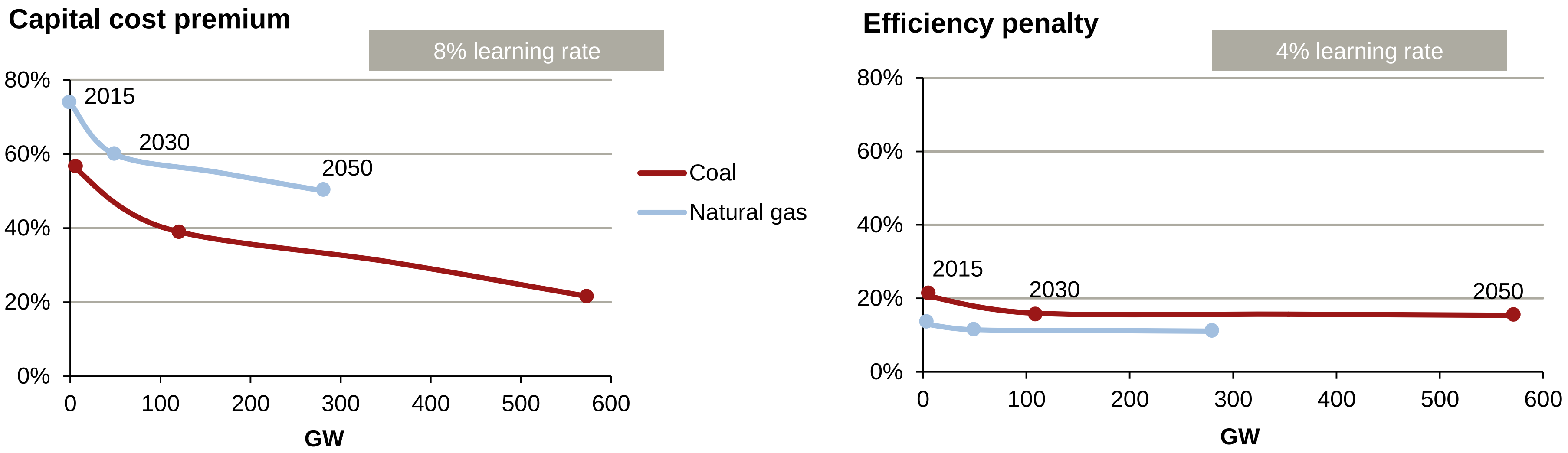
1. Excludes wind and solar resources. 8% discount rate is assumed in this study.

Source: Graph: Adapted from GCCSI (2015) "The cost of CCS and other low-carbon technologies in the US"; IEA (2015), "CCS-equipped power generation can be flexible, but it comes at a cost"

Cost reductions will happen in the long run as capacity installation grows, but few breakthroughs are expected before the end of the demonstration phase

Expected CCS Power Plant Learning curve in IEA 2DS Scenario



Capital cost premium

Efficiency penalty

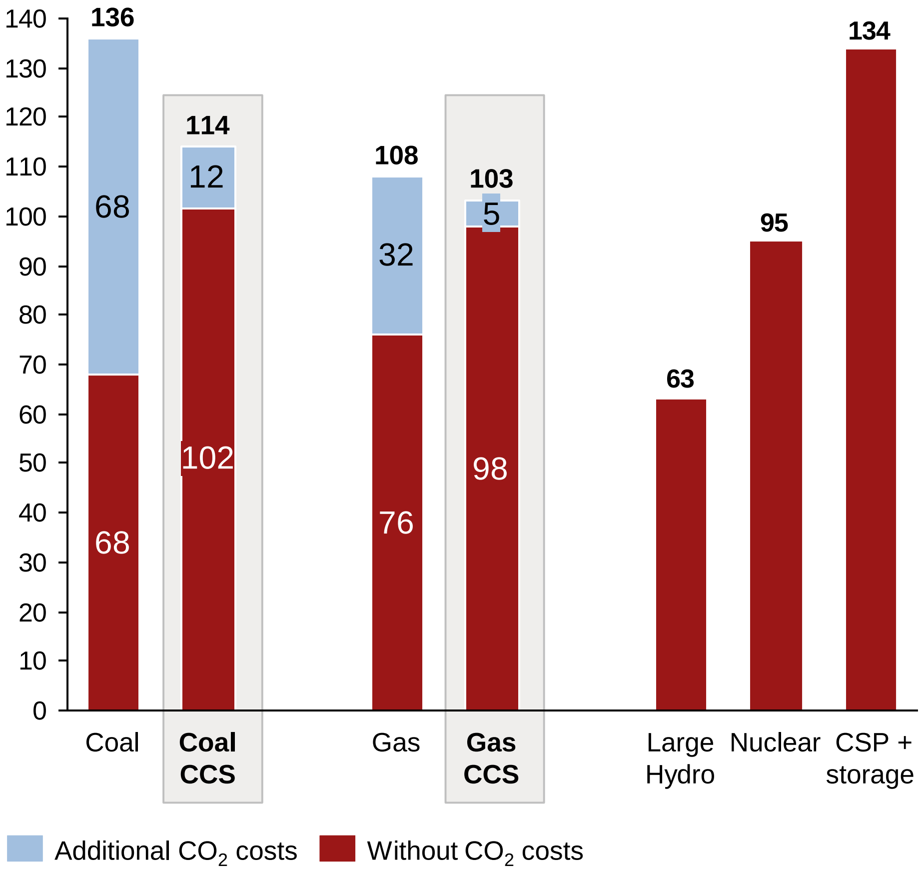
- As CCS capacity installation increases, new generations of plant design (learning-by-researching) are created and serial constructions (learning-by-doing) reduce CCS costs.
- The *learning rate* defines the percentage reduction for each doubling of cumulative capacity installed: According to IEA's 2DS scenario, CCS capital costs in power generation[1] are expected to achieve an 8% learning rate, and efficiency a 4% learning rate.
- As a consequence, the LCOE of post-combustion coal-fired CCS power plants should fall by 30% between 2020 and 2050 (13% by 2030).
- Wider deployment of CCS in coal as opposed to gas should enable deeper cost reductions for the former.

1. Note that most scenarios assume such learning, which explains the urgency in embarking the learning curve, as otherwise assumed cost reductions will not be achieved.

Source: Adapted from IEA (2015), "Energy Technology Perspective"

CCS power could become competitive with other dispatchable options by 2030 in Europe as a result of cost reductions and changes in carbon pricing

2030 Europe LCOE of dispatchable power plant in IEA 2DS Scenario[1] - $/MWh



According to the IEA 2DS Scenario:

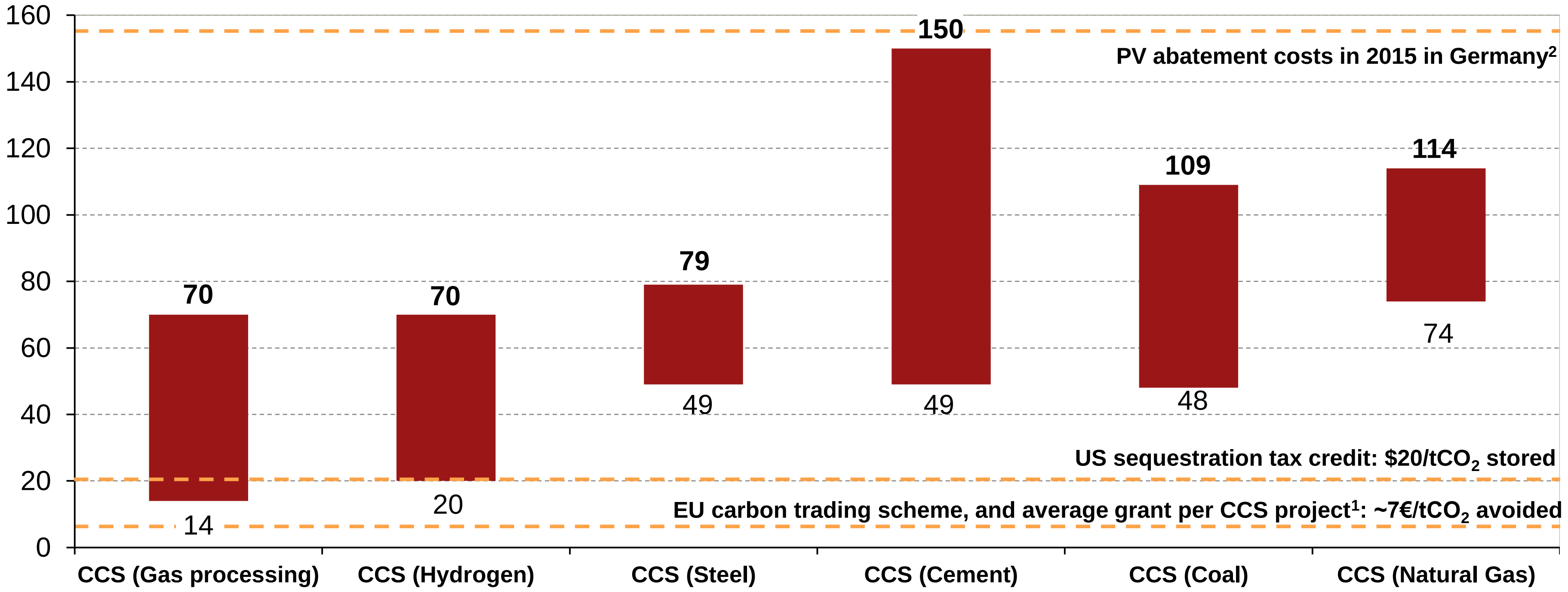
- **In Europe[1]**, by 2030:
  - CCS power plants become competitive with alternative dispatchable power plants (see graph);
  - Carbon price increases to $90 /tCO2 so that CCS actually reduces the levelized cost of a coal or gas plant (see next slide for cost of CO2 avoided);
  - Demand for coal declines and prices fall, further improving the competitiveness of coal CCS.
- **In the US[2]**, as natural gas is expected to be widely available in the medium term, CCS is only expected to be a competitive abatement option (compared with coal-to-gas switching, onshore wind and solar PV) by 2030 or 2040, after the deployment of about 200 GW of CCS power plants.
- **In China[2]**, applying CCS to coal-fired power plants will be a less expensive mitigation option than coal-to-gas switching by 2020, but will remain more expensive than onshore wind or solar PV throughout the period to 2040.

CO_2 price in 2030: $90/t; Coal: Ultra supercritical pulverized coal power plant; Gas: Combined cycle gas turbine; Nuclear: Light water reactor; CSP: Concentrated Solar Power; The LCOE for fossil fuel and nuclear technologies is calculated on the basis of a 75% capacity factor; the values for CSP with 6 h storage and large hydro assume a 40% capacity factor.

Source: 1. IEA (2015) "Energy Technology Perspective"; 2. IEA (2015) "World Energy Outlook - special report on energy and climate change"

CCS offers opportunities for CO_2-abatement at a moderate cost, especially in industrial applications where CO_2 separation is already inherent to the process

Current Costs of CO_2 avoided by CCS in the US, relative to the same plant without CCS - \$/tCO_2 avoided relative to the same plant without CCS

