LEADING THE ENERGY TRANSITION

Carbon Capture and Storage

Bringing Carbon Capture and Storage to Market
Factbook version

SBC Energy Institute
January 2013 update

Compiled by the SBC Energy Institute

About SBC Energy Institute

The SBC Energy Institute, a non-profit organization founded in 2011 at the initiative of Schlumberger Business Consulting (SBC), is a center of excellence for scientific and technological research into issues pertaining to the energy industry in the 21st century. Through its unique capability to leverage both Schlumberger's technological expertise and SBC's global network of energy leaders, the SBC Energy Institute is at the forefront of the search for solutions to today's energy supply challenges. It is overseen by a scientific committee comprised of highly experienced individuals in the areas of natural and applied sciences, business, and petroleum engineering.

About *Leading the Energy Transition* series

"Leading the energy transition" is a series of publicly available studies on low-carbon energy technologies conducted by the SBC Energy Institute that aim at providing a comprehensive overview of their development status through a technological and scientific prism.

About the Carbon Capture and Storage factbook

This factbook is based on the SBC Energy Institute report, "Bringing Carbon Capture and Storage to Market", published in June 2012. It summarizes the status of existing technologies and the main Research & Development priorities. It analyzes the economics of the main large-scale demonstration and deployment projects and gives the Institute's view of the future of CCS technologies and projects.

For further information about SBC Energy Institute and to download the report, please visit **http://www.sbc.slb.com/sbcinstitute.aspx**, or contact us at **sbcenergyinstitute@slb.com**

CCS is a useful and viable technology

CO_2 emissions reached a record high in 2010. The International Energy Agency (IEA) recently said average global temperatures are on track to rise by more than 3.5°C by 2100, and the margin for maneuver to mitigate global warming is becoming dangerously slim.

CCS, widely considered an essential technology to mitigate climate change, is technically viable. Several large-scale projects are currently capturing 23MtCO_2 per year from natural gas processing or coal gasification plants and storing it in deep saline aquifers or in oil reservoirs as part of enhanced oil recovery (EOR) operations. This is equivalent to avoiding emissions of 3.8GW of coal-based electricity. Industry players are adamant that CCS component technologies have been proven technically feasible and are ready to be demonstrated on a large scale in power generation, cement and steel production, chemicals plants and refineries.

R&D investments in CCS are significant (~$1.5 billion in 2011, compared with $1.2 billion for wind). Public laboratories and corporate players – chemicals companies, utilities and oil and gas firms – are developing efficient capture processes.

The demonstration phase is not moving fast enough, projects will only be driven by upstream oil and gas activities in the years to come

The demonstration of large-scale CCS projects has progressed far more slowly than is required to mitigate climate change. Financing for large demonstration projects (below $3 billion a year, with no sign of an increase) remains considerably below that of renewable energy sources such as wind and solar ($131 billion and $75 billion in 2011, respectively). With growth of only 6% per year over the last five years and a forecasted 52MtCO_2/year in operation by 2017, the IEA's recommended pathway towards decarbonization appears out of reach (37% annual growth required and 255MtCO_2/year stored by 2020 in the '2DS Scenario')

Nearly all large projects operating or under construction are associated with oil and gas production, wherein the CO_2 is either captured from natural gas processing plants or is sold for use in EOR. This trend is likely to continue for the next decade, as passive CO_2 storage adds complexity and bears regulatory risks, public-acceptance issues and reservoir discovery costs that EOR can avoid. To date, no CCS power plant has reached a final investment decision without both EOR revenues and strong government financial support. In 2017, over 90% of the operating CCS capacity will be associated with the upstream oil and gas sector.

CCS demands strong political will towards decarbonization

Abatement costs for coal-fired electricity with CCS range from $54/tCO2 to $92/$CO_2$. Nevertheless, CCS is a competitive way to abate CO_2 emissions in power generation, as abatement using CCS is significantly less expensive than replacing coal power plants with solar plants ($105-$239/tCO_2) or offshore wind farms ($90-$176/tCO_2). Besides, few alternatives to CCS exist for cutting emissions from industrial applications such as steel and cement production, chemicals plants and gas-processing units.

CCS is seen as a costly technology because of its high up-front costs and uncertain long-term benefits. Each commercial-scale CCS project can cost up to a billion dollars in capture costs alone, although they are capable of abating over a million tonnes of CO_2 per year for several decades (the equivalent of taking over 200,000 cars off the roads). The financial support required for each project is so large that governments rarely have the political will to subsidize CCS to the extent required. OECD governments have committed $21 billion to help CCS demonstration projects, but are struggling to allocate money to specific projects. Even so, grants that have actually been allocated so far have represented an average of just $15/t$CO_2$ avoided over the lifetime of each project. In addition, no carbon-price mechanism has yet enabled the recovery of CCS costs: European carbon prices trades below €4/tCO_2 as of January 2013, and most carbon taxes are set below $25/t$CO_2$.

There are grounds for optimism that CCS deployment may accelerate after 2020

Growing demand for the beneficial reuse of CO_2 for EOR should drive CCS forwards during this decade and help to demonstrate the technology, in conjunction with large government grants. Oil prices above $100/bbl have tended to boost CO_2 contract prices above $30/t$CO_2$, greatly improving CCS-EOR economics.

China is also rapidly driving down the cost of capture, having openly expressed the ambition to build capture-only coal power plants for its own needs and to export low-cost capture technologies. The levelized cost of electricity from coal-fired power plants with CCS – using either post- or pre-combustion technology – could decrease by 14%-21% after the first 100 GW are installed.

Looking beyond 2020, more stringent carbon policies will be required to develop CCS beyond upstream oil and gas and at the scale needed to tackle climate change. CCS may become a must-have for climate mitigation, as CO_2 emissions are being locked-in by existing plants. In addition to public funding and a more robust carbon-pricing system, public and private sector actions could contribute to CCS' wider adoption by: leveraging CCS-EOR projects; implementing stable regulation governing long-term investments; exploring new business models to assist the formation of partnerships in integrated CCS projects, etc…

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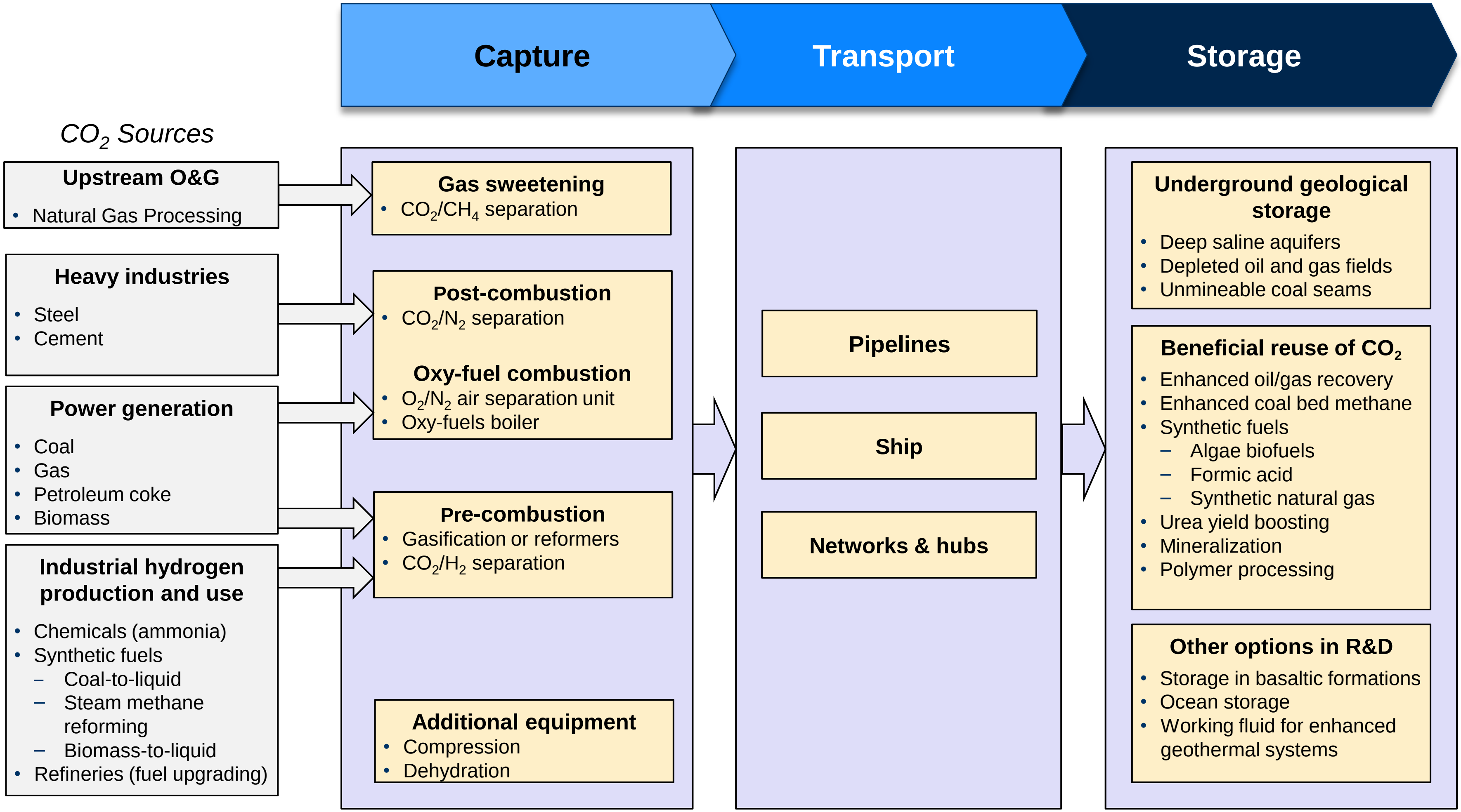
1. Technologies

CCS technologies are now proven

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



Capture → **Transport** → **Storage**

CO_2 Sources

Upstream O&G
- Natural Gas Processing

Heavy industries
- Steel
- Cement

Power generation
- Coal
- Gas
- Petroleum coke
- Biomass

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

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

Pipelines

Ship

Networks & hubs

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

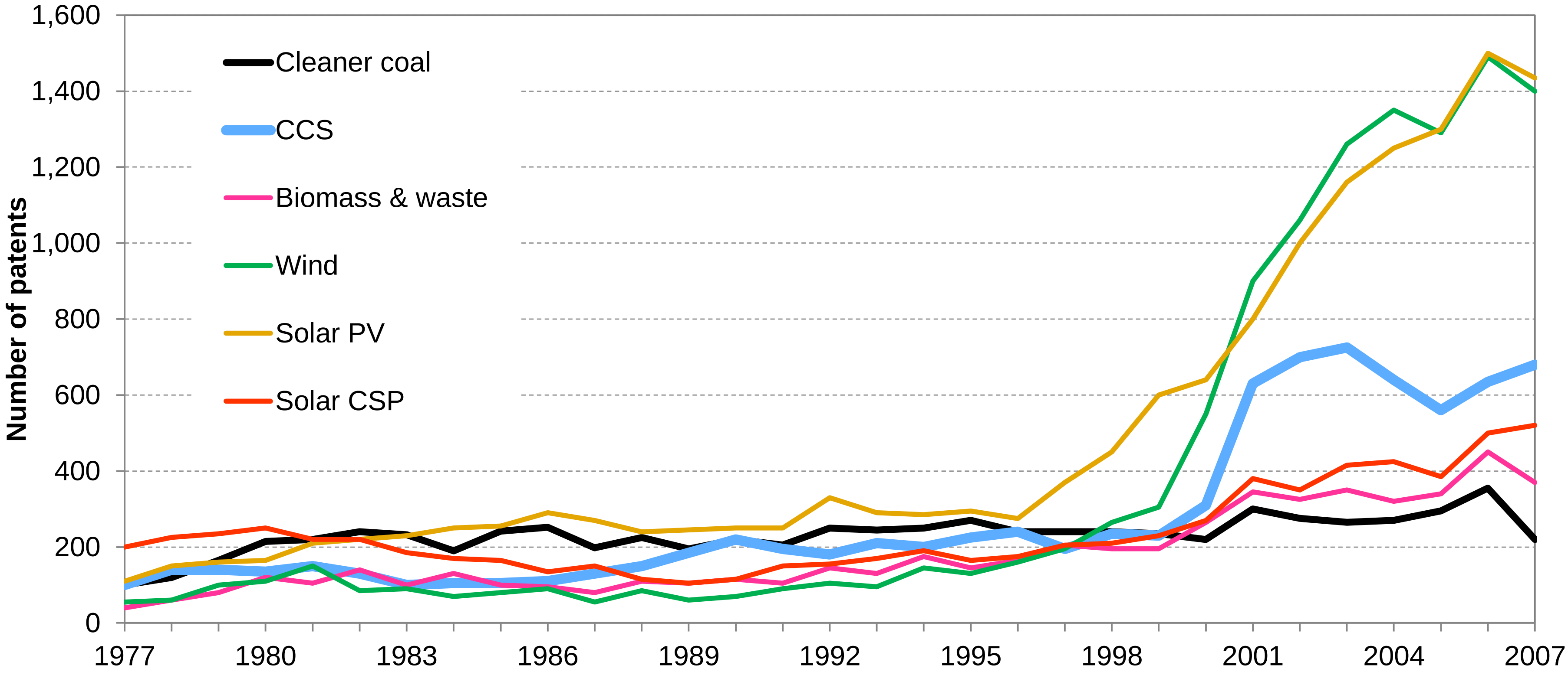
Beneficial reuse of CO_2
- Enhanced oil/gas recovery
- Enhanced coal bed methane
- Synthetic fuels
  - Algae biofuels
  - Formic acid
  - Synthetic natural gas
- Urea yield boosting
- Mineralization
- Polymer processing

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

R&D efforts in CCS accelerated in the early 2000s, but remain far below those in wind and solar

ANNUAL NUMBER OF PATENTS FILED FOR VARIOUS LOW-CARBON TECHNOLOGIES

1977-2007, in absolute number of patents



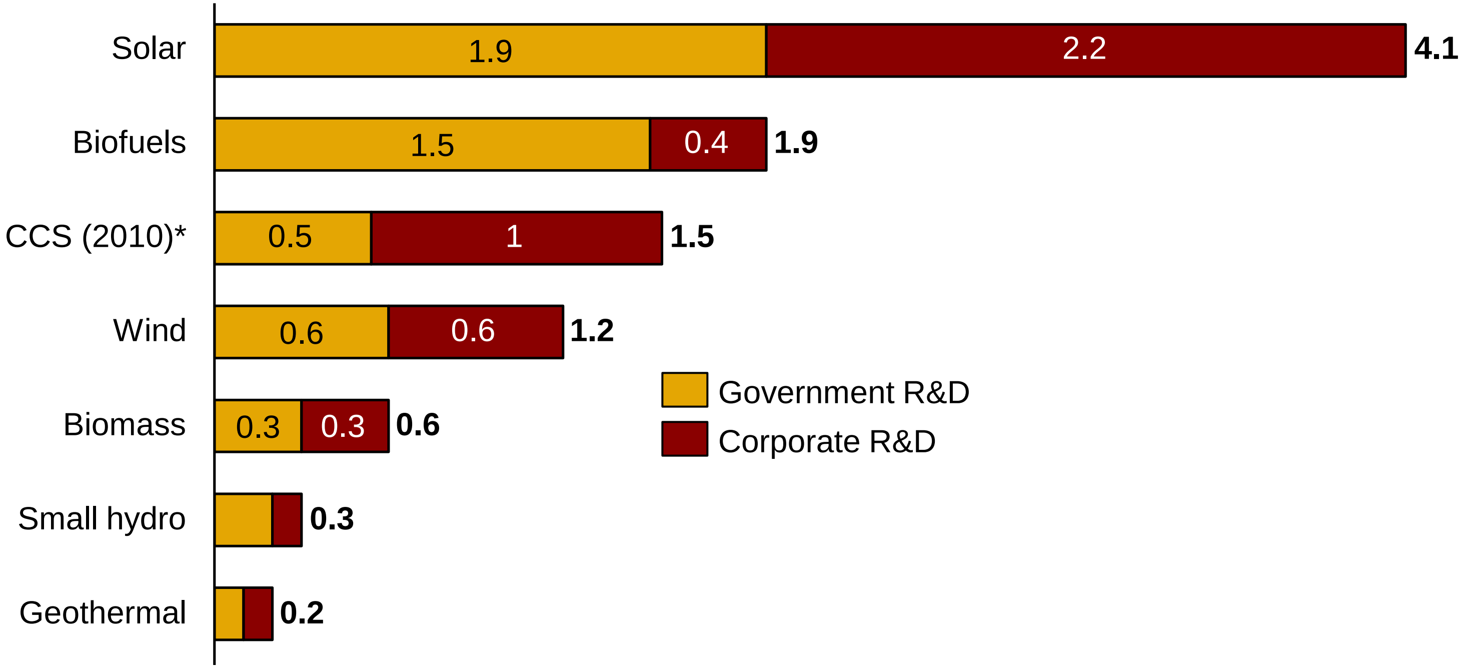
Notes: The number of patents related to carbon capture has boomed since the beginning of the century, reaching 9,160 at the end 2007. 68% of them have been filed in the US. 80% have been filed by national or multinational corporations. Around 20% of patents for clean coal are connected with integrated gasification combined cycle (IGCC) plants - so called ‘capture ready’ for pre-combustion.

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

Current R&D budgets allocated to CCS rank third after solar and biofuels

2011 R&D INVESTMENT IN CCS AND RENEWABLES

$ billion

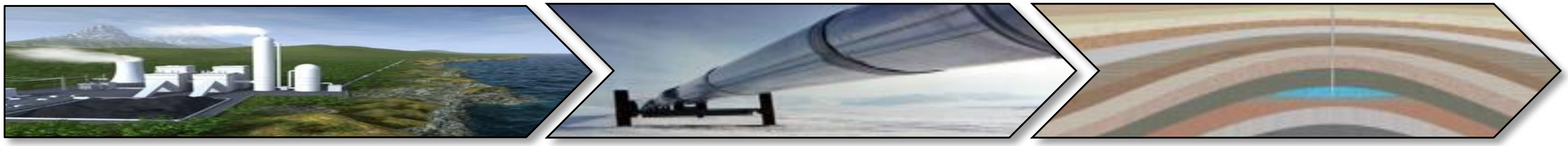


Notes: Because CCS projects are not commercial yet, the frontier between R&D and demonstration is unclear. R&D projects are defined here as all those other than Large Projects (integrated projects above 0.6 $MtCO_2$/year)

Source: SBC Energy Institute. Data for renewables are from UNEP, “Global Trend in Renewable Energy Investment” 2011. CCS expenses are SBC Energy Institute estimations based on IEA, Global Gap in CCS RR&D, 2010; and the Commission of the European Communities, 2009 for the ratio public/private R&D for CCS

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



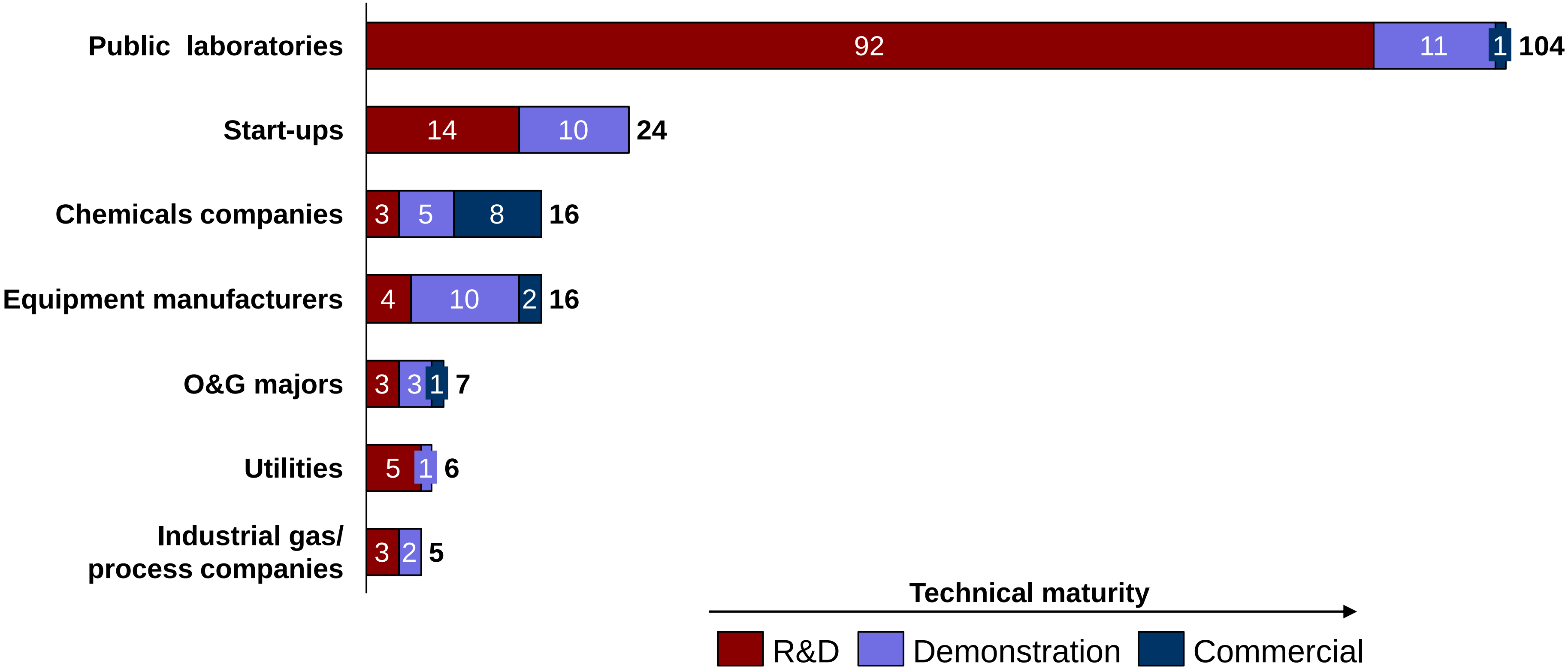
	CO_2 CAPTURE	TRANSPORT	STORAGE
Key R&D players	▪ Praxair ▪ Air Liquide ▪ Air products ▪ Linde ▪ Shell ▪ Mitsubishi ▪ ExxonMobil ▪ Arkema ▪ General electric ▪ IFPEN	▪ GDF Suez ▪ Maersk ▪ Wartsila	▪ Shell ▪ IFPEN ▪ Terralog ▪ ExxonMobil ▪ Schlumberger ▪ CDX gas ▪ Air products ▪ Diamond qc technologies ▪ Dropscone ▪ BHP Billiton

Source: SBC Energy Institute, based on UNEP, EPO and ICTSD (2010)