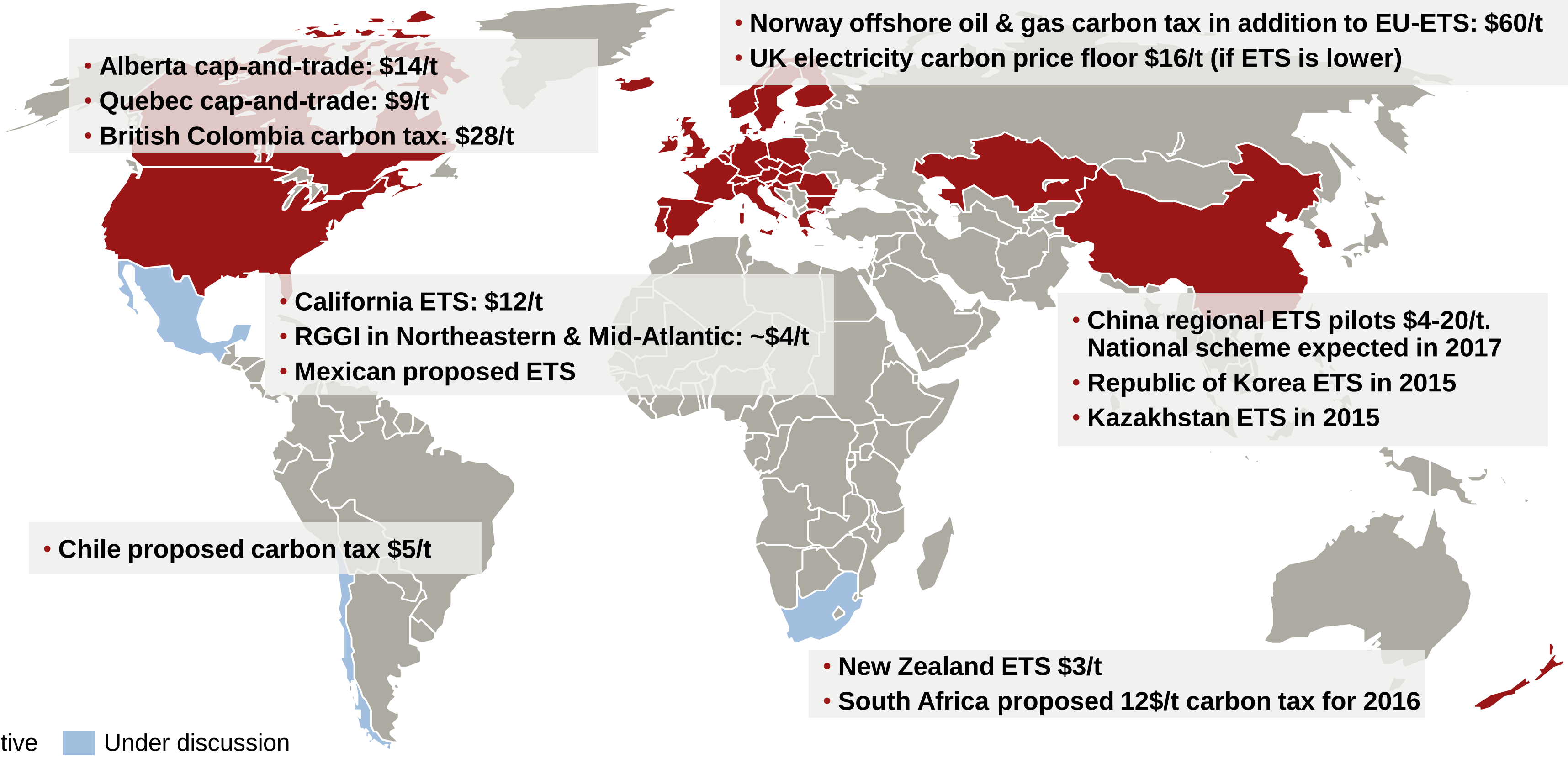


Range of studies at 8% discount rate for CCS power plants, and 10% for other. Hydrogen refers to syngas plants: coal-to-liquid, steam methane reforming, ammonia or fuel upgrading;
1. Sum of all allocated grants over the cumulated CO_2 abatement of all large projects that have received public capital grants (range: 4.5\$/tCO2 for Kemper County to 30\$/t for FutureGen 2.0), assuming a plant lifetime of 30 years; 2. 35.2 TWh of Solar PV generated in Germany in 2014 avoided about 23 MtCO_2 during the year (0.66tCO_2/MWh), at a cost of about 143€/tCO_2 avoided if using the January 2015 feed-in-tariff price of €95/MWh for utility-scale PV plants (Fraunhofer 2015)
Sources: GCCSI (2015), “The costs of CCS and other low-carbon technologies” for coal and gas; IEA (2011), “Industrial Roadmap for Hydrogen”; GCCSI (2011), “Economic assessment of CCS technologies”. Fraunhofer (2015), “Recent facts about PV in Germany”

Carbon prices are generally too low to render CCS commercial on their own, except in Norway

Explicit carbon price that could apply to CCS (cap-and-trade or carbon tax)

$/tCO2, as of Q4 2014



- **EU-ETS ~$8/t**
- **Norway offshore oil & gas carbon tax in addition to EU-ETS: $60/t**
- **UK electricity carbon price floor $16/t (if ETS is lower)**

- **Alberta cap-and-trade: $14/t**
- **Quebec cap-and-trade: $9/t**
- **British Colombia carbon tax: $28/t**

- **California ETS: $12/t**
- **RGGI in Northeastern & Mid-Atlantic: ~$4/t**
- **Mexican proposed ETS**

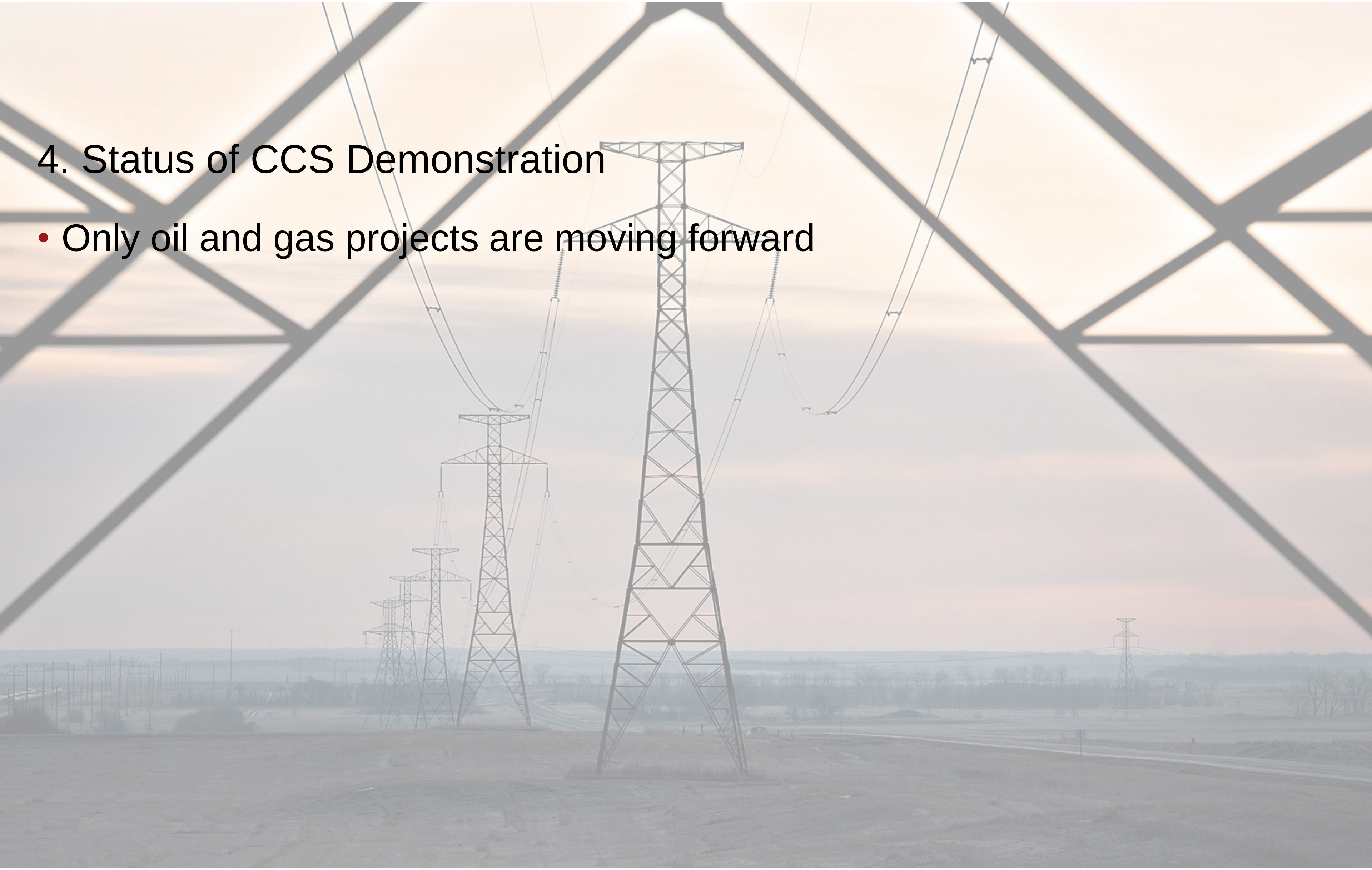
- **China regional ETS pilots $4-20/t. National scheme expected in 2017**
- **Republic of Korea ETS in 2015**
- **Kazakhstan ETS in 2015**

- **Chile proposed carbon tax $5/t**

- **New Zealand ETS $3/t**
- **South Africa proposed 12$/t carbon tax for 2016**

🟥 Active 🟦 Under discussion

Source: World Bank (2014), “State and Trends of Carbon Pricing”

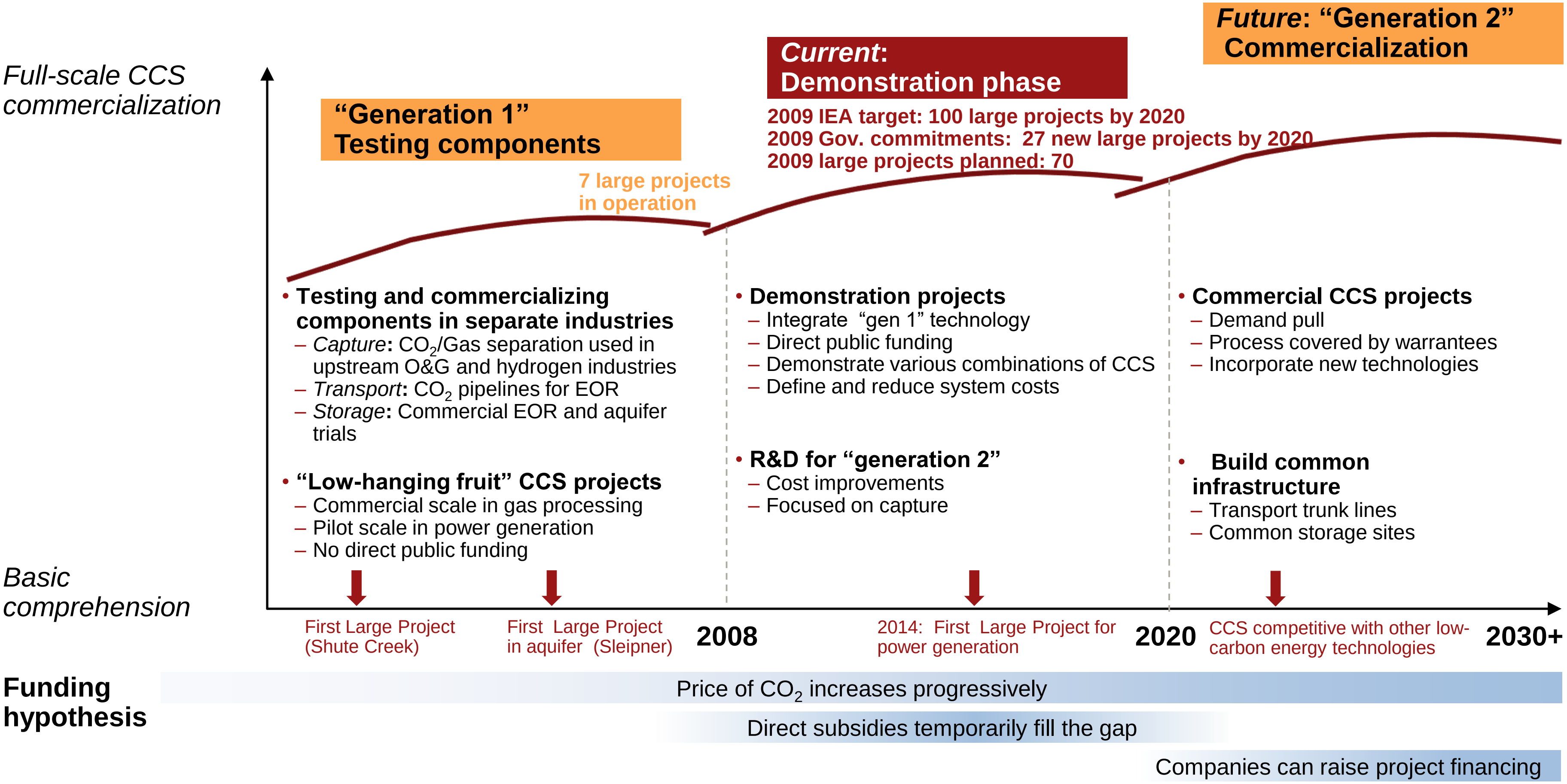


4. Status of CCS Demonstration

- Only oil and gas projects are moving forward

Since 2009, many companies have taken part in CCS pilot projects

Stage of CCS development



- **Testing and commercializing components in separate industries**
  - *Capture*: CO_2/Gas separation used in upstream O&G and hydrogen industries
  - *Transport*: CO_2 pipelines for EOR
  - *Storage*: Commercial EOR and aquifer trials
- **“Low-hanging fruit” CCS projects**
  - Commercial scale in gas processing
  - Pilot scale in power generation
  - No direct public funding

- **Demonstration projects**
  - Integrate “gen 1” technology
  - Direct public funding
  - Demonstrate various combinations of CCS
  - Define and reduce system costs
- **R&D for “generation 2”**
  - Cost improvements
  - Focused on capture

- **Commercial CCS projects**
  - Demand pull
  - Process covered by warrantees
  - Incorporate new technologies
- **Build common infrastructure**
  - Transport trunk lines
  - Common storage sites

Funding hypothesis

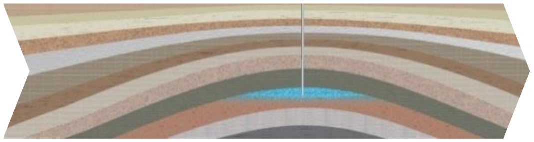
Price of CO_2 increases progressively

Direct subsidies temporarily fill the gap

Companies can raise project financing

Large Projects’ refers to integrated CCS projects larger than 0.6 MtCO2/year.
Source: A.T. Kearney Energy Transition Institute

CCS entered the demonstration phase in 2008, initially supported by strong government commitments toward decarbonization

	CO_2 capture	**Transport**	**Storage**
			
Key service providers	• **Equipment manufacturers**: Alstom, MHI,GE, Siemens, Swann Hill, Babcock & Wilcox, Pall Corp • **Industrial gas producers**: Air Liquide, Air Product, Linde, Praxair, Aker • **Chemicals producers**: UOP, Lurgi, Dow, Flour, BASF, Akema • **Utilities and O&G companies**: ConocoPhillips, ExxonMobil, Statoil, Tokyo, Tohoku and Hokuriku Electric Power, Vattenfall, NorskHydro…) • **Start-ups** in second-generation capture	• National Grid • Maersk Tankers • Kinder Morgan • Trinity Pipeline • GDF Suez	• EOR producers: Denbury Resources, Chaparral Energy, Enhance Energy, Chevron • **Passive storage service providers**: Schlumberger, Halliburton, Petrofac, C12 company, Geogreen, Shell, TAQA • HTC Purenergy (services along the whole CCS value chain)
Key project owners	• **European utilities**: 2CO Energy, Drax Power, Electrabel, E.ON, Enel, Endesa, PGE, RWE, Scottish and Southern Energy, Scottish Power, Vattenfall • **American utilities**: AEP, Captial Power, SCS Energy, Southern Company, Summit Power, SaskPower, Tenaska, TransAlta • **Asia-pacific utilities**: China Datang Corp, Dongguan Power, GreenGen, Huaneng Group (China); KEPCO (South Korea) ; SC Energy (Australia) • **Major O&G companies**: Shell, BP, ExxonMobil, Total, Eni, Chevron • **National Oil Companies**: Statoil, Sonatrach, Kuwait Petroleum Corporation, Saudi Aramco, Masdar, Petrobras, Pemex • **Coal**: Consol Energy, Peabody Energy, Rio Tinto, Xstrata Coal • **Chemicals, fertilizers, synfuels**: Archer Daniels Midland, Air Products, Koch Nitrogen, Shenhua Group, Sasol • **Steel** : ULCOS consortium (Arcelormittal, and other European steelmakers), Emirate Steel		

Source: A.T. Kearney Energy Transition Institute (2012) “Bringing CCS to Market”

The first large-scale CCS power plant began operation in October 2014 in Canada, marking a landmark in clean fossil-fuel power generation

Saskpower Boundary Dam CCS Project

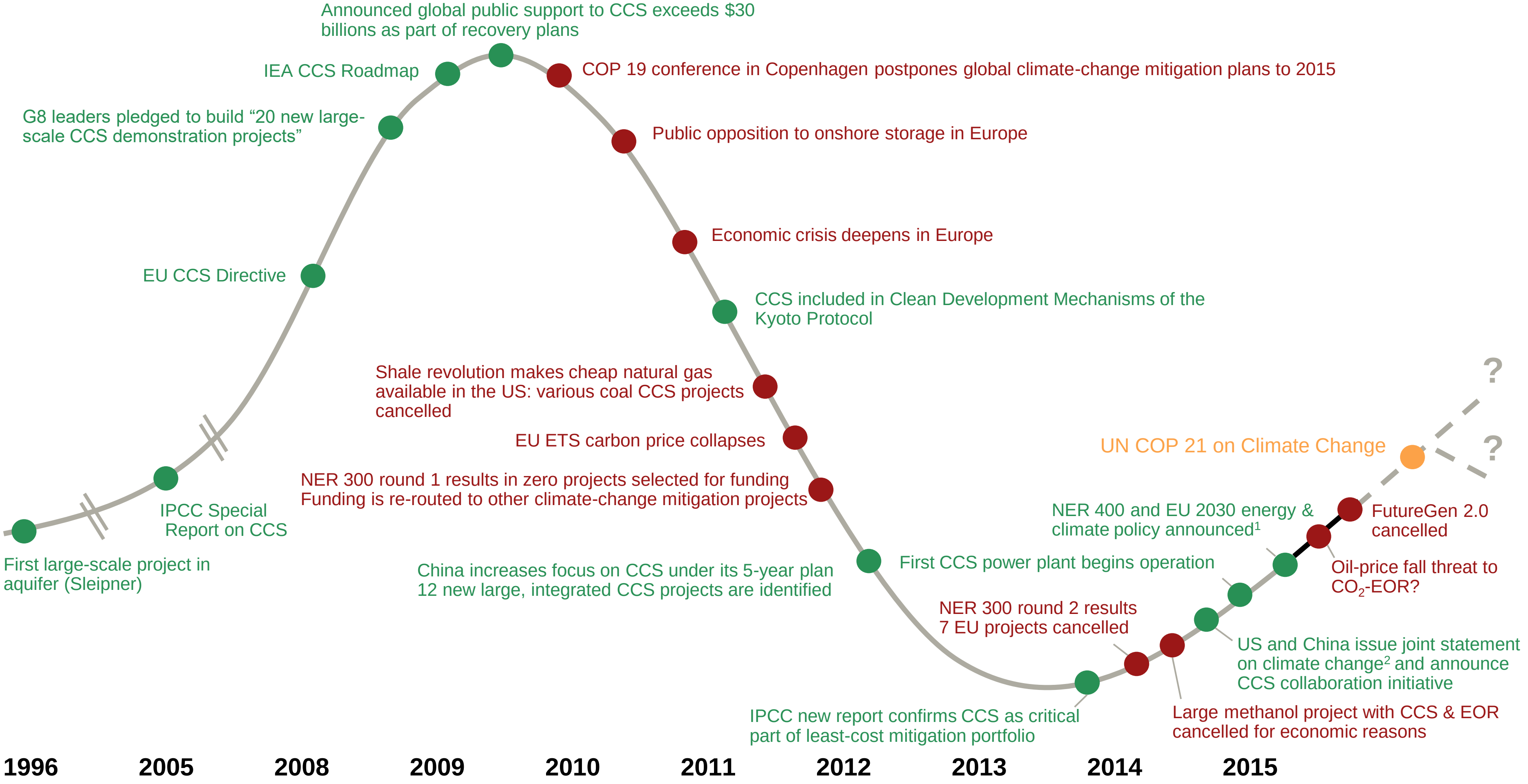
Project characteristics	Details
Power capacity with CCS	• 110MW, 90% CO$_2$ emissions captured, 1 MtCO$_2$/year
Total capital costs	• $1.42 billion (8% over budget)
Carbon capture unit cost	• $620 million
Government funding	• $314 million
Capture type	• Post-combustion by Cansolv (Shell)
Transport type	• Pipeline (built and owned by Cenovus)
Storage type	• EOR (sold to Cenovus)
Planning	• Plan start: Feb 2008. Construction start: Apr 2011. Operation start: Oct 2014 (6 month delays)

- After more than six years in planning, **CCS for power generation has finally become a reality** with the opening of the SaskPower Boundary Dam, the first large-scale CCS power plant in operation.
- After initial start-up hic-ups, the plant appears to be running "exceptionally well“ as of Q1 2016, and has captured 0.75MtCO$_2$ since operational start-up
- **This project illustrates the substantial up-front costs required by each large integrated CCS project**: $640m in pure capture costs excluding pipelines (~$20m for 100 km), storage site characterization and storage facilities (up to a dozen injection wells, depending on reservoir quality).
- **Although of commercial-scale, Boundary Dam is not a commercial initiative**: SaskPower, a state-owned utility monopoly, has received public grants and increased electricity tariffs to finance the project.
- Other facilitating factors for SaskPower include low-cost local fuel (lignite), CO$_2$ sales for EOR, and the absence of transport costs, as Cenovus is building and owns the related transport pipeline.
- Saskpower CEO estimates the LCOE for Boundary Dam to be similar to that of a new-build gas combined cycle plant in the region.

Source: BNEF (2014) “Operational CCS in Canada: blueprint or one-hit wonder?”. Picture Credit: Adapted from Saskpowerccs.com

CCS is currently at a crossroad

CCS Political Attractiveness Curve



First large-scale project in aquifer (Sleipner)

IPCC Special Report on CCS

EU CCS Directive

G8 leaders pledged to build "20 new large-scale CCS demonstration projects"

IEA CCS Roadmap

Announced global public support to CCS exceeds $30 billions as part of recovery plans

COP 19 conference in Copenhagen postpones global climate-change mitigation plans to 2015

Public opposition to onshore storage in Europe

Economic crisis deepens in Europe

CCS included in Clean Development Mechanisms of the Kyoto Protocol

Shale revolution makes cheap natural gas available in the US: various coal CCS projects cancelled

EU ETS carbon price collapses

NER 300 round 1 results in zero projects selected for funding
Funding is re-routed to other climate-change mitigation projects

China increases focus on CCS under its 5-year plan
12 new large, integrated CCS projects are identified

First CCS power plant begins operation

IPCC new report confirms CCS as critical part of least-cost mitigation portfolio

NER 300 round 2 results
7 EU projects cancelled

Large methanol project with CCS & EOR cancelled for economic reasons

US and China issue joint statement on climate change[2] and announce CCS collaboration initiative

NER 400 and EU 2030 energy & climate policy announced[1]

Oil-price fall threat to CO_2-EOR?

FutureGen 2.0 cancelled

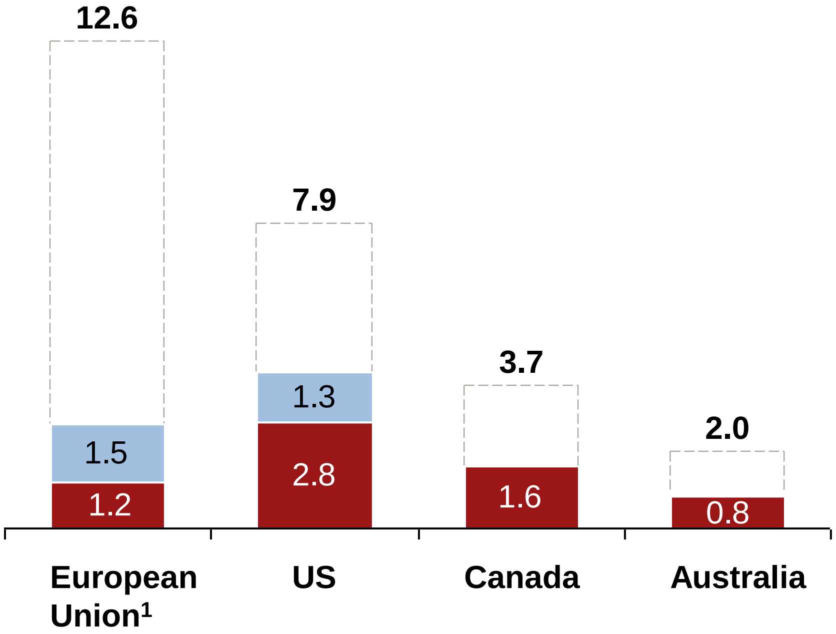
UN COP 21 on Climate Change

COP: United Nation Conference of the Parties. NER: New Entrant Reserve fund for climate mitigation in Europe. EU ETS: European Emission Trading Scheme; 1. EU GHG reduction goal: 40% by 2030; 2. US GHG reduction goal: 26-28% by 2030. China's reduction goal: from 2030 onwards.
Source: A.T. Kearney Energy Transition Institute

Committed public funding is a fraction of initially hoped-for levels, due to depressed carbon prices, projects being cancelled and funds not being reallocated

Global Public Funds Committed TO CCS demonstration plants (2007-2015)

$ billion



Total as of 2015 = $9.2 billion committed

- ⬚ Q4 2011 estimates: $26 billion
- 🟦 Unallocated as of 2015: $2.8 billion
- 🟥 Allocated as of 2015: $6.4 billion to 14 large projects

- In Europe, two funding schemes (EERP and NER 300)2 originally hoped to provide funding of €7-10 billion for CCS demonstration. Less than 10% of this amount has been granted to the only three remaining projects, because of depressed ETS carbon prices, and other projects being cancelled or failing to comply with the various financial and schedule requirements. A new NER 400 grant has been announced, which envisages giving 400 million allowance units (€3 billion at current prices) to clean technologies – including CCS – by 2020 (not included in this graph). In the UK, a £1bn funding for the UK CCS Commercialisation Competition and a proposed multi-billion pounds electricity levy for CCS was also abandoned.
- The US has allocated various grants for CCS demonstration under the AARA2, as well as tax credits for the disposal of CO2 in secure geological storage (US$20/tCO2) or for EOR (US$10/t). However, several projects awarded grants have been cancelled before spending them, and the money has not been reallocated.
- Canada's grant programs have delivered various successful CCS-demonstration projects, including the world's first CCS power plant in 2014. Grant funding has diminished because some projects have been cancelled for economic reasons.
- Funding available under Australia's flagship CCS-grant program, financed by a levy on coal production, has been slashed from the originally expected $1.9 billion.