Public labs are at the forefront of developing novel capture processes

NUMBER OF CO_2 SEPARATION TECHNOLOGIES DEVELOPED BY ORGANIZATION TYPE

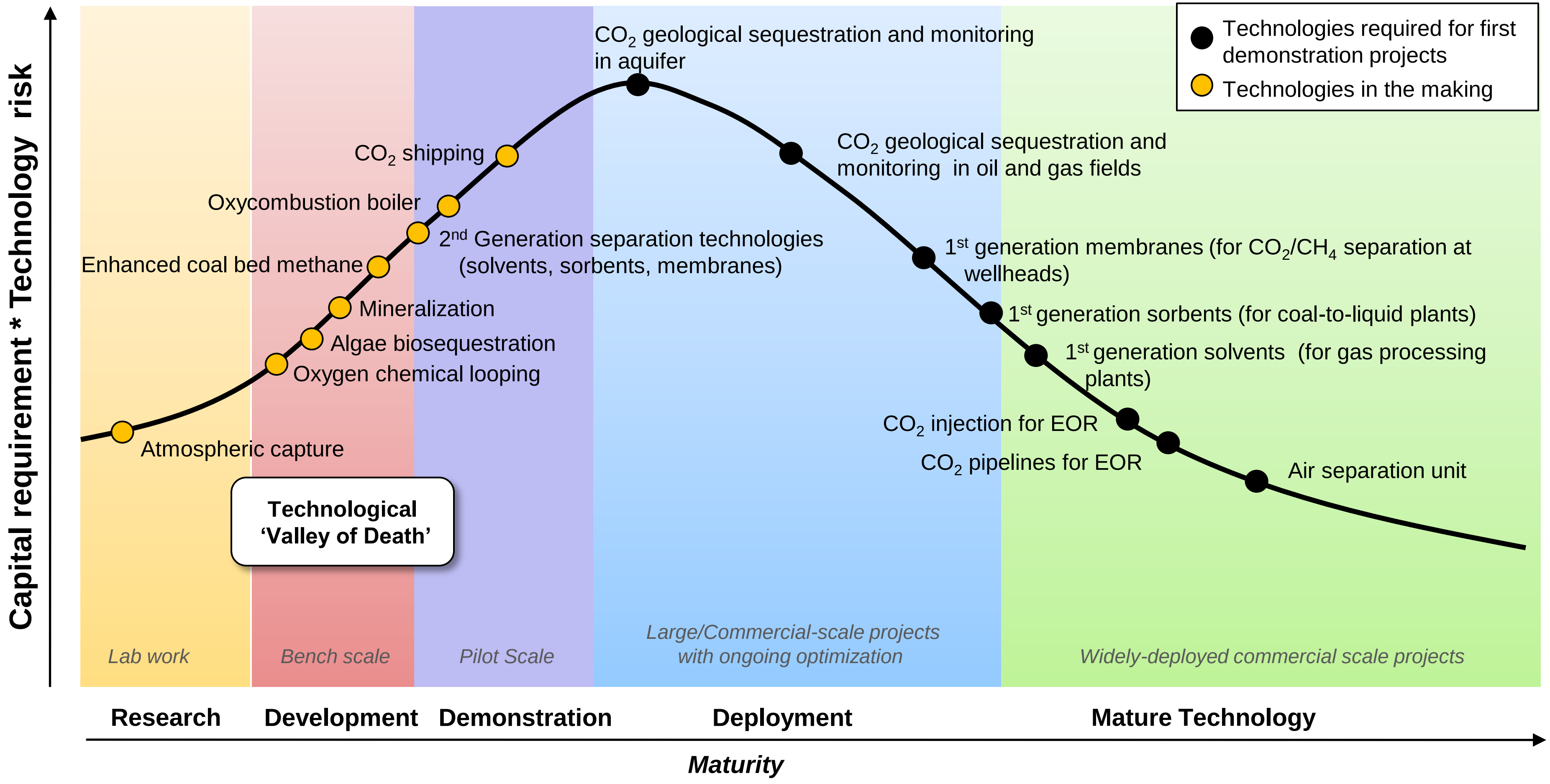
Absolute numbers



Source: SBC Energy Institute, based on BNEF database, accessed in July 2011

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

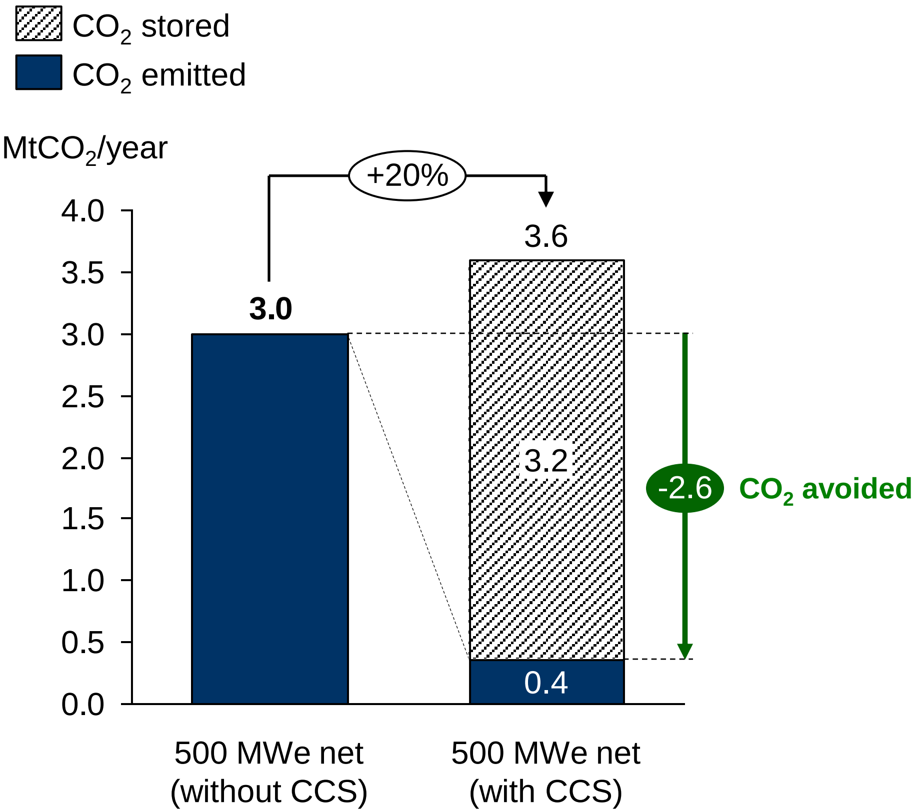
INVESTMENT-RISK CURVE OF INDIVIDUAL CCS TECHNOLOGIES



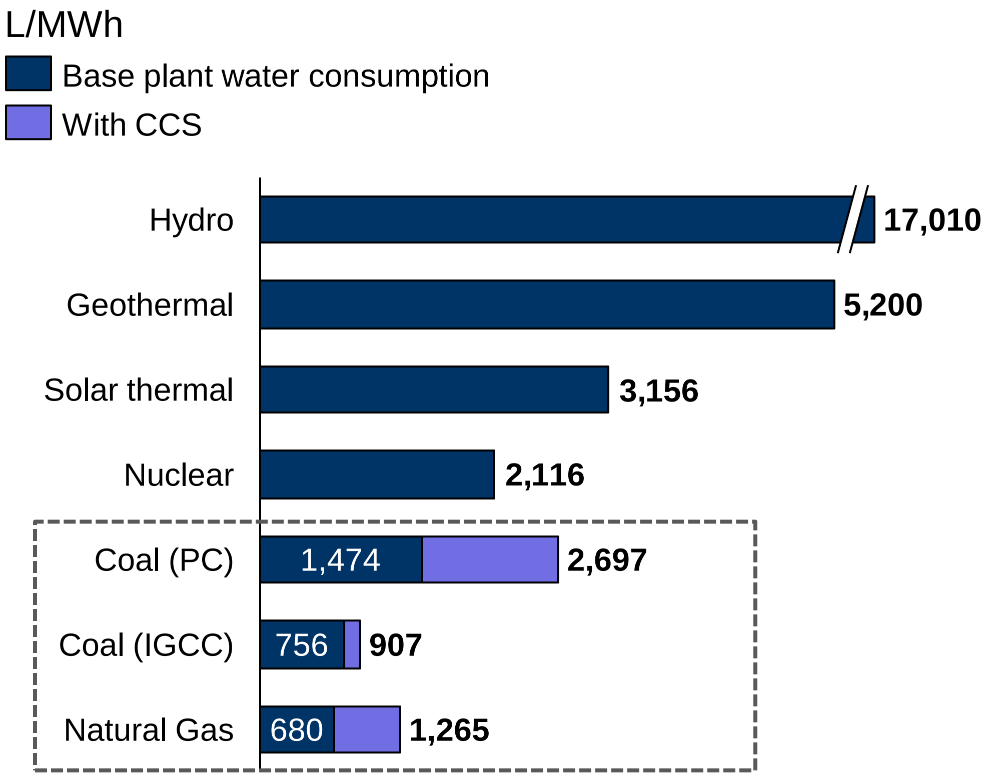
Source: SBC Energy Institute

R&D efforts are focused on reducing CCS energy and water penalty

ILLUSTRATION OF A 20% ENERGY PENALTY ON A 500MWe COAL PLANT



WATER CONSUMPTION OF VARIOUS PLANT TYPES

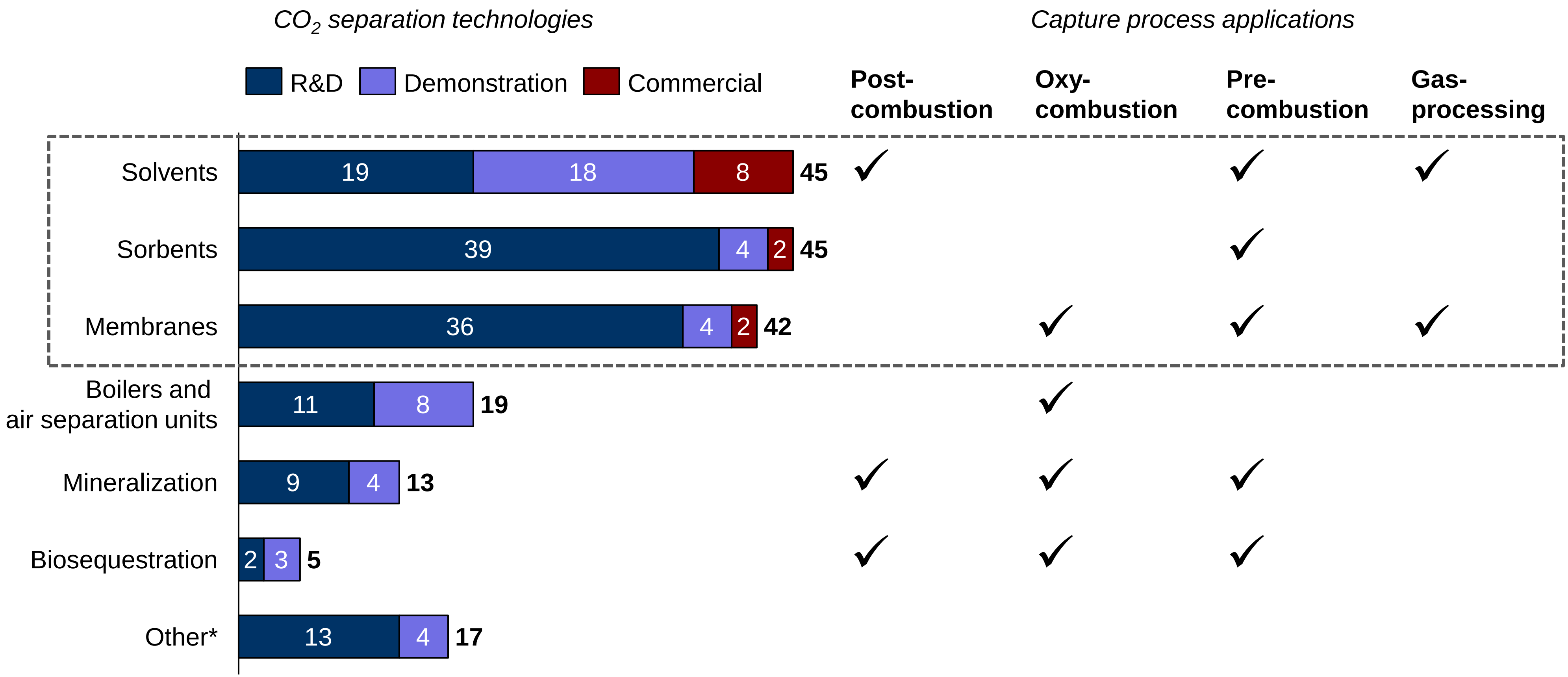


- Energy penalty currently ranges between 16% and 43%, depending on the capture process
- Water penalty currently ranges between 10% and 80%, depending on the capture process

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

Various CO_2 separation technologies are being developed in order to improve the efficiency of the four main capture processes

NUMBER OF CO_2 SEPARATION TECHNOLOGIES DEVELOPED FOR CCS AND POTENTIAL APPLICATION FOR EACH CAPTURE PROCESS



CO_2 separation technologies | *Capture process applications*

	R&D	Demonstration	Commercial		Post-combustion	Oxy-combustion	Pre-combustion	Gas-processing
Solvents	19	18	8	45	✓		✓	✓
Sorbents	39	4	2	45			✓	
Membranes	36	4	2	42		✓	✓	✓
Boilers and air separation units	11	8		19		✓		
Mineralization	9	4		13	✓	✓	✓	
Biosequestration	2	3		5	✓	✓	✓	
Other*	13	4		17				

Notes: *Other includes: hydrates, electro reduction, etc…

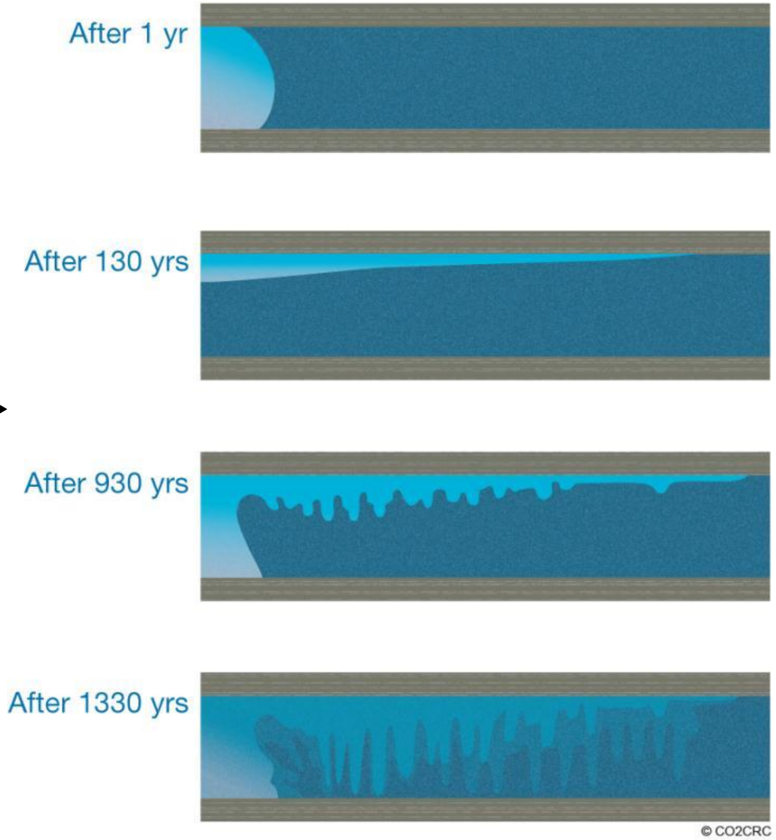
Source: SBC Energy Institute analysis, BNEF database accessed in July, 2011

In storage, R&D is split between upstream reservoir finding and downstream CO_2 behavior understanding

MAIN STORAGE R&D AXIS

- 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 from depleted oil and gas reservoir are good candidates but geographically limited
- Understand CO_2 behavior, through: →
  - Software modeling tools
  - Large-scale field demonstrations in aquifers
  - Monitoring, verification and accounting (MVA)
  - International standards for MVA and risk assessments
  - Reservoir engineering to manage risk of leakage

SCHEMATIC REPRESENTATION OF INJECTION IN A HORIZONTAL AQUIFER



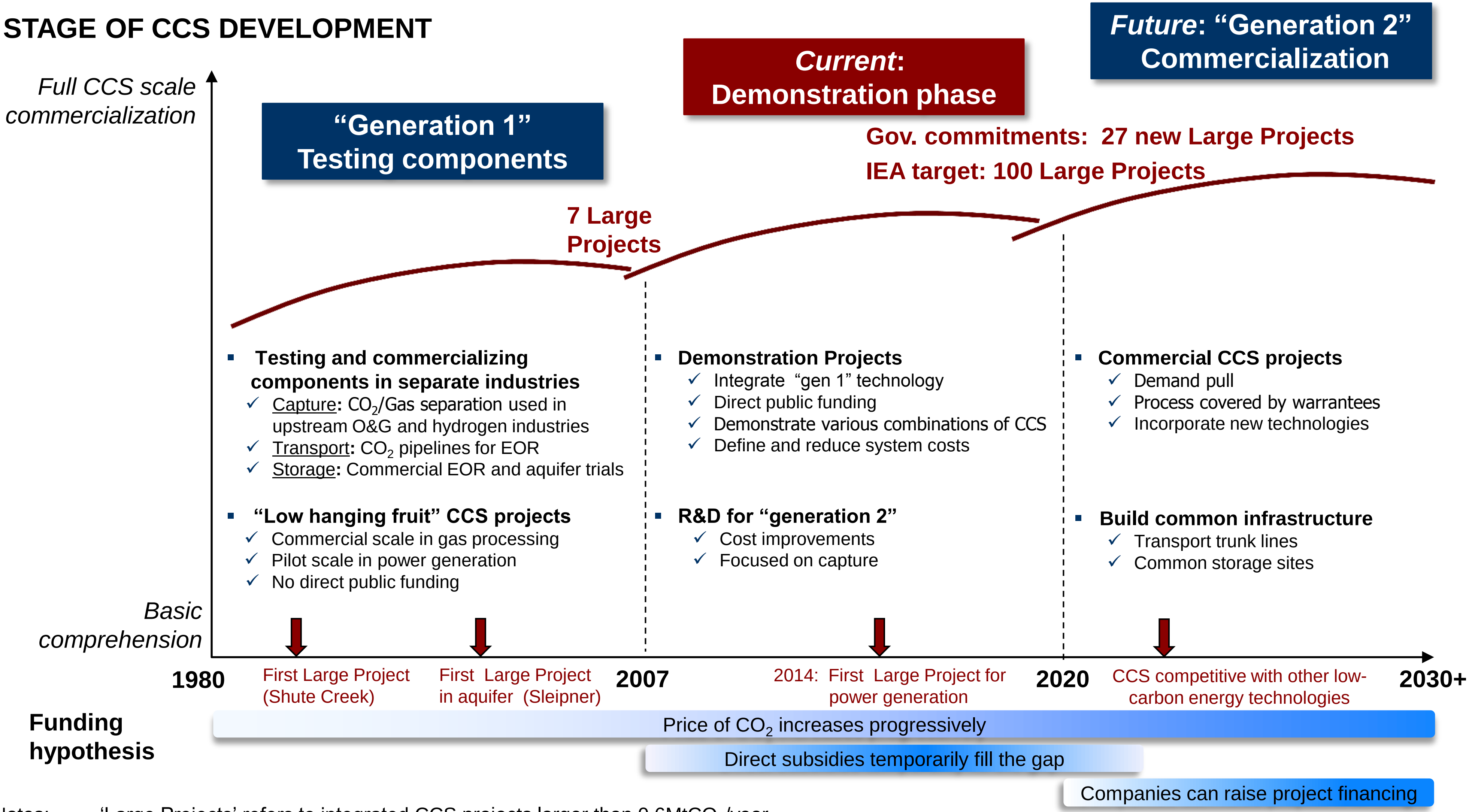
Source: CO2CRC, online image library

2. Projects

Only oil and gas related projects are moving forward

CCS entered the demonstration phase in 2008

STAGE OF CCS DEVELOPMENT



Full CCS scale commercialization

Basic comprehension

"Generation 1" Testing components

***Current*: Demonstration phase**

***Future*: "Generation 2" Commercialization**

7 Large Projects

Gov. commitments: 27 new Large Projects

IEA target: 100 Large Projects

- **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

1980

First Large Project (Shute Creek)

First Large Project in aquifer (Sleipner)

2007

2014: First Large Project for power generation

2020

CCS competitive with other low-carbon energy technologies

2030+

Funding hypothesis

Price of CO_2 increases progressively

Direct subsidies temporarily fill the gap

Companies can raise project financing

Notes: 'Large Projects' refers to integrated CCS projects larger than $0.6MtCO_2$/year
Source: SBC Energy Institute

Many companies are now involved in CCS demonstration

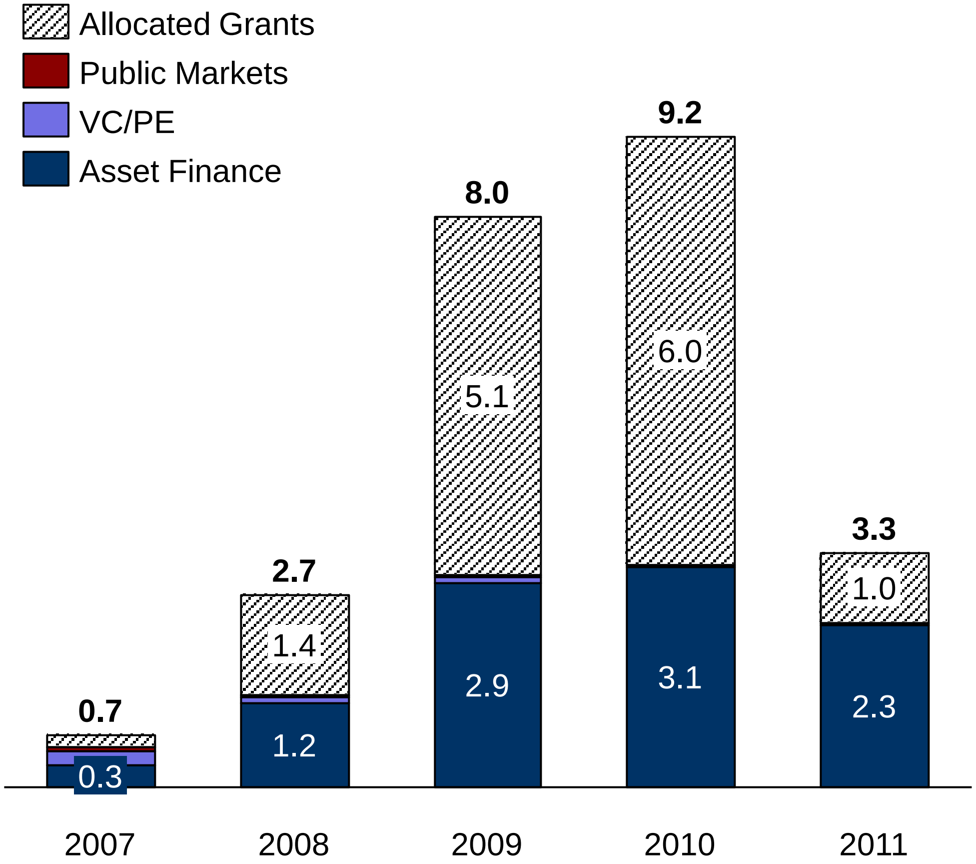
	CO$_2$ capture	Transport	Storage
Key service providers	▪ **Equipment manufacturers**: Alstom, MHI,GE, Siemens, Swann Hill, Babcock & Wilcox, Pall Corp ▪ **Industrial gas producers**: Air Liquide, Air Product, Linde, Praxair, Aker ▪ **Chemicals producers**: UOP, Lurgi, Dow, Flour, BASF, Akema ▪ **Utilities 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: SBC Energy Institute