1. Includes EU member state grant schemes: £1 billion from CCS Flagship Program (UK) and €300 million from the Netherlands; 2. AARA: American Recovery and Reinvestment Act; EERP: Energy Program for Recovery; NER 300 and NER 400 are funding processes organized by the European Commission that aim to sell 300 and 400 million allowance units, respectively, from the EU-ETS to subsidize clean technologies, including CCS;

Source: A.T. Kearney Energy Transition Institute based on Global CCS Institute (2013) and MIT CCS Initiative online database, and BNEF (2012), "Q4 2011 CCS Outlook"

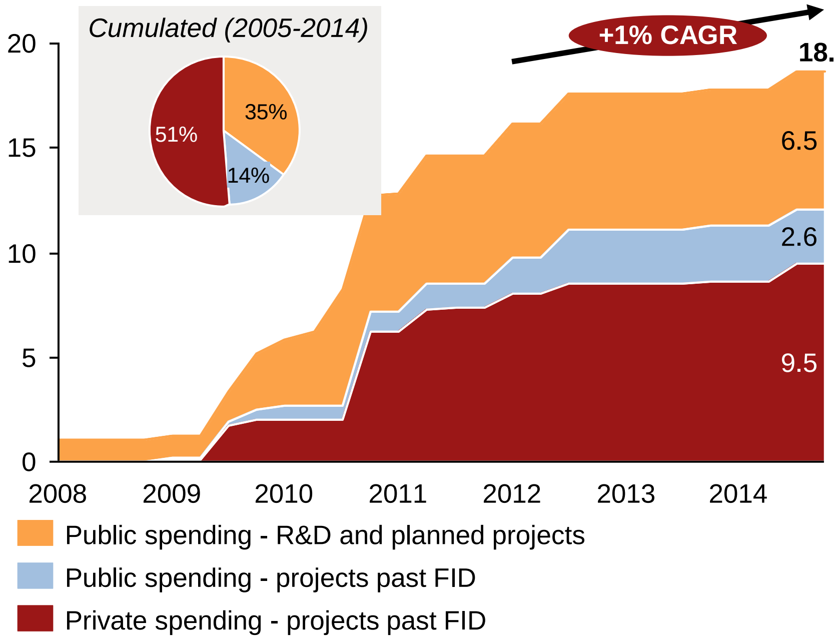
Actual spending on CCS projects has virtually stalled since 2012, and now amounts to less than $20 billion, half of which is privately invested in integrated plants

Global Public Funds Committed TO CCS demonstration plants (2007-2015)

$ billion

Actual Money Spent on CCS

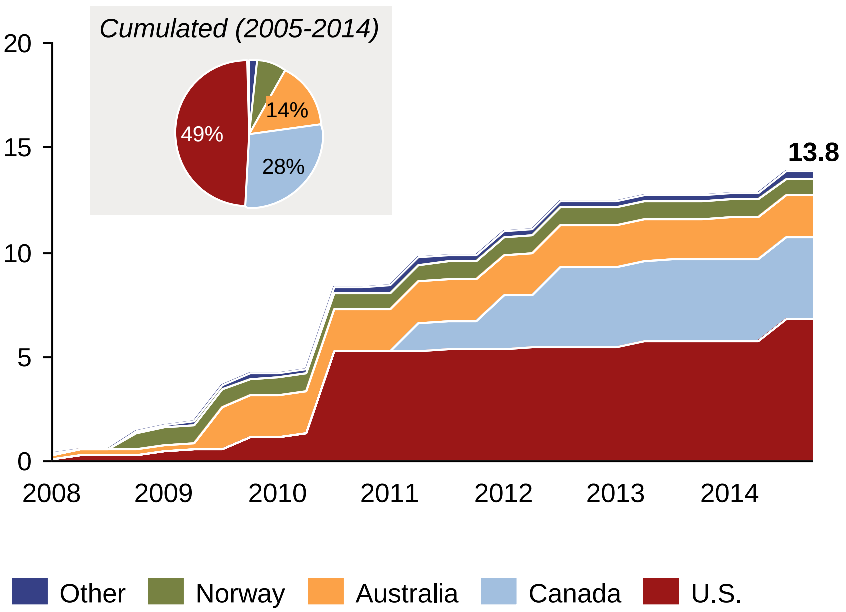
$ billion, cumulated since 2007



- Since 2012, no new public funding has been announced for integrated projects, and CCS investments have paused

Actual Money Spent on integrated plants

$ billion, cumulated since 2007



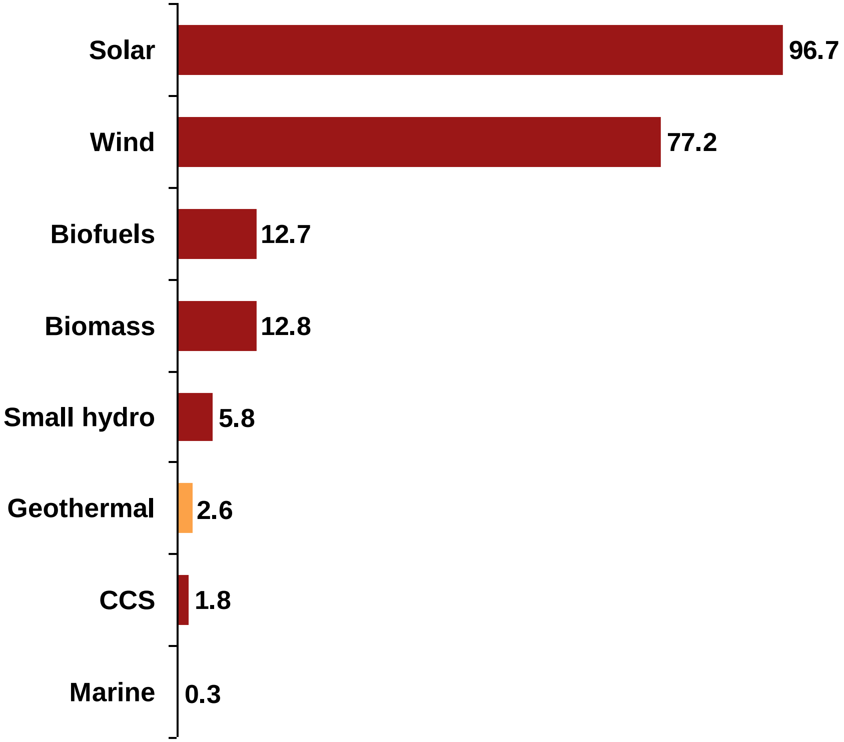
- The vast majority of integrated projects' investments have been made in North America, especially since 2010.
- No integrated project has passed FID in Europe yet.

Actual money spent refers to confirmed investments that have passed financial investment decisions (FID). It excludes private R&D figures, which are mostly undisclosed, and those related to capture-ready plants and gas-processing plants that sell CO2 for EOR.
Source: BNEF (2015), "H1 2015 CCS Market Outlook"; IEA (2015), "Energy Technology Perspective"

CCS investments remain insignificant compared with those in renewables, and the growth rate of CCS is well below the IEA's recommended level

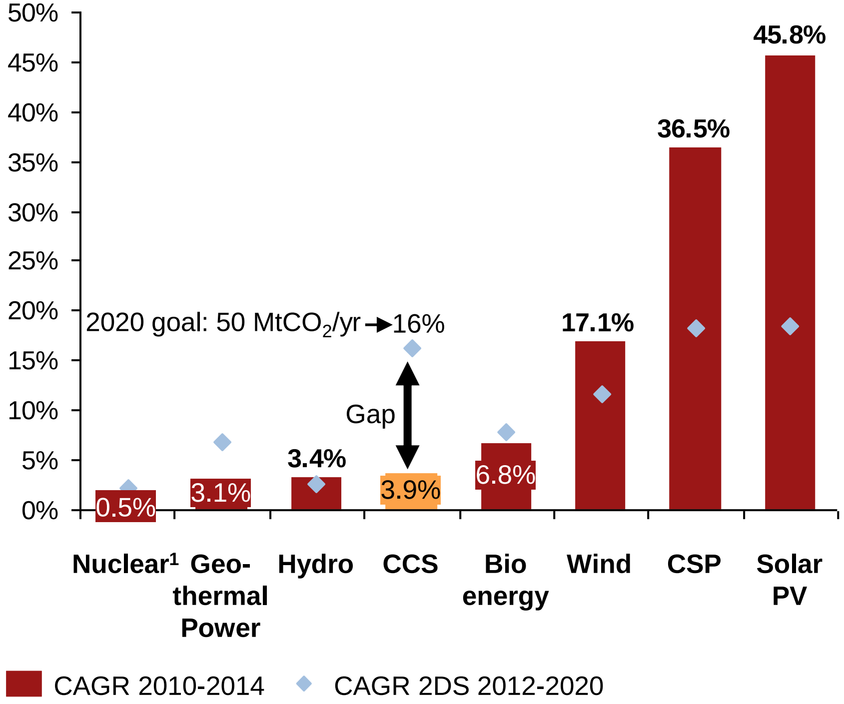
Annual project finance Investments in selected clean technologies

$ billion, 2007-2013 average



Actual Versus Recommended Growth Rate in IEA's 2DS Scenario

Compound annual growth rate (CAGR) in installed capacity



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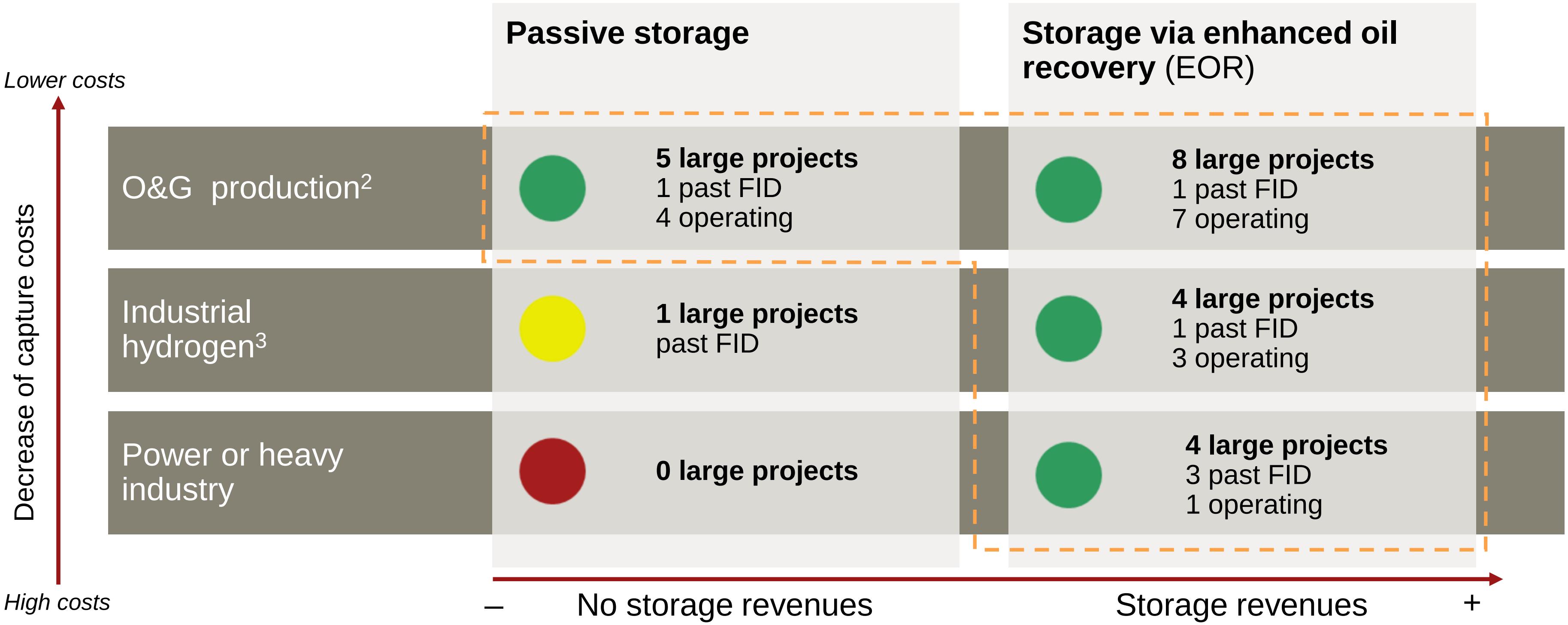
1. Nuclear actual CAGR is for 2000-2012;

Source: Left graph: UNEP (2014), "Global Trend in renewable Investment"; right graph: A.T. Kearney Energy Transition Institute, based on IEA (2015) "Energy Technology Perspective"; IRENA (accessed 2015), "Data and statistics"; GCCSI (2014), "Global Status of CCS"

So far, CCS has been advancing at two speeds: O&G-related projects are making progress, but CCS in power and industrial plants without EOR has stagnated

Distribution of the 22 Large Projects[1] in operation or past final Investment decision (FID) - As of April 2016



	Passive storage	**Storage via enhanced oil recovery** (EOR)
O&G production[2]	🟢 **5 large projects** 1 past FID 4 operating	🟢 **8 large projects** 1 past FID 7 operating
Industrial hydrogen[3]	🟡 **1 large projects** past FID	🟢 **4 large projects** 1 past FID 3 operating
Power or heavy industry	🔴 **0 large projects**	🟢 **4 large projects** 3 past FID 1 operating

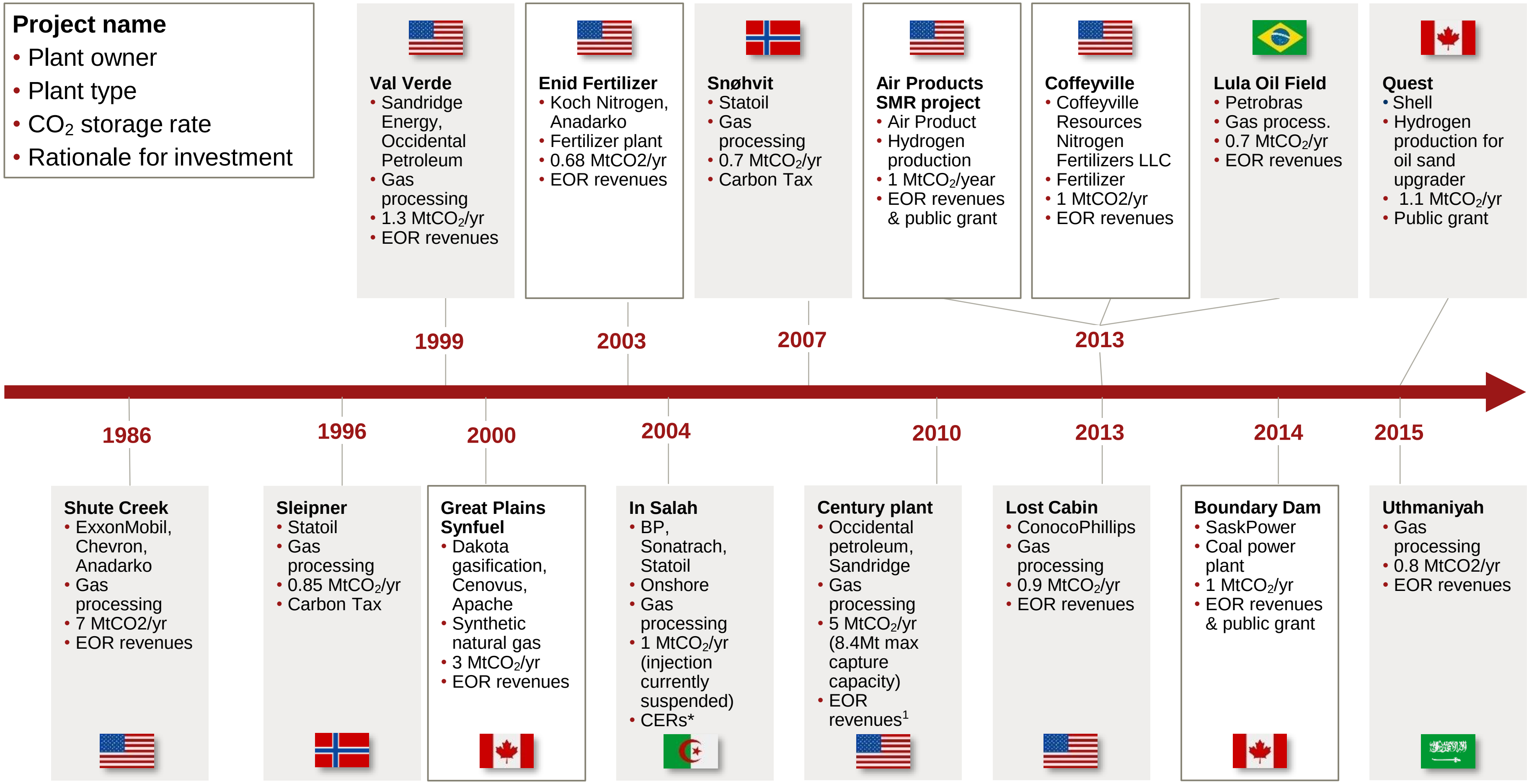
⬚ O&G-related 🟢 Proven 🟡 Final investment decisions made 🔴 Standstill

1. "Large projects" refers to integrated CCS projects above 0.6 MtCO2/year; 2. Natural-gas processing plant, oil sand upgraders or synthetic natural gas; 3. Steam methane reformers or coal gasification plants producing hydrogen for chemicals or fertilizers. FID: Final Investment Decision

Source: A.T. Kearney Energy Transition Institute analysis based on GCCSI database

All integrated projects in operation are associated with the oil and gas industry

Project name
- Plant owner
- Plant type
- CO_2 storage rate
- Rationale for investment



1986

Shute Creek
- ExxonMobil, Chevron, Anadarko
- Gas processing
- 7 MtCO2/yr
- EOR revenues

1996

Sleipner
- Statoil
- Gas processing
- 0.85 $MtCO_2/yr$
- Carbon Tax

1999

Val Verde
- Sandridge Energy, Occidental Petroleum
- Gas processing
- 1.3 $MtCO_2/yr$
- EOR revenues

2000

Great Plains Synfuel
- Dakota gasification, Cenovus, Apache
- Synthetic natural gas
- 3 $MtCO_2/yr$
- EOR revenues

2003

Enid Fertilizer
- Koch Nitrogen, Anadarko
- Fertilizer plant
- 0.68 MtCO2/yr
- EOR revenues

2004

In Salah
- BP, Sonatrach, Statoil
- Onshore
- Gas processing
- 1 $MtCO_2/yr$ (injection currently suspended)
- CERs*

2007

Snøhvit
- Statoil
- Gas processing
- 0.7 $MtCO_2/yr$
- Carbon Tax

2010

Century plant
- Occidental petroleum, Sandridge
- Gas processing
- 5 $MtCO_2/yr$ (8.4Mt max capture capacity)
- EOR revenues[1]

2013

Air Products SMR project
- Air Product
- Hydrogen production
- 1 $MtCO_2/year$
- EOR revenues & public grant

Coffeyville
- Coffeyville Resources Nitrogen Fertilizers LLC
- Fertilizer
- 1 MtCO2/yr
- EOR revenues

Lula Oil Field
- Petrobras
- Gas process.
- 0.7 $MtCO_2/yr$
- EOR revenues

2013

Lost Cabin
- ConocoPhillips
- Gas processing
- 0.9 $MtCO_2/yr$
- EOR revenues

2014

Boundary Dam
- SaskPower
- Coal power plant
- 1 $MtCO_2/yr$
- EOR revenues & public grant

2015

Quest
- Shell
- Hydrogen production for oil sand upgrader
- 1.1 $MtCO_2/yr$
- Public grant

2015

Uthmaniyah
- Gas processing
- 0.8 MtCO2/yr
- EOR revenues

▨ O&G processing plant ☐ EOR Storage

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1. Certified Emissions Reductions (Kyoto Protocol)

Source: A.T. Kearney Energy Transition Institute

Power or heavy-industry projects without EOR or other operating revenue streams are not reaching final investment decisions, despite large public grants

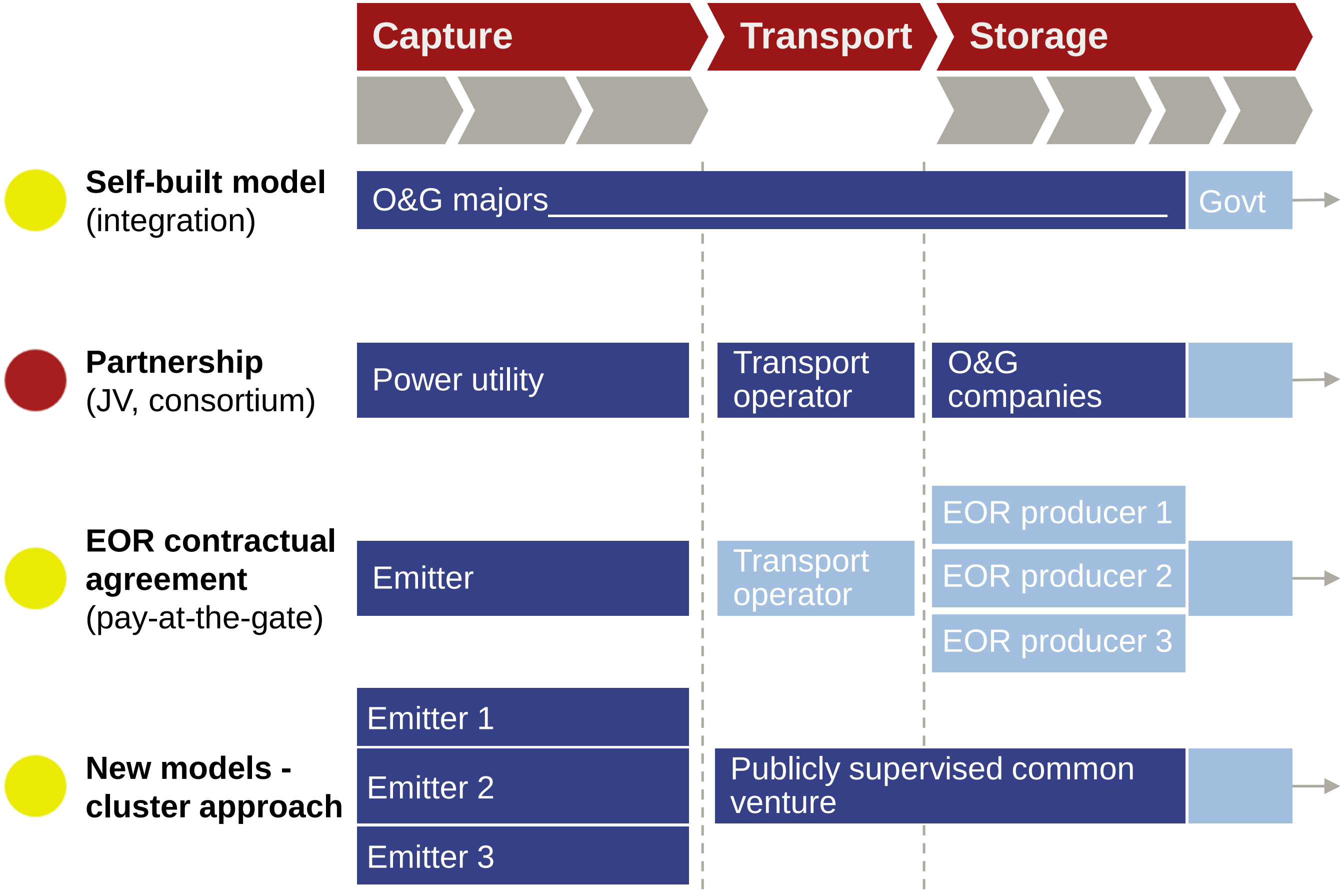
Promising CCS Projects Cancelled in advanced stage of planning