Investments in CCS are still much lower than in renewables, and public money allocated to CCS projects has not yet been spent

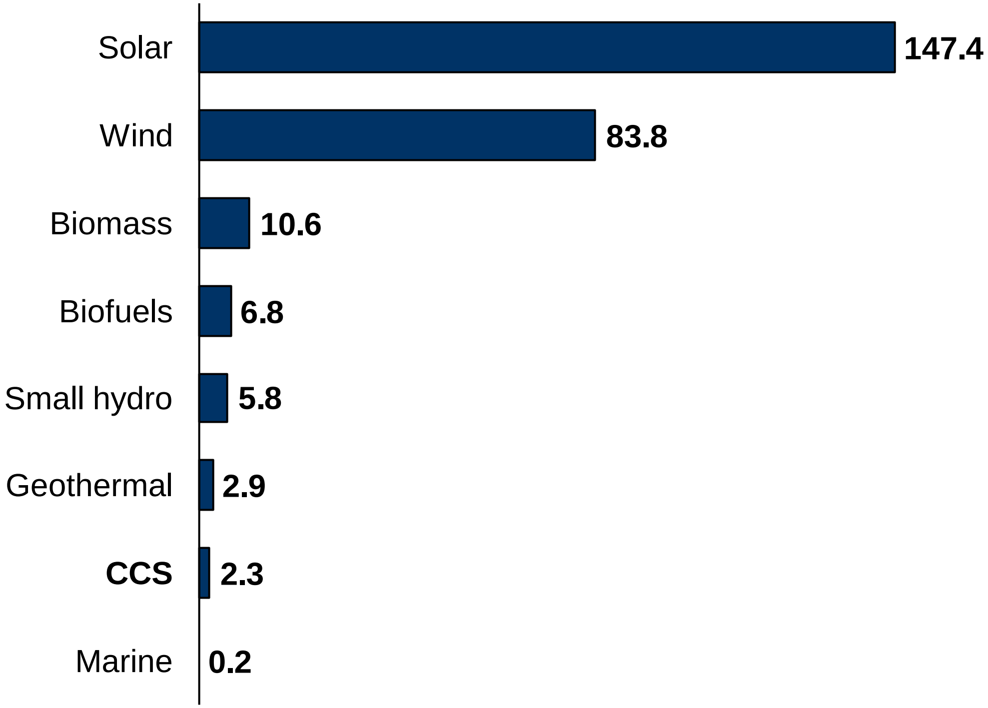
TOTAL INVESTMENTS IN CCS (2006-2011)

$ billion



TOTAL INVESTMENTS IN RENEWABLES AND CCS (2011)

$ billion



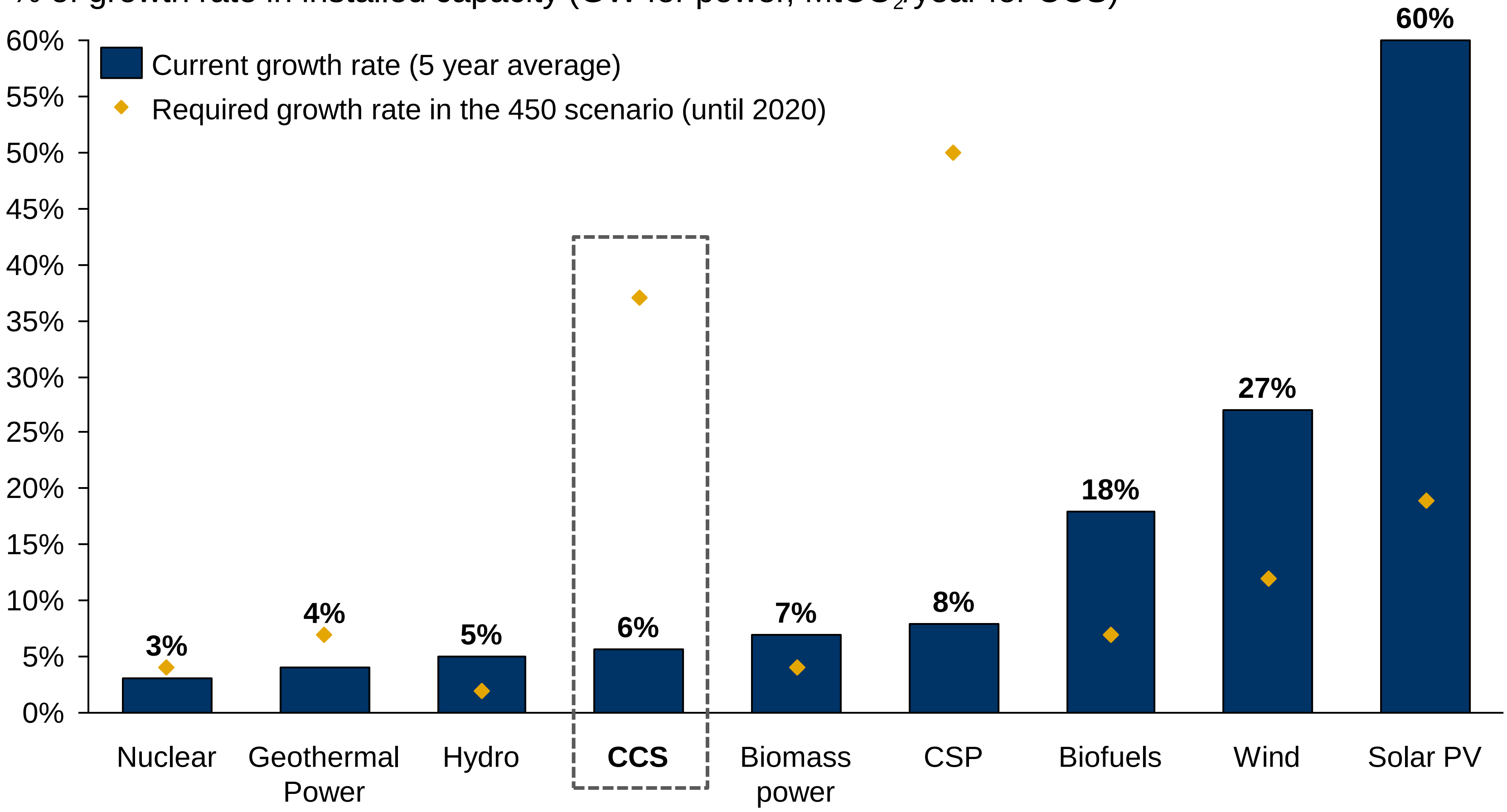
Notes: Private investments include project financing, equipment manufacturing scale-up, R&D and small distributed capacity (below 1MW). The data only include completed deals that have not been cancelled or postponed.

Source: UNEP (2012) “Global Trend in renewable Investment” and Bloomberg New Energy Finance, extracted from database July 27 2012

As a result, CCS development is not seeing the necessary growth rate recommended by the IEA for its demonstration phase

GAP IN ANNUAL GROWTH RATE REQUIRED IN IEA'S *450 SCENARIO*

% of growth rate in installed capacity (GW for power, $MtCO_2$/year for CCS)



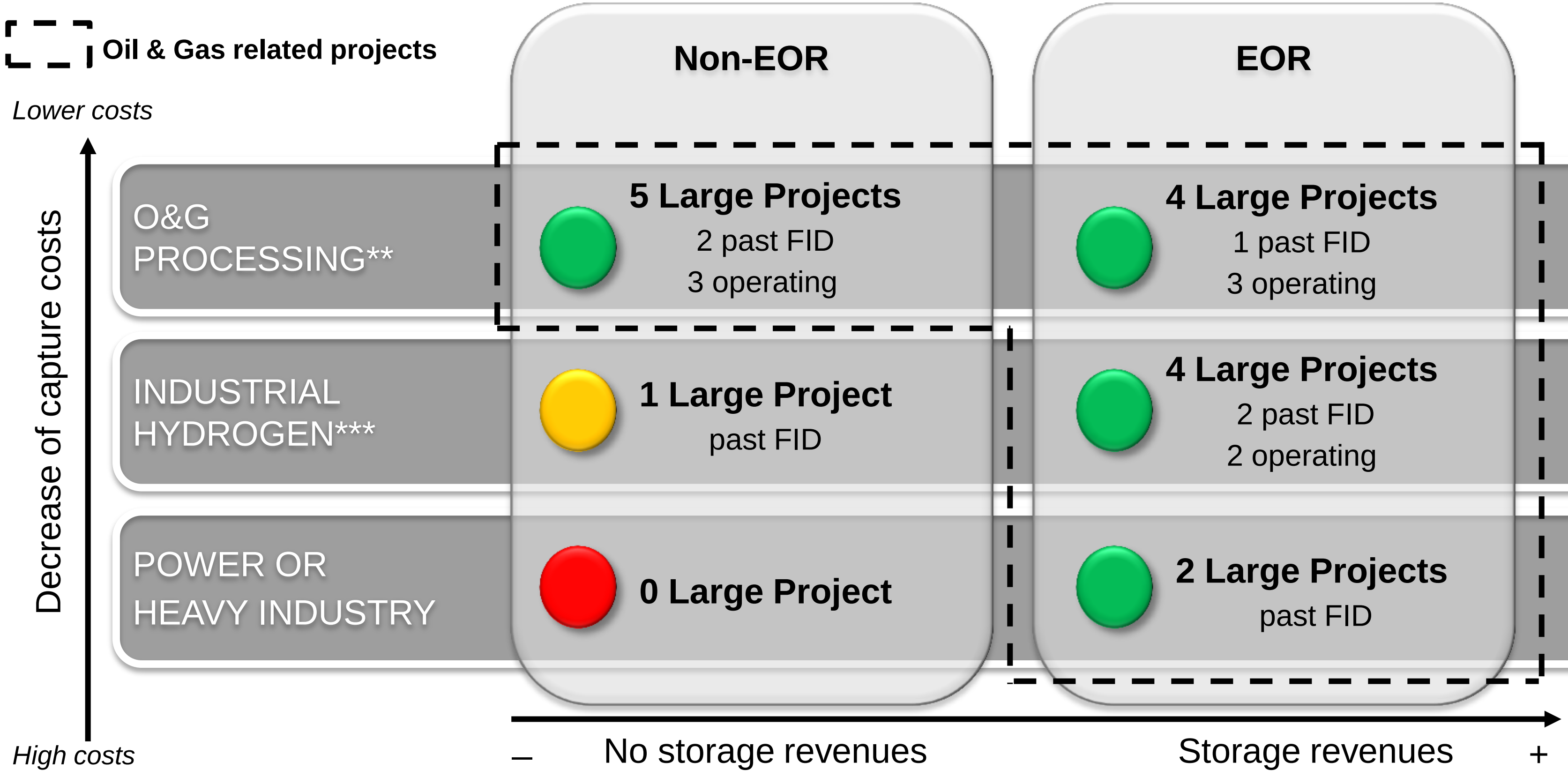
Notes: Growth rates are a function of installed generation capacity (GW) or installed storage rate capacity (MtCO2/year) for CCS. The current rate for wind and biofuels is the annual average growth rate from 2005 -2010. For solar PV, biomass, geothermal, and CSP, this period is 2004-2009. The current rate and status of nuclear includes capacity under construction. Required growth rate in the 450 scenario is for the period 2010-2020

Source: IEA (2011), "Clean Energy Progress Report" and IEA(2009), "Technology Roadmap, Carbon capture and storage"

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

DISTRIBUTION OF THE 16 LARGE PROJECTS* IN OPERATION OR PAST FINAL INVESTMENT DECISION (FID)

As of October 2012

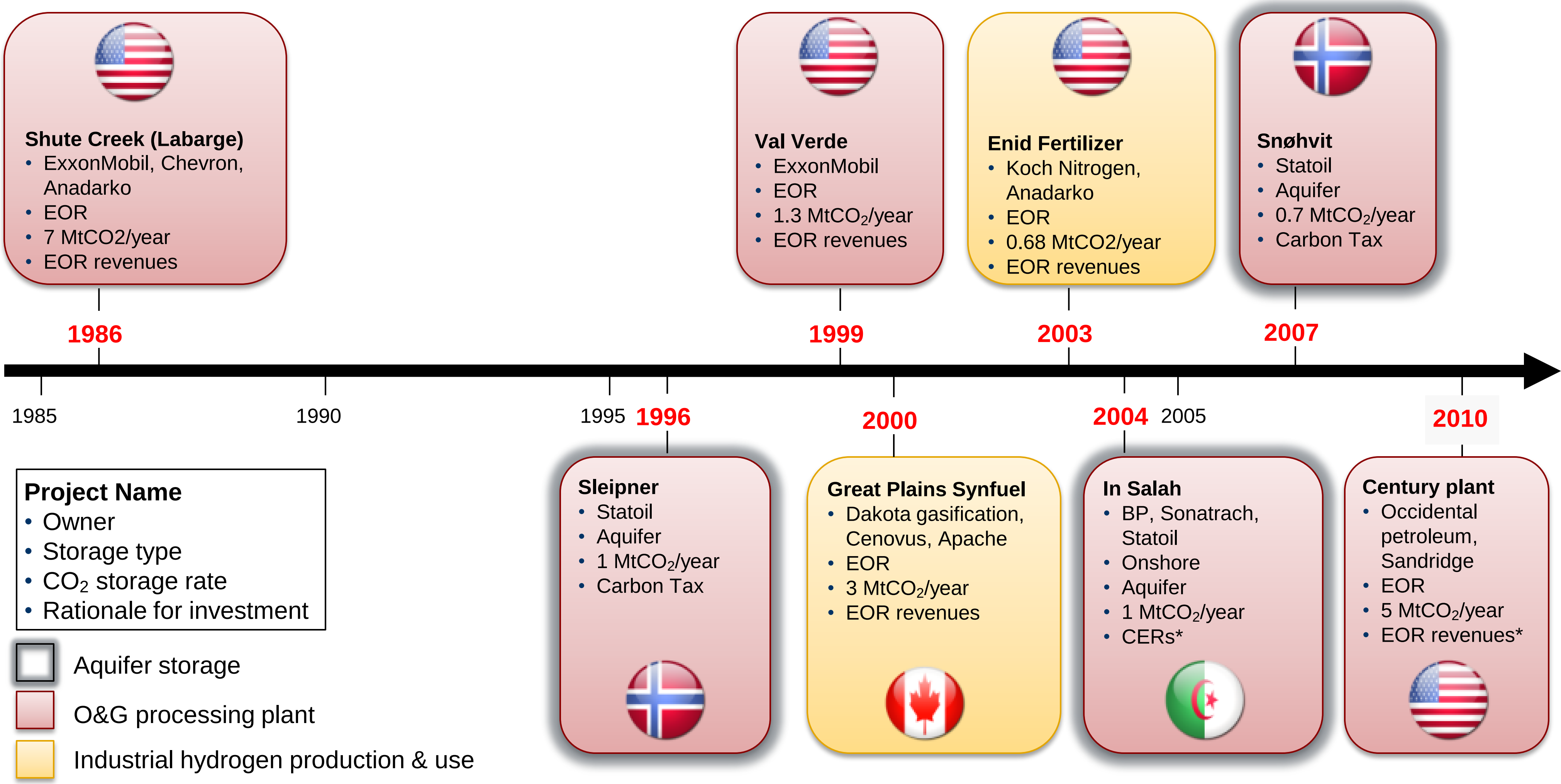


	Non-EOR	EOR
O&G PROCESSING**	🟢 **5 Large Projects** 2 past FID 3 operating	🟢 **4 Large Projects** 1 past FID 3 operating
INDUSTRIAL HYDROGEN***	🟡 **1 Large Project** past FID	🟢 **4 Large Projects** 2 past FID 2 operating
POWER OR HEAVY INDUSTRY	🔴 **0 Large Project**	🟢 **2 Large Projects** past FID