Project (Date)		Project Type & Grants	Reason For Cancellation
Eemshaven, Barendrecht, Jänschwalde (2010, 2011)	🇳🇱 🇩🇪	*3 onshore passive storage projects, $200m granted*	• *Local public opposition: Dutch government banned onshore CO_2 storage. Lack of storage legislation in Germany.*
Mountaineer (2011)	🇺🇸	Coal & passive storage $334 million granted	• *Economics*: Uncertain climate policy had weakened the strategic case for the project, but cost-sharing issues with West Virginia commissioners eventually derailed it.
ZeroGen (2011)	🇦🇺	Coal & passive storage $300 million granted	• *Economics*: Abandoned by the Queensland government, due to escalating costs.
Longannet (2011)	🇬🇧	Coal & passive storage $1,500 million granted	• *Economics*: Grant proved insufficient to retrofit this old and inefficient plant.
Pioneer (2012)	🇨🇦	Coal & passive storage $782 million granted	• *Economics*: Horizontal multi-frac well technology is delaying the needs for CO_2-EOR in Alberta's mature oil fields.
ULCOS (2012)	🇫🇷	Steel & passive storage Potentially large grant winner	• *Economics*: Project withdrew its candidacy for EU NER300 €1.5 billion grant scheme despite being the only remaining candidate, amid economic turmoil in Europe's steel sector.
Trailblazer, Taylorville (2013)	🇺🇸	Coal & possibly EOR $400 million tax credit	• *Economics*: Regulatory uncertainties, low natural gas prices, and the continuing decline in the cost of renewables.
Mongstadt (2013)	🇳🇴	Refinery, CO_2 fate unknown	• *Economics*: Government dropped support due to cost overruns and delays.
Belchatow (2013)	🇵🇱	Coal & passive storage, €180million granted	• *Economics*: Lack of funding, lack of interest from oil & gas companies for CO_2 storage contracts, and public opposition to onshore storage.
Porto Tolle (2014)	🇮🇹	Power & passive storage, €100million granted	• *Local public opposition* and difficulties in achieving closure for the financial structure of the project.
Lake Charles (2014)	🇺🇸	Methanol plant & EOR $261million granted	• Economics: Methanol market was becoming crowded, and methanol-production costs were uncompetitive, despite government support & EOR.
FutureGen (2015)	🇺🇸	Coal & passive storage $1 billion granted	• *Economics*: FutureGen1.0 cancelled in 2004 due to rising costs. FutureGen2.0 funding from DOE cancelled in 2015 due to delays and inability to raise private financing.
White Rose CCS, Peterhead (2015)	🇬🇧	Power generation & passive storage	• *Economics*: Projects cancelled after the UK announced the suspension of the $1bn UK CCS Competition
HECA (2016)	🇺🇸	Power generation & EOR, $800m grants & tax credits	• *Project delays* led to the expiration of funds granted by the US. DOE. While the company hopes to resurrect HECA, it remains unclear when that might happen.

Source: A.T. Kearney Energy Transition Institute

Such integrated projects also incur planning and coordination difficulties that do not affect CCS projects related to oil and gas

Business models for integrated projects



- Single integrated project owner: high level of control, no coordination issues.
- Limited to Oil & Gas majors or very large utilities only.

- Several project owners share costs and risks
- Risk of cancellation if a partner pulls out.
- Difficulties in managing differing industrial cultures, paperwork…

- Business model easy to implement.
- Shields storage risks from public opposition or long-term liabilities.
- Limited to EOR.

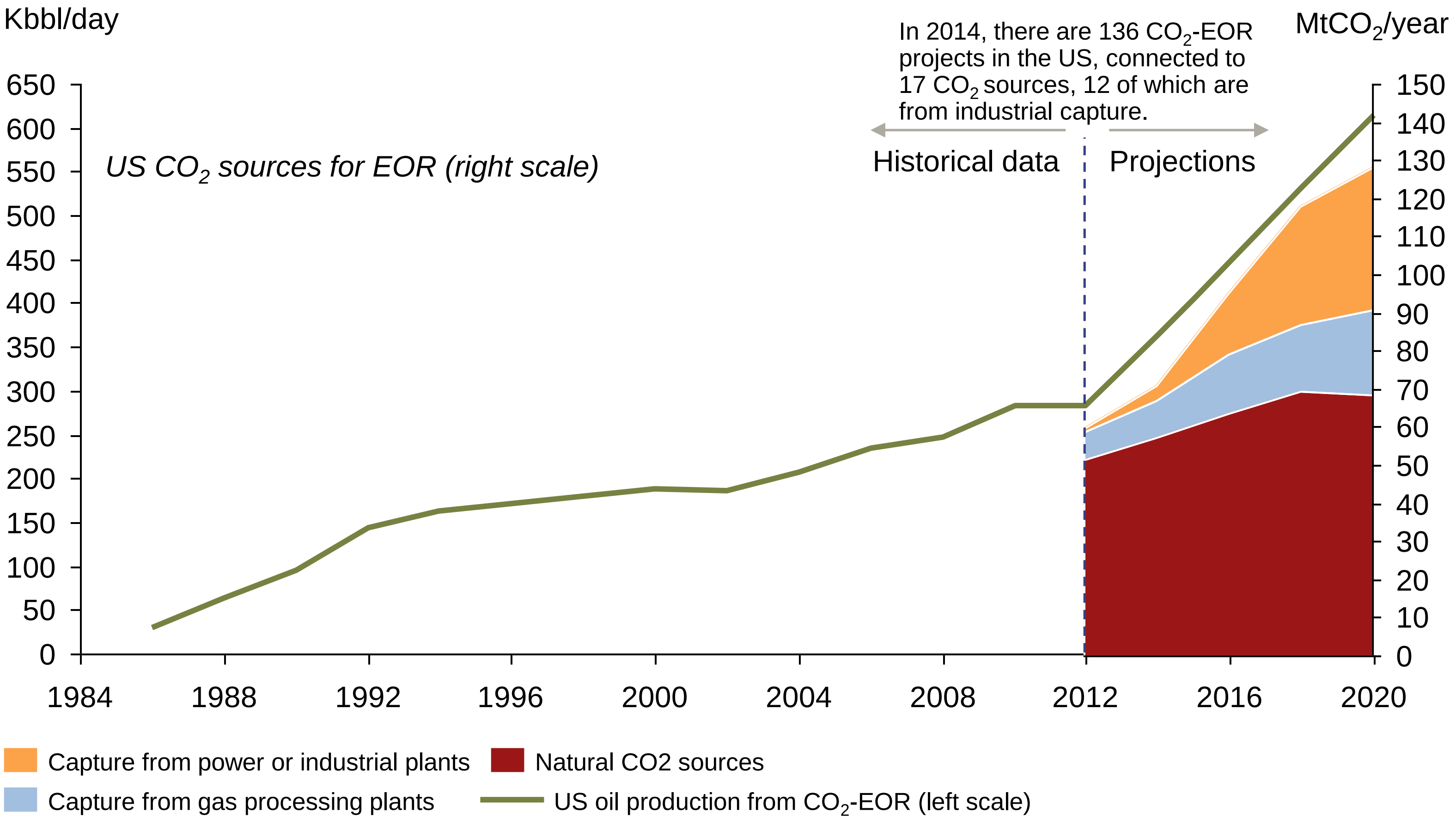
- Shared infrastructure for transport and storage reduces up-front capex.
- Involvement of public authorities facilitates public acceptance.
- Not for early demonstration phase.

■ Project owner (potentially eligible for emissions reductions) ■ Secondary stakeholder

Source: A.T. Kearney Energy Transition Institute

By contrast, CO_2-EOR is now mainstream commercial technology in the US, and an increasing proportion of CO_2 supply is expected to come from CCS

CO_2-EOR in the US: OIL Production and CO_2 supply - (1986 – 2020)



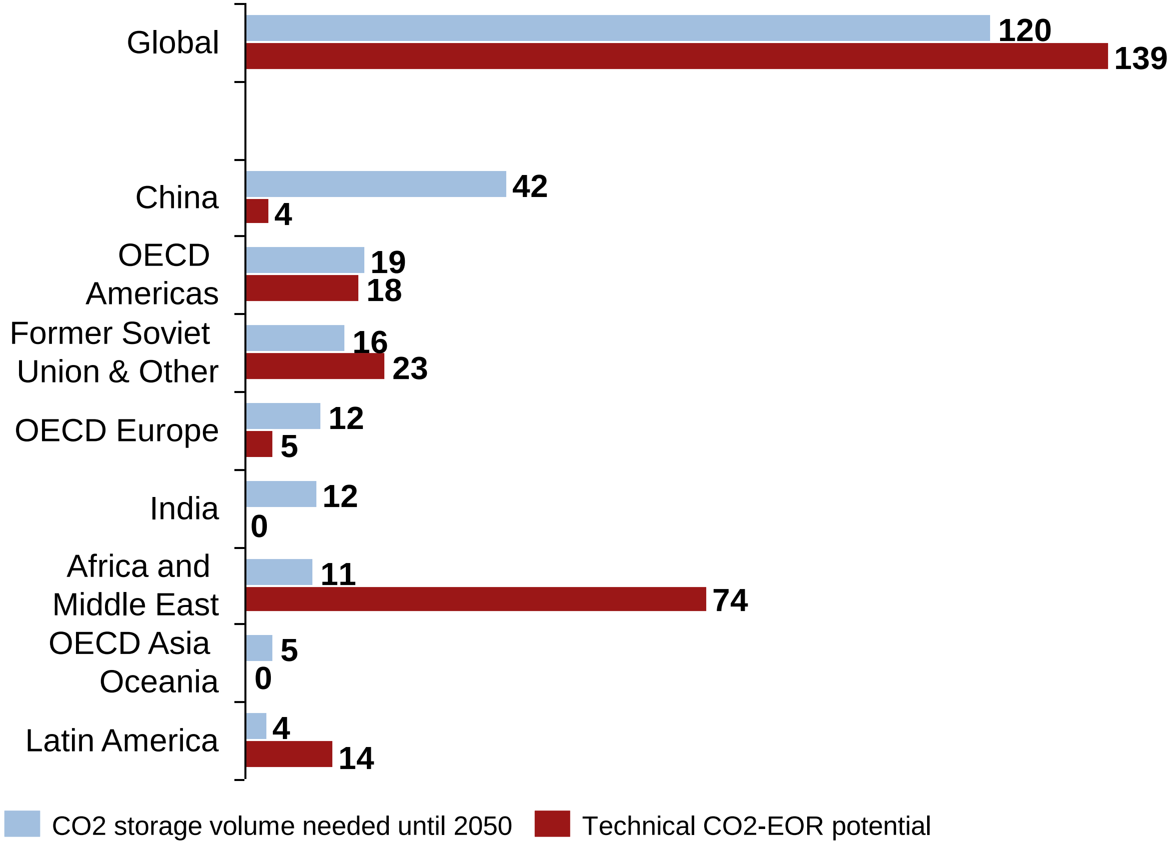
In 2014, there are 136 CO_2-EOR projects in the US, connected to 17 CO_2 sources, 12 of which are from industrial capture.

60 MtCO$_2$/year anthropogenic CO_2 supply, equivalent to 10 GW of coal power plant with CCS.

Notes: CO_2-EOR refers to enhanced oil recovery through CO_2 injection.
Source: US DOE NETL (2014), 'Near-Term Projections of CO_2 Utilization for Enhanced Oil Recovery"

Over the long term, in some regions, studies expect EOR to be technically capable of storing enough CO2 to allow for full-scale CCS deployment

Cumulated CO_2 storage required until 2050 in IEA 2DS scenario, versus technical storage potential for CO_2-EOR - $GtCO_2$

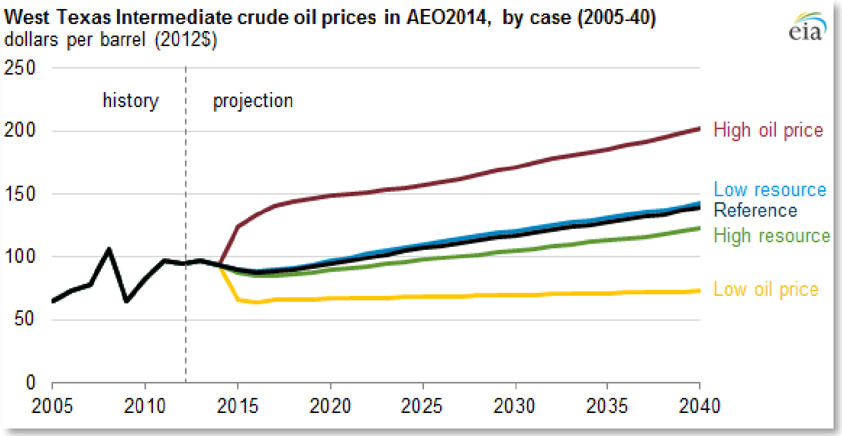


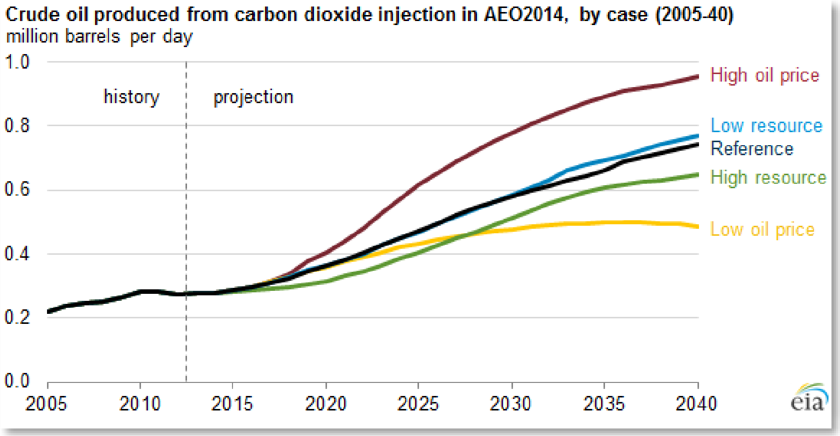
- Global cumulated CO_2 storage volumes associated with a full CCS roll-out as recommended by the IEA 2DS scenario would amount to 120 $GtCO_2$ by 2050.
- This is equivalent to the estimated global technical potential of CO_2 storage through EOR operations.
- However, EOR potential will be insufficient to meet regional storage volumes needs in China, India, OECD Europe and Oceania