Note: * "Large Projects" refers to integrated CCS projects above 0.6MtCO2/year.
** Natural gas processing plant or oil sand upgrader
*** hydrogen production plant for chemical or fertilizer, including steam methane reforming and coal gasification plants
FID: Final Investment Decision

Source: SBC Energy Institute based on GCCSI database

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



1986

Shute Creek (Labarge)
- ExxonMobil, Chevron, Anadarko
- EOR
- 7 MtCO2/year
- EOR revenues

1996

Sleipner
- Statoil
- Aquifer
- 1 $MtCO_2$/year
- Carbon Tax

1999

Val Verde
- ExxonMobil
- EOR
- 1.3 $MtCO_2$/year
- EOR revenues

2000

Great Plains Synfuel
- Dakota gasification, Cenovus, Apache
- EOR
- 3 $MtCO_2$/year
- EOR revenues

2003

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

2004

In Salah
- BP, Sonatrach, Statoil
- Onshore
- Aquifer
- 1 $MtCO_2$/year
- CERs*

2007

Snøhvit
- Statoil
- Aquifer
- 0.7 $MtCO_2$/year
- Carbon Tax

2010

Century plant
- Occidental petroleum, Sandridge
- EOR
- 5 $MtCO_2$/year
- EOR revenues*

Project Name
- Owner
- Storage type
- CO_2 storage rate
- Rationale for investment

☐ Aquifer storage

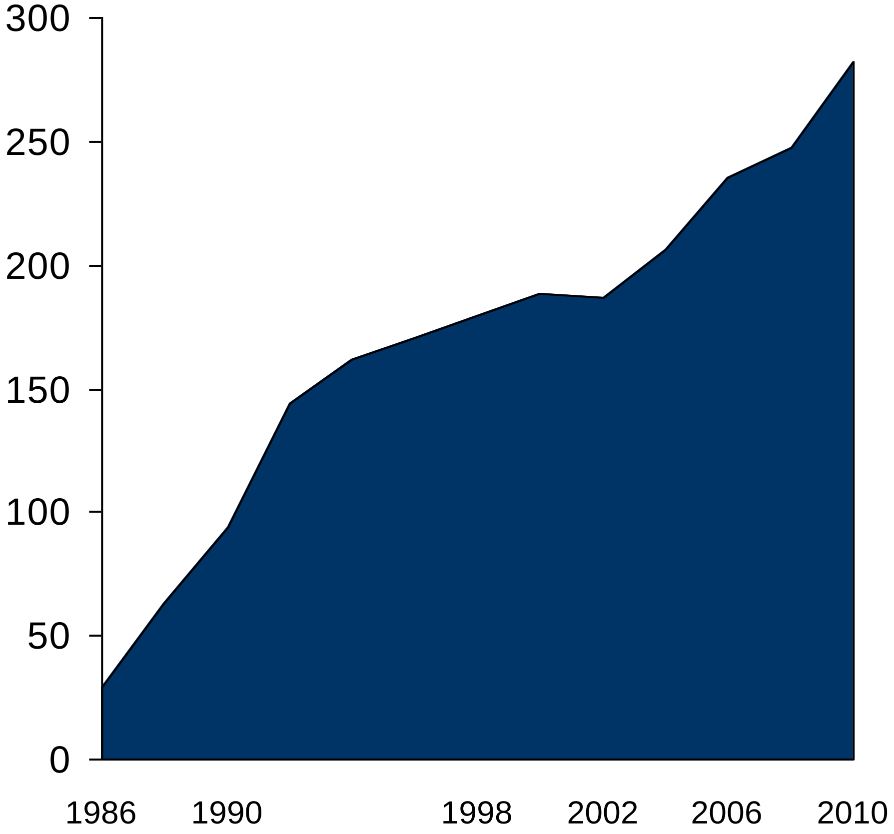
🟥 O&G processing plant

🟨 Industrial hydrogen production & use

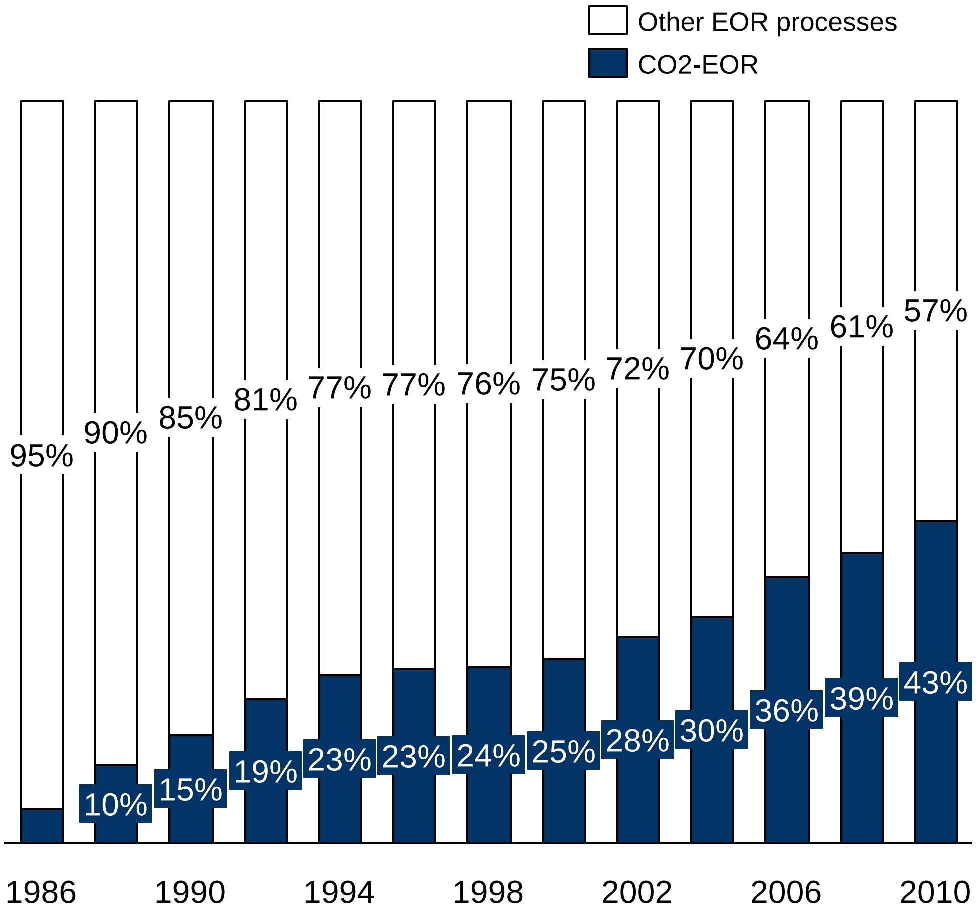
Notes: *Certified Emissions Reductions (Kyoto Protocol)
Source: SBC Energy Institute.

CO_2-EOR is now mainstream commercial technology in the US

US CO_2-EOR PRODUCTION
k bbl/d, 1986-2010



US CO_2-EOR VS. OTHER EOR
%, 1986-2010



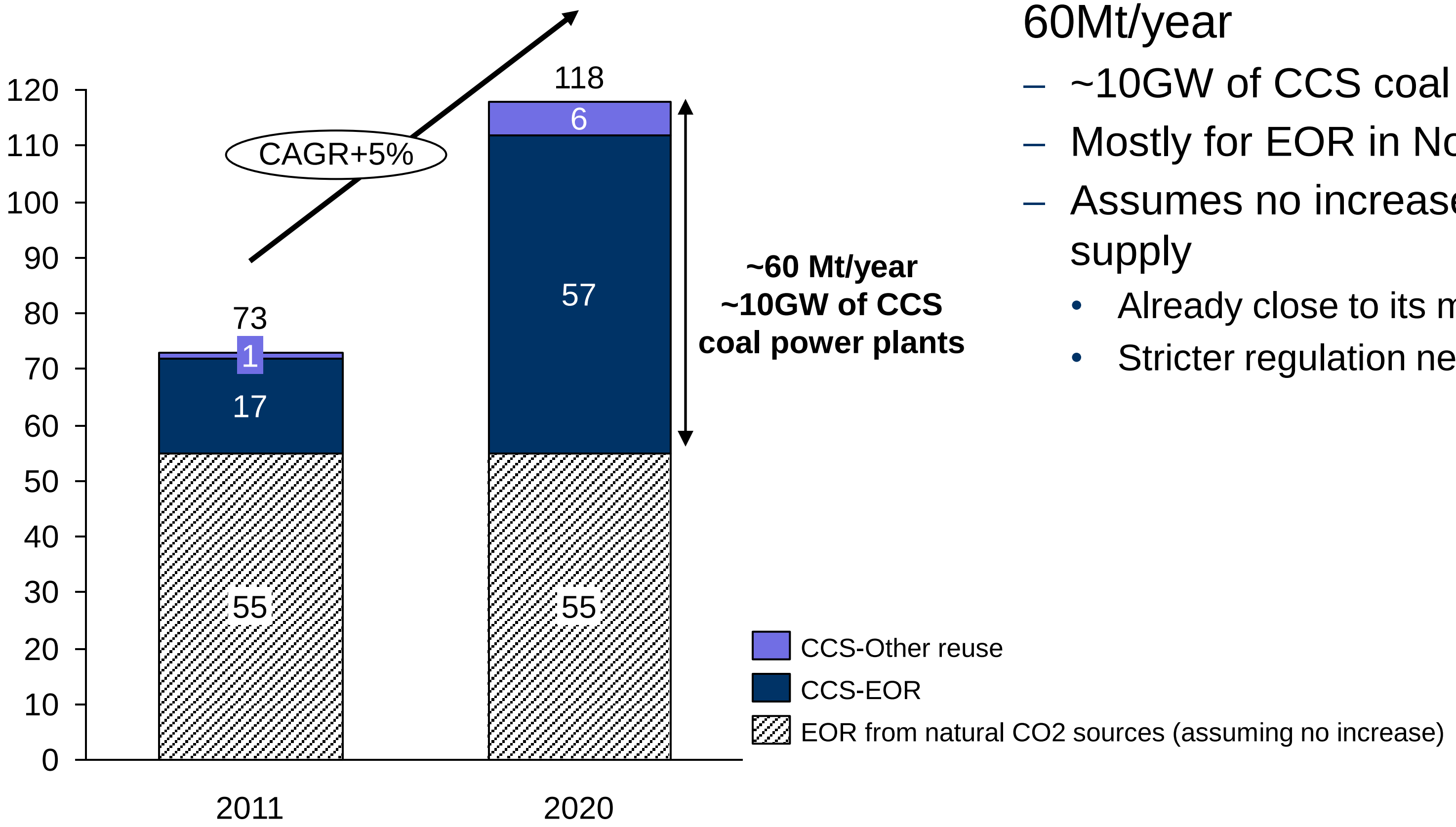
Note: CO_2-EOR refers to enhanced oil recovery through CO2 injection. Other EOR processes include thermal EOR, natural gas EOR, water EOR etc…

Source: Oil & Gas Journal 2010, Bloomberg New Energy Finance Note other states includes Oklahoma, Utah, Pennsylvania, Michigan, California, Montana, Alabama and Louisiana; Oil & Gas Journal 2010, Bloomberg New Energy Finance.

Growing demand for beneficial reuse of CO_2 should support several CCS projects during the next decade

CONSERVATIVE ESTIMATE OF THE GLOBAL INDUSTRIAL DEMAND FOR CO_2 IN 2020

$MtCO_2$/year



~60 Mt/year ~10GW of CCS coal power plants

- Anthropogenic CO_2 demand in 2020: 60Mt/year
  - ~10GW of CCS coal power
  - Mostly for EOR in North America
  - Assumes no increase in natural CO_2 supply
    - Already close to its maximum capacity
    - Stricter regulation needed

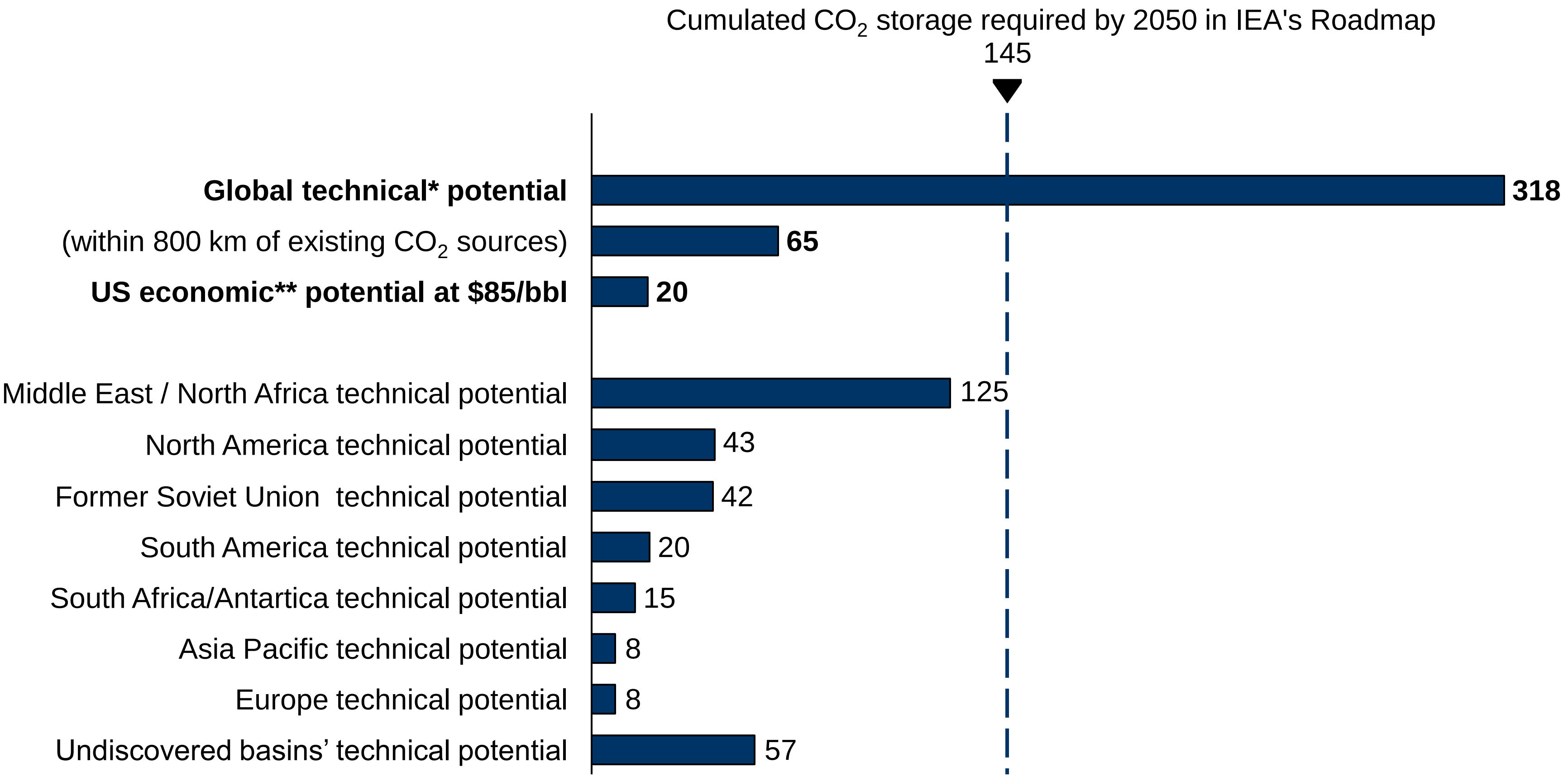
Note: CO_2-EOR refers to enhanced oil recovery through CO2 injection. Other EOR processes include thermal EOR, natural gas EOR, water EOR etc…

Source: Oil & Gas Journal 2010, Bloomberg New Energy Finance Note other states includes Oklahoma, Utah, Pennsylvania, Michigan, California, Montana, Alabama and Louisiana; Oil & Gas Journal 2010, Bloomberg New Energy Finance.

Over the long run, optimistic studies estimate EOR to be technically capable of storing twice the volume specified in the IEA's roadmap for CCS

GLOBAL LONG-TERM POTENTIAL FOR CO_2-EOR

$GtCO_2$ stored



Notes: * With next-generation CO2-EOR technologies
** At an oil price of $85/bbl, a CO2 market price of $40/Mt, and a 20% ROR before tax

Source: Advanced Resources International, 2011

Projects for CCS power plants without EOR revenues are facing difficulties

NINE PROMISING CCS POWER PLANTS HAVE BEEN CANCELLED

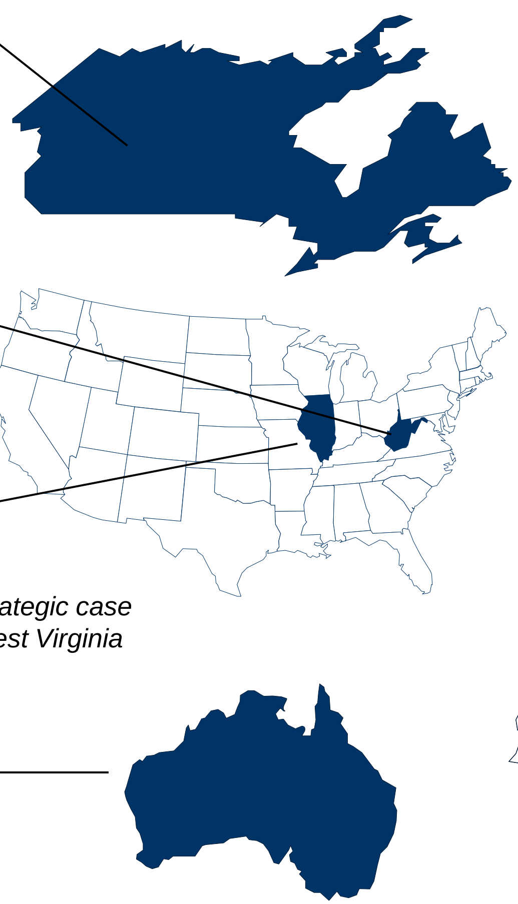
In red when abandoned mainly due to local public opposition

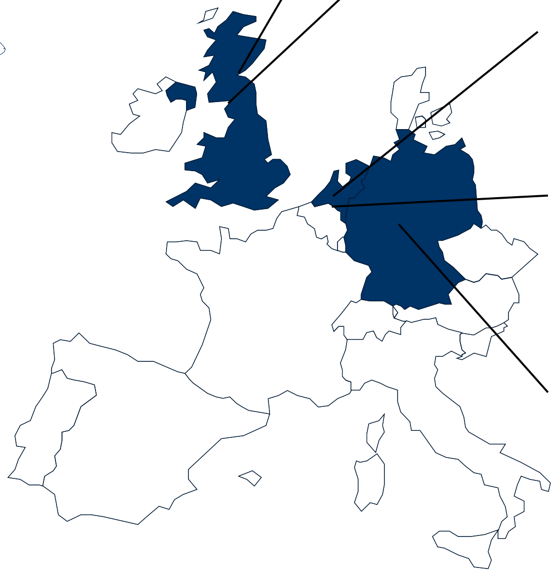
TransAlta Project Pioneer
$782 million granted
Economic reasons
Horizontal multi-frac well technology is delaying the needs for CO2-EOR in Alberta's mature oil fields. The CCS project without EOR revenues became non-commercial

FutureGen
$700 million granted
Economic reasons
Dates back 2004, was cancelled due to rising costs. A new project, FutureGen2.0, smaller in size, is still struggling to pass FID and is not expected to be built before 2016

AEP Mountaineer
$334 million granted
Economic reasons
Uncertain climate policy had weakened the strategic case for the project, but cost-sharing issues with West Virginia commissioners eventually derailed it

ZeroGen
$300 million granted
Economics reasons
Abandoned by the Queensland government, due to escalating costs





Scottish Power Longannet
$1,500 million granted
Economic reasons
Grant proved insufficient to retrofit this old and inefficient plant

Hunterston
Underlying plant cancelled
Overwhelming local opposition to the construction of the coal power plant

RWE Eemshaven
Storage opposition
Dutch government banned onshore CO2 storage

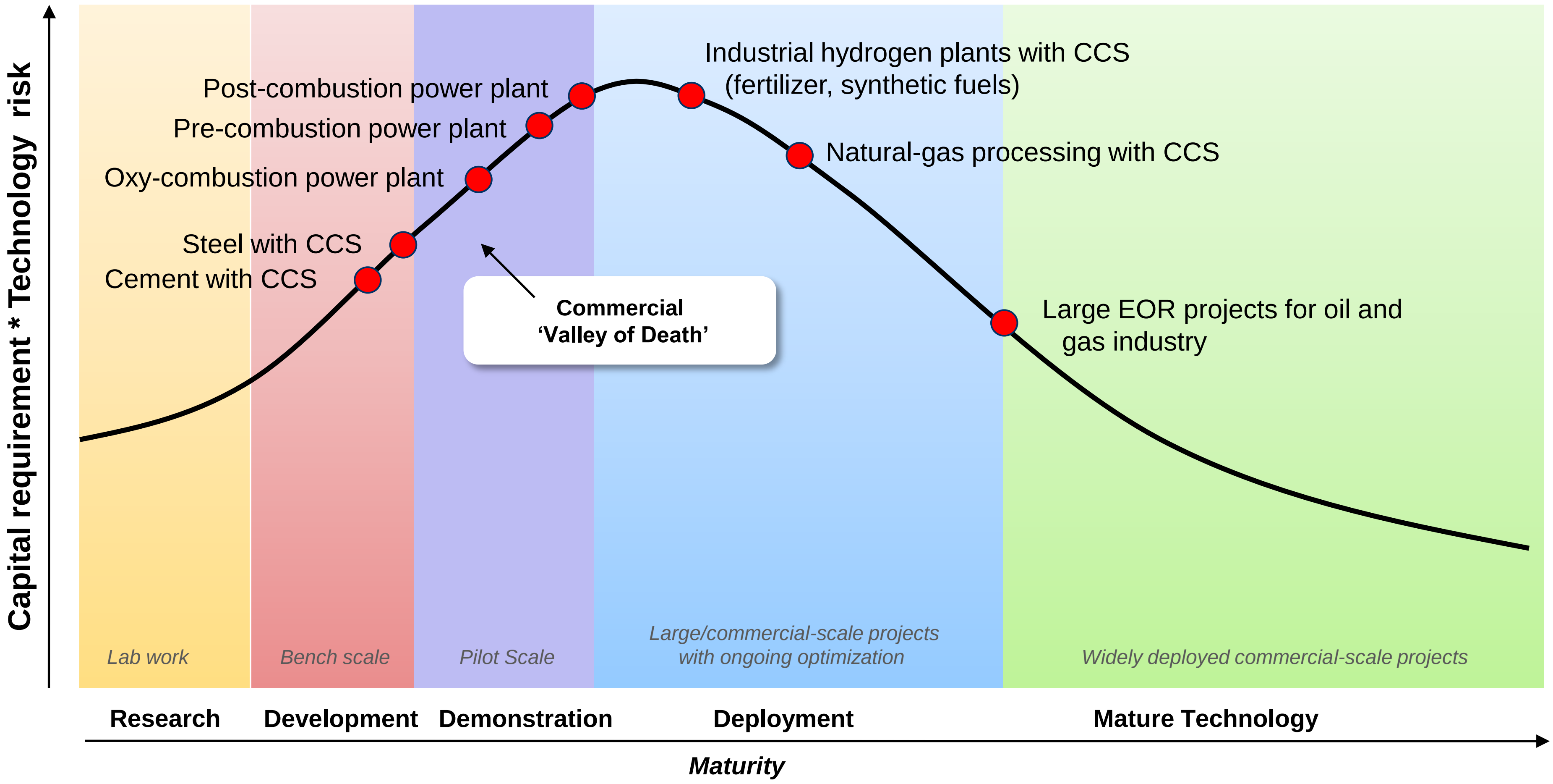
Shell Barendrecht
$40 million granted
Storage opposition
Dutch government banned onshore CO2 storage

Vattenfall Jänschwalde
$180 million granted
Storage opposition
Lack of political will to provide legislation needed for CCS in Germany, especially on storage

Source: SBC Energy Institute

Integrated CCS projects for the power and heavy industries are locked in the commercial 'valley of death'

INVESTMENT-RISK CURVE: INTEGRATED PROJECTS



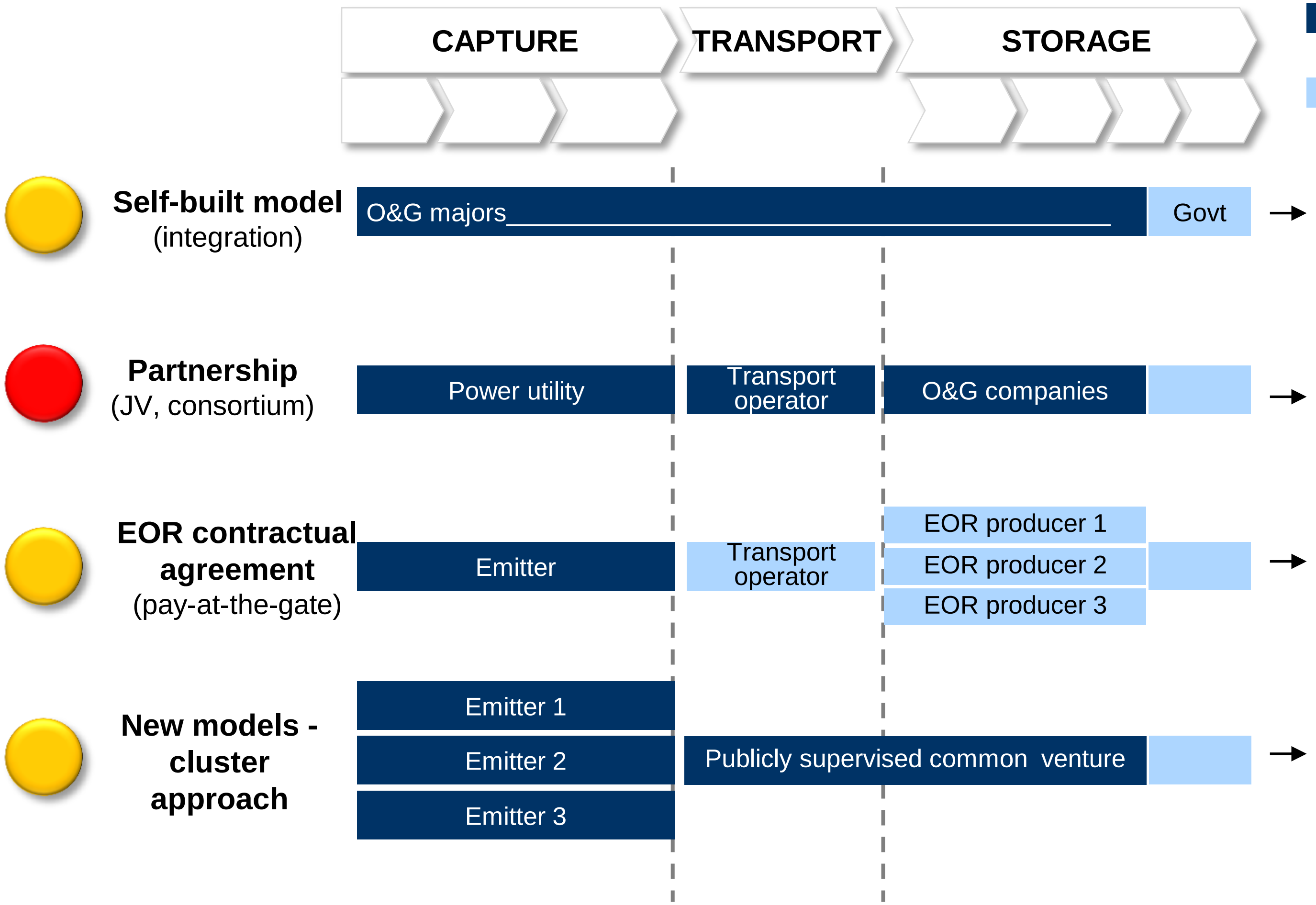
Source: SBC Energy Institute

Power and industry CCS projects incur planning and coordination difficulties that do not affect O&G-related CCS projects

BUSINESS MODELS FOR INTEGRATED PROJECTS

■ Project owner (potentially eligible for emissions reductions)

□ Secondary stakeholder



	CAPTURE	TRANSPORT	STORAGE	
🟡 **Self-built model** (integration)	O&G majors			Govt
🔴 **Partnership** (JV, consortium)	Power utility	Transport operator	O&G companies	
🟡 **EOR contractual agreement** (pay-at-the-gate)	Emitter	Transport operator	EOR producer 1 EOR producer 2 EOR producer 3	
🟡 **New models - cluster approach**	Emitter 1 Emitter 2 Emitter 3	Publicly supervised common venture		