Notes: Technical potential with next-generation CO2-EOR technologies.
Source: Advanced Resources International (2011), “Sectoral Assessment CO2 Enhanced Oil Recovery”; IEA (2013), “Technology Roadmap for CCS”

Weaker oil prices may undermine demand for CO_2-EOR in the future

Oil price scenarios and associated US CO_2-EOR production forecasts


West Texas Intermediate crude oil prices in AEO2014, by case (2005-40)
dollars per barrel (2012$)


Crude oil produced from carbon dioxide injection in AEO2014, by case (2005-40)
million barrels per day

- In the US, the price of bulk CO_2 bought to enhance oil recovery is generally pegged to WTI oil prices. An oil price of $80/bbl generally results in a price of $20-30/t$CO_2$.
- The recent drop in oil prices below $60/bbl is expected to reduce CO_2 prices and demand, depressing CCS-EOR project economics
- Competition between EOR and shale-oil projects may partly determine the future of CCS-EOR in the U.S

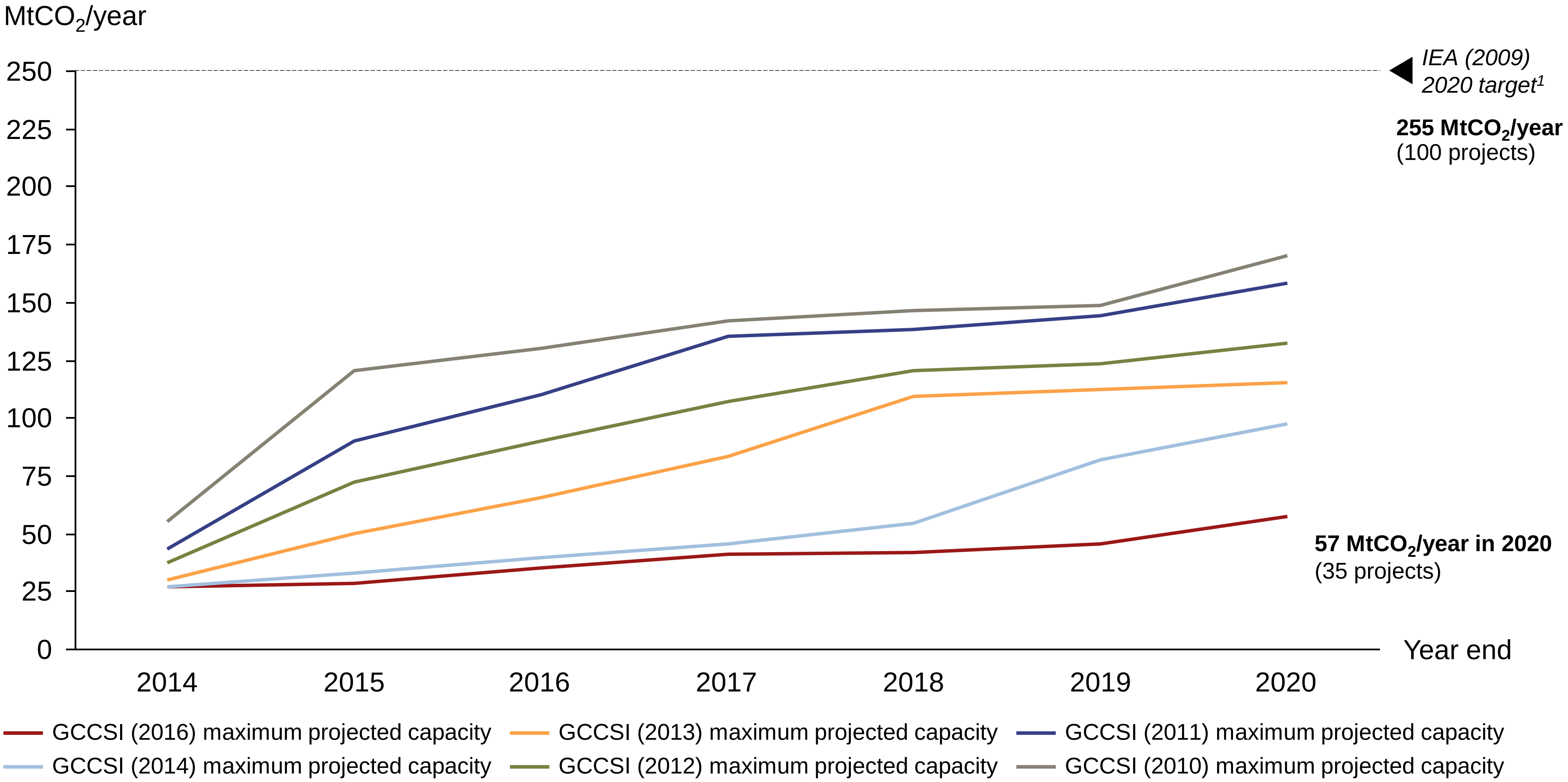
Source: A.T. Kearney Energy Transition Institute analysis; US DOE (2014), "Annual Energy Outlook"

5. Perspectives

- The pipeline of CCS projects is getting thinner

The CCS project pipeline has been dramatically reduced in size since the demonstration phase began and will largely miss its initial targets

Potential CCS capacity installed until 2020

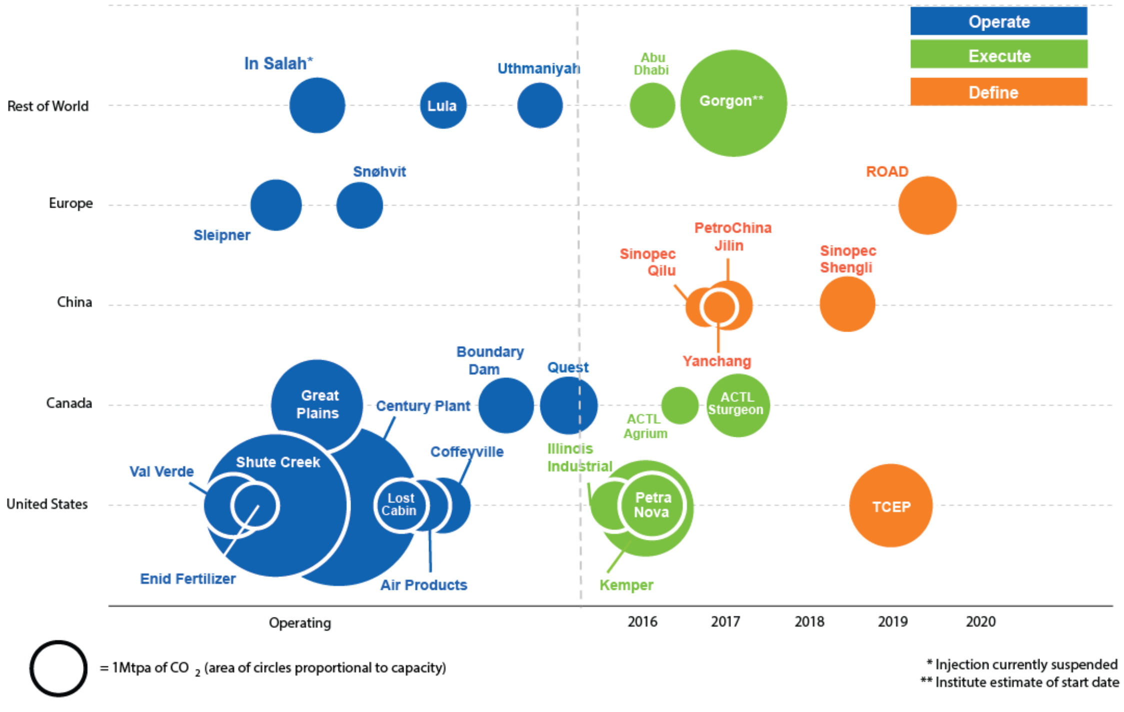


1. BLUE Map target, lowest-cost pathway to stabilize global warming below 2°C; 2 Total identified project pipeline;
Sources: A.T. Kearney Energy Transition Institute; GCCSI (2010, 2011, 2012, 2013, 2014, 2015), "Global Status of CCS"; IEA (2009), "Technology Roadmap for CCS"

North America will continue to lead CCS demonstration, Europe is falling short of expectations, and China is considering CCS-EOR and capture-ready plants

CCS Project pipeline: By region and lifecycle stage

(Excluding earliest stage of planning*)



* Injection currently suspended
** Institute estimate of start date

- There are 28 large projects in sufficiently advanced stages of planning to be representative of the current CCS landscape[1].
- The vast majority are located in North America (57% in number, 76% in capacity), driven by EOR.
- In Europe, until relatively recently, there were plans to have 10 projects in operation by 2015. But only one project remains, in early stage of planning in the Netherlands.
- China is the only country in which the CCS project pipeline is growing. Already a world leader in R&D and pilot-scale plants, it is now considering commercial-scale CCS for beneficial reuse of CO_2, and plans to become a competitive exporter of capture-ready plants. Passive CO_2 storage is less of a focus at the moment.
- The Middle East has low-cost opportunities for CCS (easy storage and CO_2-intensive industries), and is building the world's first steel CCS project. However, large-scale CO_2 demand for EOR remains 20-30 years away.
- Australia's initial ambition to demonstrate power or industrial CCS has ended, but the world largest CCS projects using aquifers to as storage sites are being built at the Gorgon gas-processing facility.

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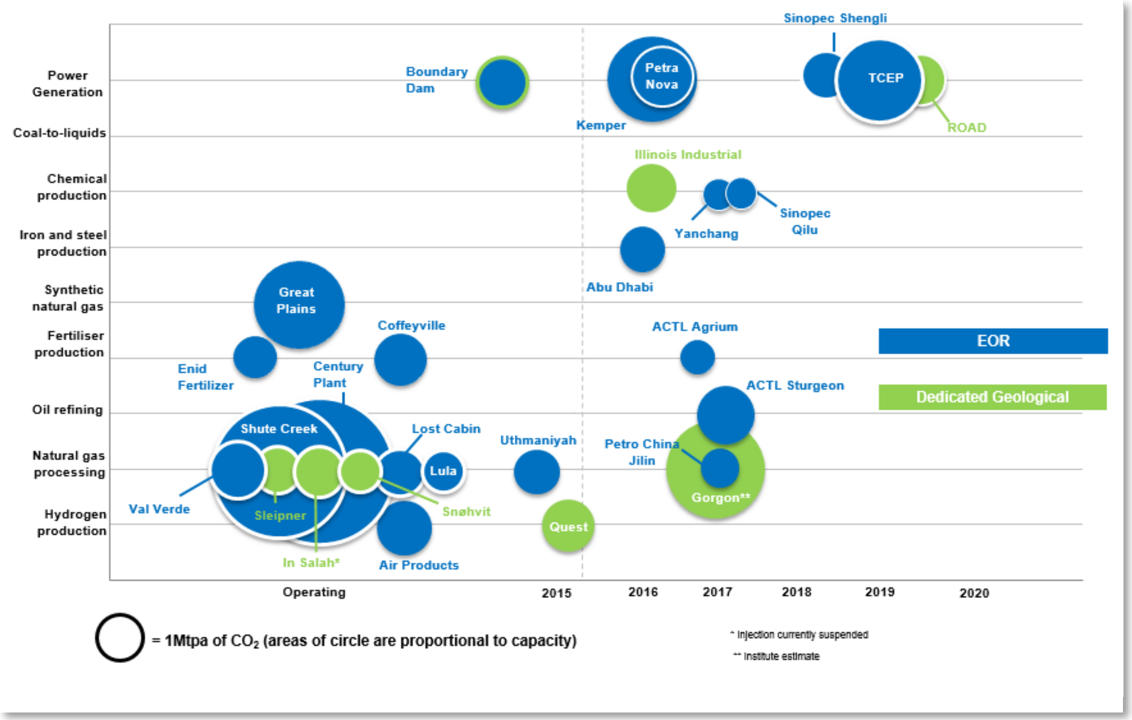
1. Given the long lead time from planning to operation, typically 7-10 years, only projects past or near FID (define stage) are shown in this graph. Projects in the earliest stages of planning, such as "identify" and "evaluate", have little chance of actually operating before 2020.