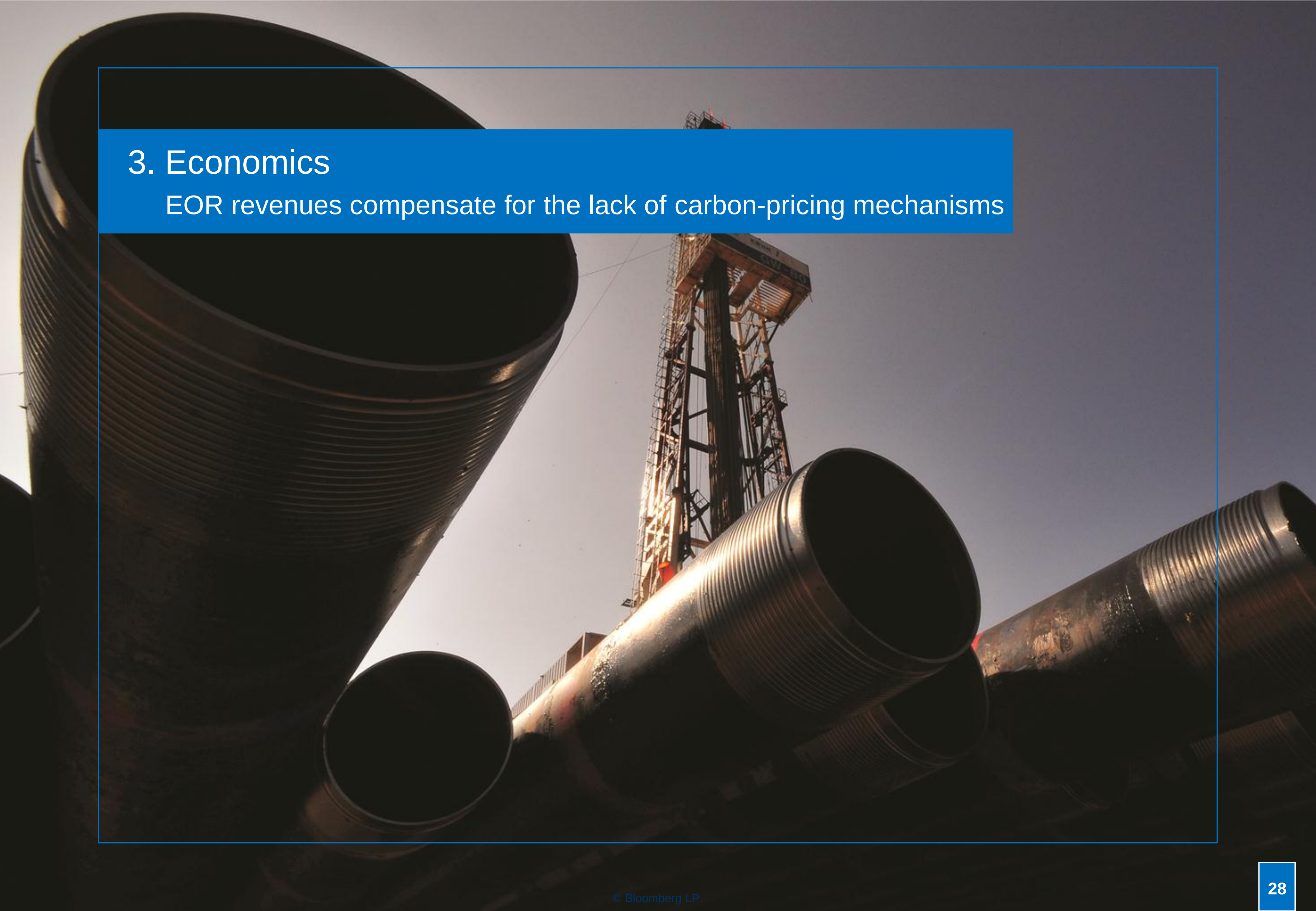
Self-built model →
- Single integrated project owner: high level of control, no coordination issues
- Limited to Oil & Gas majors or very large utilities only

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

EOR contractual agreement →
- Limited to EOR

New models - cluster approach →
- Shared infrastructures for transport and storage reduce up-front capex
- Involvement of public authorities facilitates public acceptance
- Not for early demonstration phase

Source: SBC Energy Institute



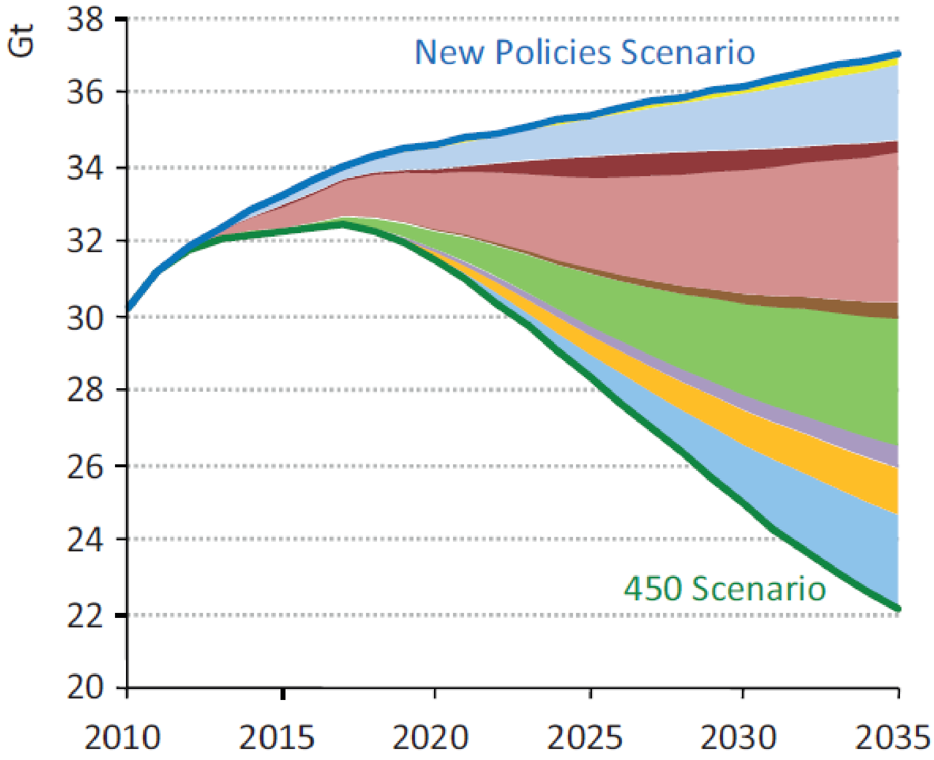
3. Economics

EOR revenues compensate for the lack of carbon-pricing mechanisms

CCS is expected to play an important role in achieving the lowest-cost pathway to mitigating CO_2 emissions

CO_2 ABATEMENT LEVERS IN THE IEA'S *450 SCENARIO* RELATIVE TO *NEW POLICIES SCENARIO*

Annual energy-related CO_2 emissions (Gt)



	CO_2 abatement	2020	2035
🟨	Activity	2%	2%
🟦	End-use efficiency	18%	13%
🟥	Power plant efficiency	3%	2%
🟥	Electricity savings	50%	27%
🟫	Fuel and technology switching in end-uses	2%	3%
🟩	Renewables	15%	23%
🟪	Biofuels	2%	4%
🟧	Nuclear	5%	8%
🟦	CCS	4%	17%
	Total (Gt CO_2)	**3.1**	**15.0**

Energy Efficiency

Notes: The 450 scenario is the lowest cost pathway to mitigate CO2 concentration level below 450ppm in the future and gives a 50% chance to limit global warming below 2°C, the UNFCCC target. The New Policy Scenario is IEA's central case taking into account existing policies and declared intentions, even if they are yet to be implemented

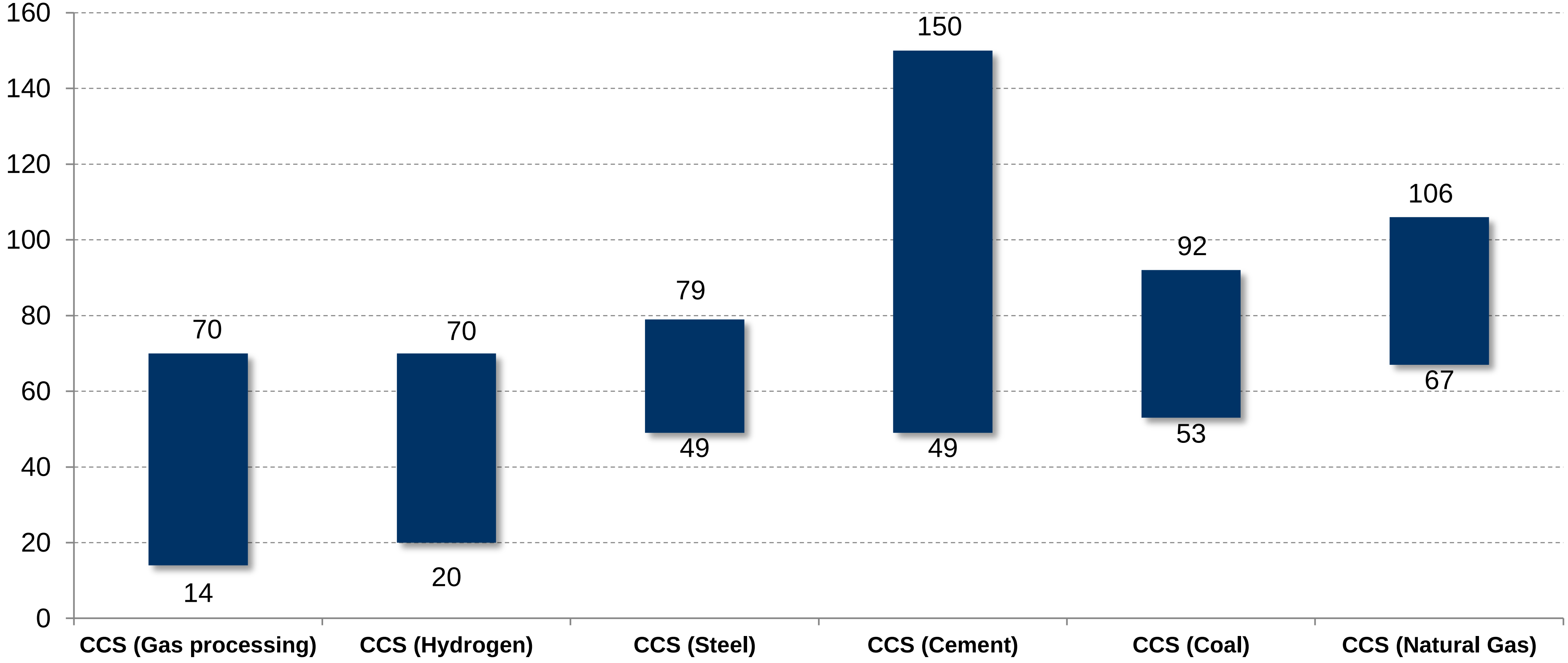
Activity describes changes in the demand for energy services, such as lighting or transport services, due to price responses. Power plant efficiency includes emissions savings from coal-to-gas switching

Source: IEA, World Energy Outlook 2012

In industrial applications, CCS offers CO_2 abatement opportunities at a very low cost

RANGE OF CURRENT COSTS OF CO_2 AVOIDED BY CCS APPLICATION IN THE US

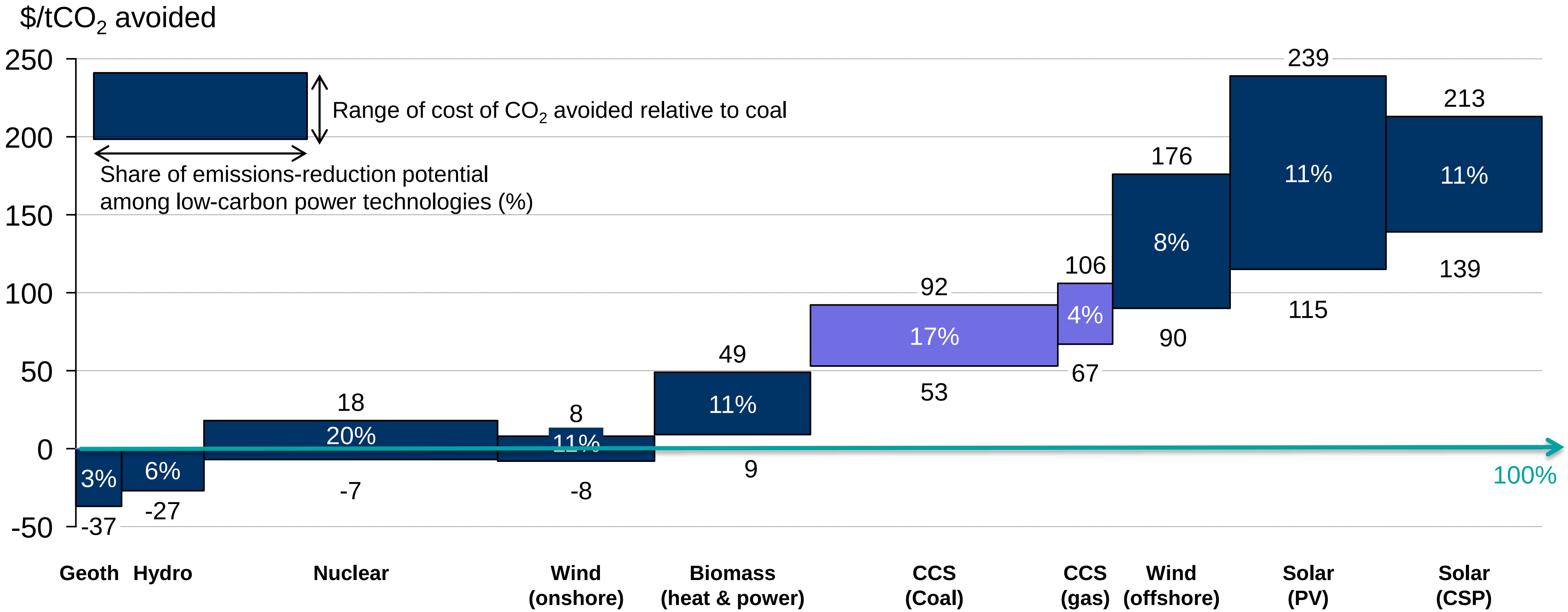
$/t$CO_2$ avoided



Notes:	Costs of CO_2 avoided are for first-of-a-kind plants, relative to the same plant without CCS. Estimated costs in the United States with current available technologies
Source:	SBC Energy Institute. CO_2 market price for EOR is from Bloomberg New Energy Finance (2012). Estimated costs in the United States with current available technologies derive from 19 international studies gathered by the Global CCS Institute in “The costs of CCS and other low-carbon technologies – issues brief 2011, No.2”. One figure with an abatement cost of only $23/t for coal CCS and has been voluntarily excluded from this dataset. Other studies included in these ranges by SBC Energy Institute are: IEA “Industrial Roadmap for CCS”, 2011; and Global CCS Institute, “Economic assessment of CCS technologies”, 2011 Update. Sleipner and In Salah’s actual abatement costs have been used to establish the lower range for CCS (gas processing).

In power generation, CCS offers significant CO_2 abatement potential at a reasonable cost

CURRENT COSTS OF CO_2 AVOIDED BY LOW-CARBON POWER TECHNOLOGY* VERSUS RESPECTIVE SHARES OF CO_2 EMISSIONS-REDUCTION POTENTIAL IN 2050**



Notes: * Cost of CO_2 avoided with current technologies in the US relative to coal, except for CCS (gas), which is compared with a gas-fired power plant. Coal is taken as the reference plant because it emits the highest level of CO_2 of all power-generation technologies. The cost of CO_2 avoided can be negative, implying that the technology is more cost-effective than coal even without considering the emissions impact. This is the case for hydropower and conventional geothermal power.