Source: A.T. Kearney Energy Transition Institute analysis; GCCSI (2015), "Global Status of CCS"

CCS has become a reality in the power sector, but remains dependent on synergies with the upstream oil & gas industry

CCS Project pipeline: by Plant and Storage type

(Excluding earliest stage of planning[1])



- All operating projects, and most of those in development, are related to upstream oil & gas production. The first two CCS projects outside upstream will begin operations in 2015 in the US, separating CO_2 from hydrogen and chemical plants at a low additional cost.
- The world's first commercial CCS power plant began operating in Canada in 2014, and two further commercial power plants are being built in the US, all selling CO_2 for EOR.
- Cement factories are not yet using CCS.

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1. Given the long lead time from planning to operation, typically 7-10 years, only projects past or near FID (define stage) are shown in this graph. Projects in the earliest stages of planning, such as "identify" and "evaluate", have little chance of actually operating before 2020.

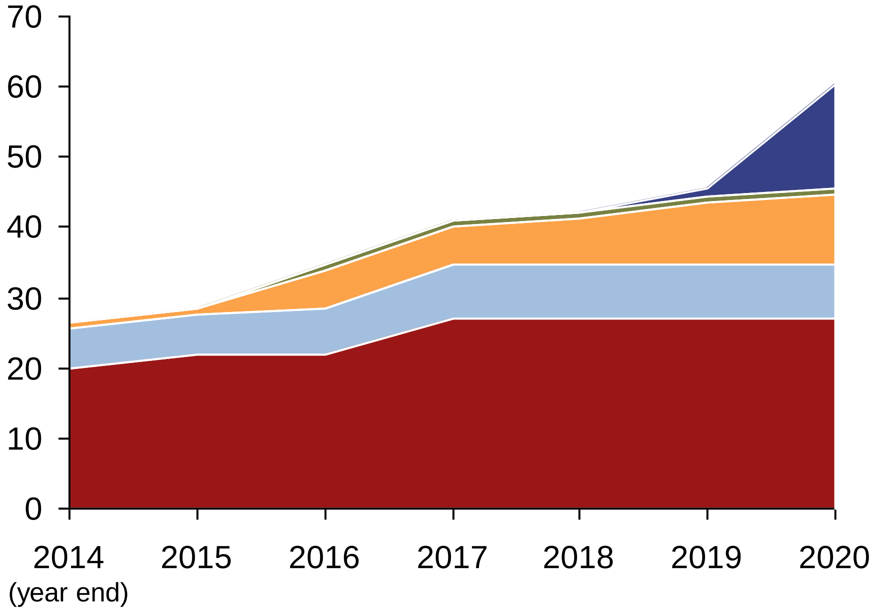
Source: A.T. Kearney Energy Transition Institute analysis; GCCSI (2015), "Global Status of CCS"

By 2020, at least three-quarters of installed CCS capacity will still be related to upstream oil & gas operations

CCS Large-Projects deployment forecast, 2015-2020

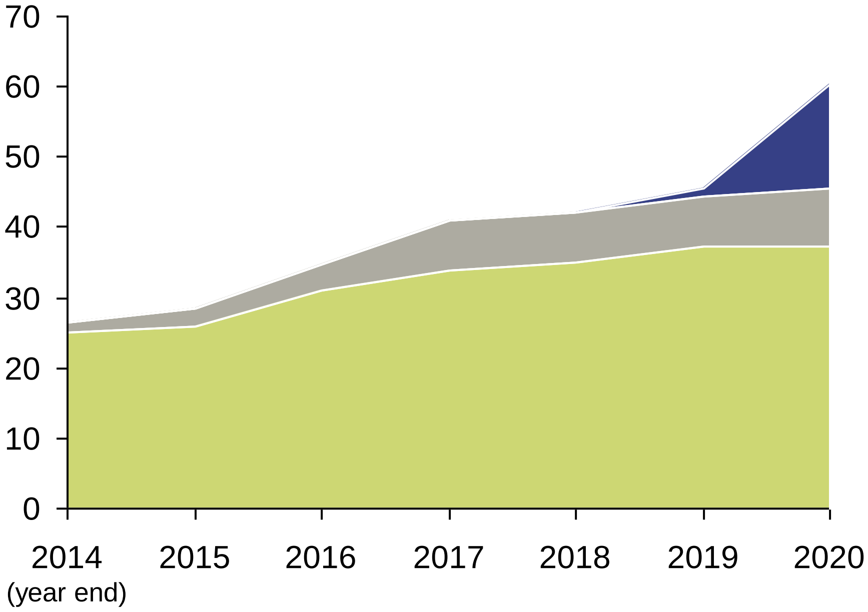
In $MtCO_2$/year

Plant type



Power plants should account for 20% of operating capacity by 2020.

Storage type



EOR may account for 80% of the operating capacity by 2020.

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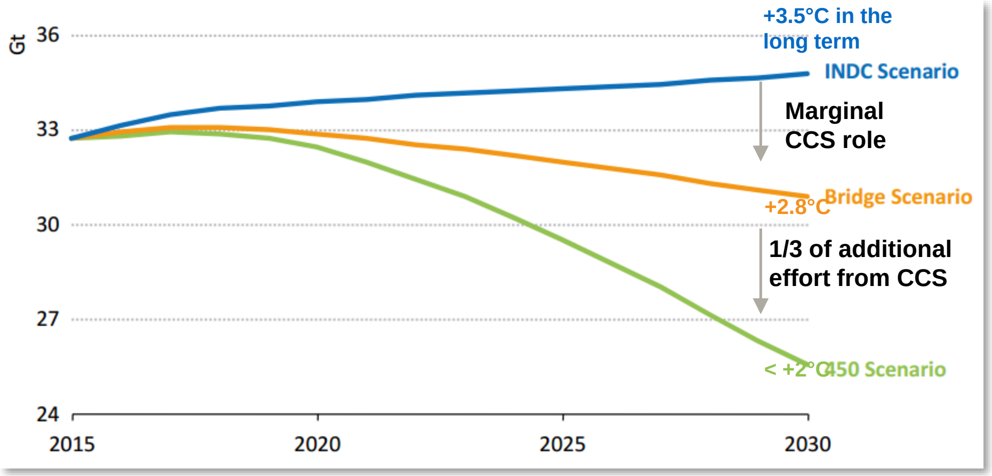
1. Projects in the early stages of planning, such as “identify” and “evaluate”, have little chance of actually operating before 2020.

Source: A.T. Kearney Energy Transition Institute analysis based on GCCSI database

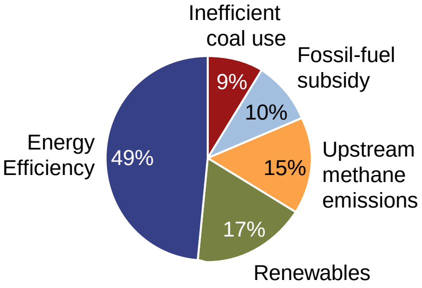
CCS is only expected to play a significant role in climate-change mitigation if ambitious policies are pursued to limit global temperature increases below 2°C

Global Energy-related CO_2 emissions per IEA scenario

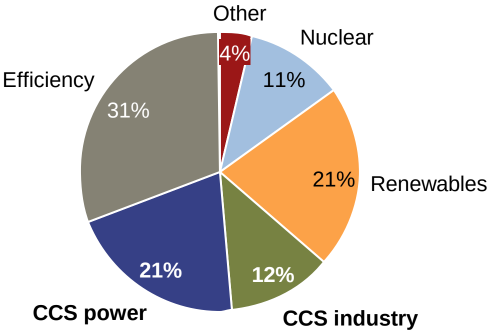


Emission-reduction efforts between scenario

Bridge vs. INDC
(in 2030)



450 vs. Bridge
(2015-2040 cumulated)



- **The INDC scenario** refers to the IEA's best-guess scenario when considering only energy policies adopted and proposed as of May 2015 (Intended Nationally Determined Contribution). In this scenario, CCS runs the risk of never developing beyond the subsidized demonstration phase.
- **The Bridge scenario** suggests how INDC could be enhanced by a series of immediately practicable steps, so as to achieve a peak in global greenhouse-gas emissions as early as possible, in a way that is compatible with all countries' short-term economic constraints. In this scenario, CCS only plays a marginal role before 2030. The key levers are energy efficiency, renewables, upstream methane-emissions reductions, the phase-out of fossil-fuel subsidies, and more efficient use of coal.
- **The 450 scenario** refers to the lowest-cost pathway towards the limitation of global temperature rises to a maximum of 2°C by capping the concentration of GHGs in the atmosphere at 450ppm. It is the only scenario in which CCS becomes genuinely viable, accounting for one-third of the additional emissions-reduction efforts needed by 2040 to put the world on track to 2°C. CCS is deployed at full speed in the 2030s, when annual investments reach up to \$110 billion and capacity additions reach 50 GW per year.

Source: Adapted from IEA (2015), "World Energy Outlook - Special Report on Energy and Climate"

Appendix & Bibliography

Some orders of magnitude

Energy-related CO_2 emissions per year

- One passenger car: 5tCO_2
- New York City: 50 MtCO_2
- United Kingdom: 500 MtCO_2
- US: 5 GtCO_2
- World 30 GtCO_2

What does a tonne of CO_2 represent?

- CO_2 captured by 25 trees grown for 10 years
- One return ticket from Paris to New York
- Worldwide average CO_2 emissions *per capita* in 3.6 months
- 1.35 MWh of electricity produced in a supercritical pulverized black-coal power plant

What is the cost of CO_2 emissions?

- Environmental carbon taxes are generally below \$20/tCO_2
- Market prices for EOR reached \$30/tCO_2 when the oil price was averaging \$100/bbl.
- Each tonne of CO_2 avoided by using CCS in a coal power plant is likely to cost \$53-\$92/tCO_2
- Developed economies generate \$2,000-\$6,000 of GDP per tonne of CO_2 emitted (carbon-emissions intensity)

Largest CCS integrated project in operation

- ExxonMobil Shute Creek CCS-EOR project in North America
- Captures and stores 6.5 MtCO2/year
- Equivalent to ~1 million passenger vehicles taken off the roads

Standard coal power plant (supercritical pulverized black coal) without CCS

- Nominal capacity: 500MW
- Average load factor: 0.9
- Produces 4,000 GWh of electricity per year
- Emits 3 MtCO2/yr

Standard coal power plant with post-combustion CCS

- Produces 3,200 GWh per year (CCS energy penalty: 20%)
- Captures 90% of CO2 emissions
- Avoids 2.6 MtCO2/yr

How to produce low-carbon electricity for one million people in Europe (~3TWh per year)

- One CCS power unit with extensive mining if burning coal
- A 30 km² PV farm with market-leading efficiency
- A modern wind farm with 400 large turbines spread over more than 100 km²

Acronyms

CAPEX: capital expenditure
CCS: carbon capture and storage
CDM: Clean Development Mechanism
CER: Certified Emissions Reduction
CSP: concentrated solar power
ECBM: enhanced coal-bed methane
EOR: enhanced oil recovery
ETP: Energy Technology Perspectives
ETS: Emissions Trading Scheme
EUA: European Union Allowance
FEED: front-end engineering design
FID: final investment decision
IGCC: integrated gasification combined cycle
JV: joint venture
LCOE: levelized cost of electricity
Large Project: integrated CCS projects of demonstration or commercial scale (above 0.6 MtCO2/year)
MtCO2/yr: million tonnes CO2 per year
MVA: monitoring, verification and accounting
NER300: new entrants reserve
NGCC: natural gas combined cycle
OXY: oxy-combustion capture
PCC: post-combustion capture
PV: photovoltaic
R&D: research & development
RD&D: research, development & demonstration
SNG: synthetic natural gas
US DOE: US Department of Energy
WEO: World Energy Outlook

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The A.T. Kearney Energy Transition Institute is an independent nonprofit organization. It provides leading insights on global trends in energy transition, technologies, and strategic implications for private sector businesses and public sector institutions. The Institute is dedicated to developing objective technological insights and exploring how businesses may both capture the opportunities that arise and address the challenges faced as a result of the rapidly changing energy landscape. The independence of the Institute fosters unbiased primary insights and the ability to co-create new ideas and insights with sponsors from across the energy transition landscape.

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