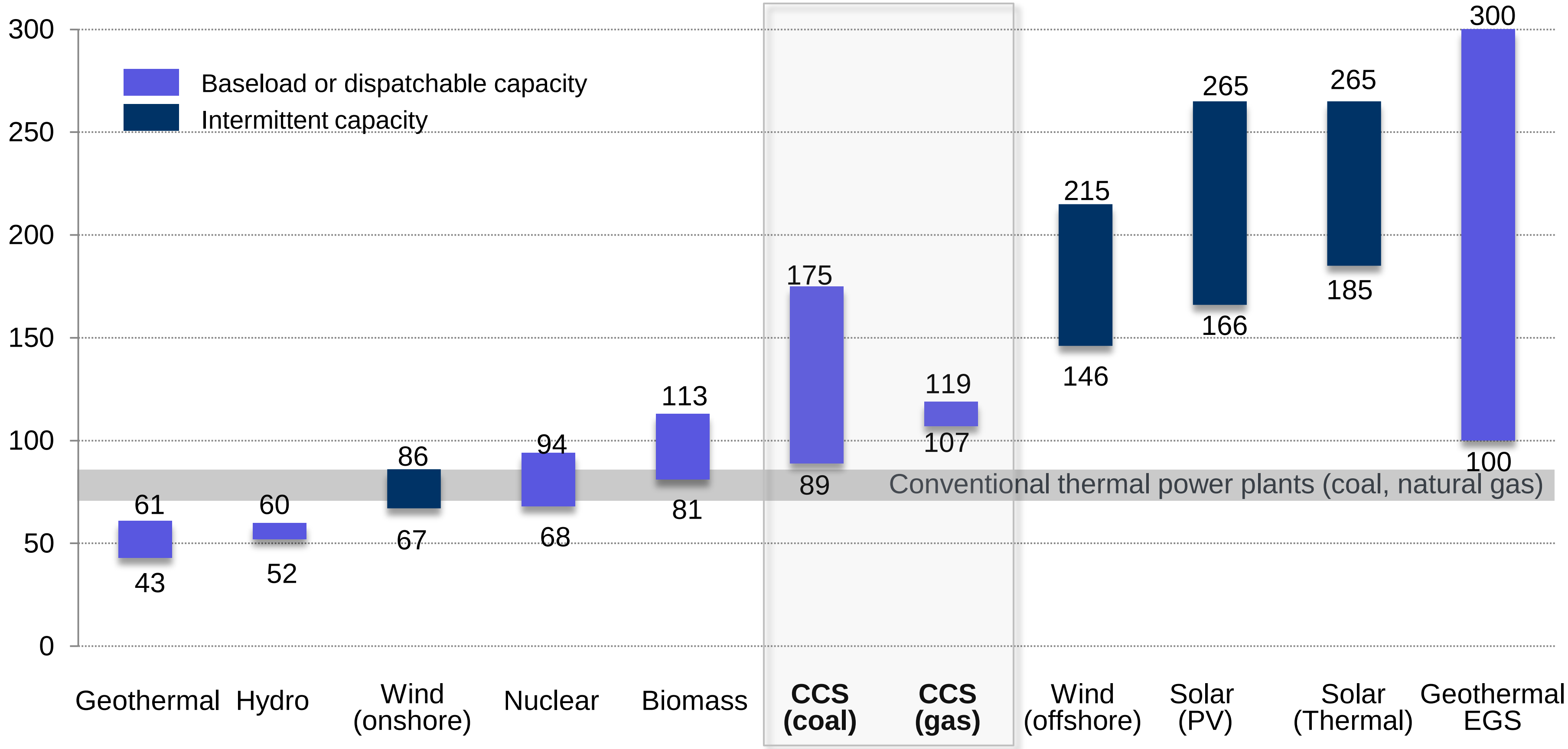
** Economic potential of each technology to contribute – at the global level – to the lowest-cost pathway to limiting global warming to 2°C compared with business-as-usual projection by 2050 (IEA's 2DS and 6DS scenario in Energy Technology Perspective, 2012)

Source: *SBC Energy Institute.* Costs derive from 19 international studies gathered by the Global CCS Institute in "The costs of CCS and other low-carbon technologies – issues brief 2011, No.2". One figure gave an abatement cost of only $23/t for coal CCS and has been voluntarily excluded from this dataset. Other sources include: Bloomberg New Energy Finance for Wind and Solar; IEA, "Industrial Roadmap for CCS", 2011;

CCS electricity could be competitive with other decarbonized options while providing baseload power capacity

RANGE OF LEVELIZED COST OF ELECTRICITY (LCOE) IN THE US WITH CURRENT TECHNOLOGIES

$ per MWh

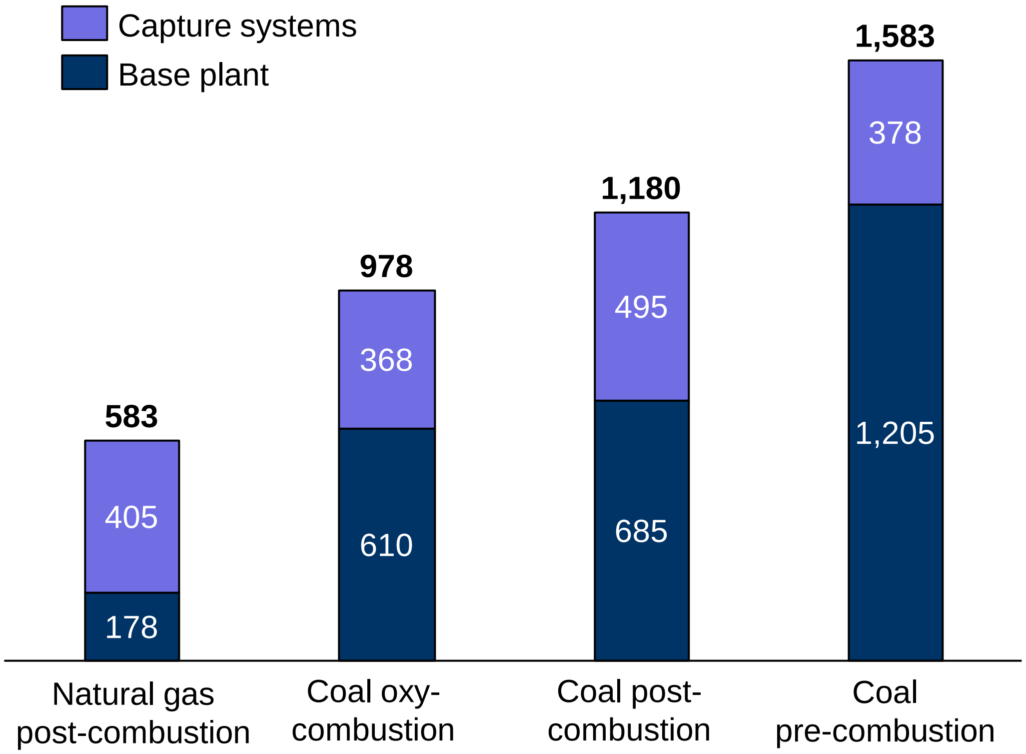


Notes: Levelized costs of electricity do not include back-up capacity needs and grid-integration costs incurred by the intermittency of variable renewable output

Source: Estimates are ranges of LCOE in the United States with current available technologies, and derive from 19 international studies gathered by the Global CCS Institute in “The costs of CCS and other low-carbon technologies – issues brief 2011, No.2”.
Estimates for EGS are highly hypothetical and derive from models from MIT, 2006; and Huenges and Frick, 2010.

CCS projects in the power sector require substantial up-front costs

CAPEX OF A 250 MW POWER PLANT WITH CO_2 CAPTURE SYSTEMS (FIRST-OF-A-KIND)
$ million



- A 250 MW power plant with CO_2 capture can require over a **billion dollars of investment, with up to 500 million dollars for the capture system**
- This does not include the costs of pipelines (~$20m for 100 km), storage site characterization and storage facilities (2-20 injection wells, depending on the reservoir quality)

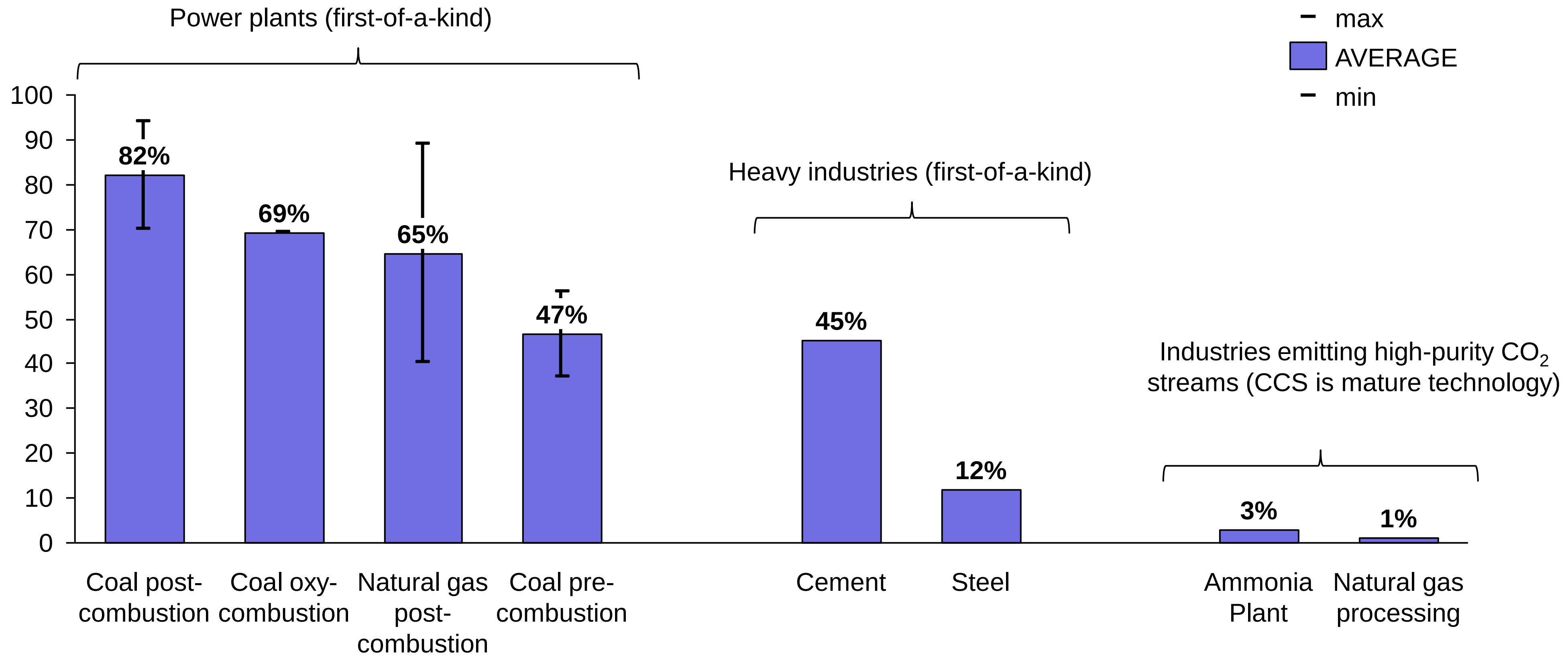
Note: Natural gas plant is based on combined-cycle technology. Post-combustion and oxy-combustion base plants are supercritical pulverized coal. Pre-combustion base plant is an integrated gasification combined-cycle unit.
Capture systems refer to all additional equipment needed for CCS at the plant (air-separation units, gas-separation systems, solvents, oxy-combustion boilers, purifiers, compressors…).

Source: Carbon capture & storage – Research note, Bloomberg New Energy Finance 2011

Applying CCS to a plant increases its levelized costs 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



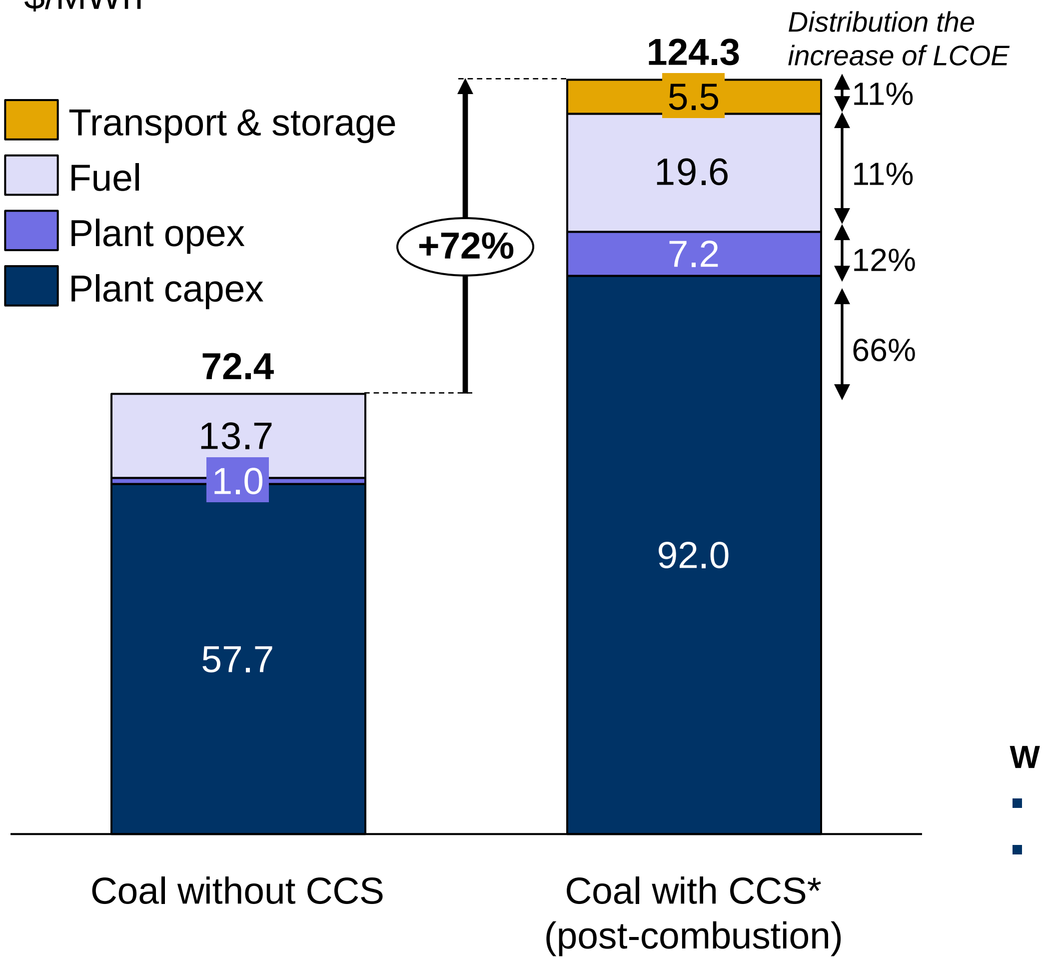
Notes: Natural gas plant uses combined cycle technology (NGCC). Post-combustion and oxy-combustion base plant are supercritical pulverized coal. Pre-combustion base plant is an integrated gasification combined-cycle unit.

Source: Global CCS Institute, “Economic Assessment of Carbon Capture and Storage Technologies” 2011 update; Bloomberg New Energy Finance 2012

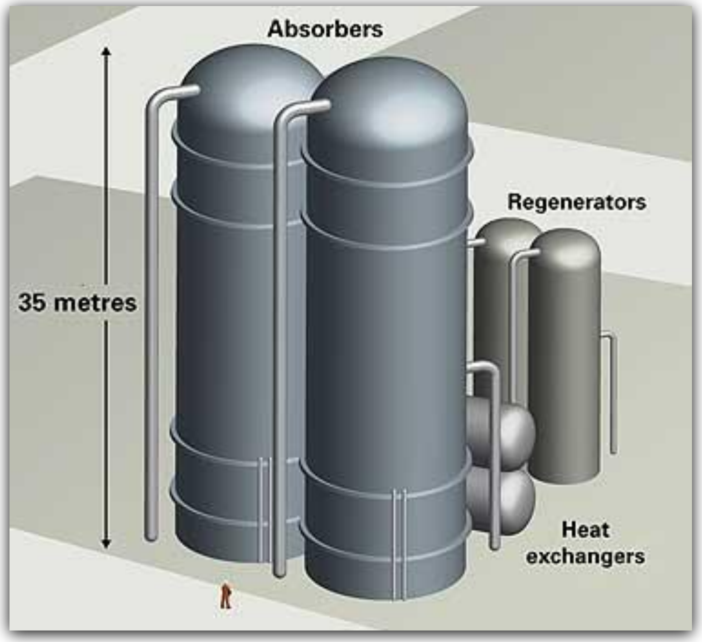
Capture is generally responsible for the large majority of these additional costs

LEVELIZED COST OF ELECTRICITY

$/MWh



500MW POST-COMBUSTION SYSTEM



Whatever capture technology is used:

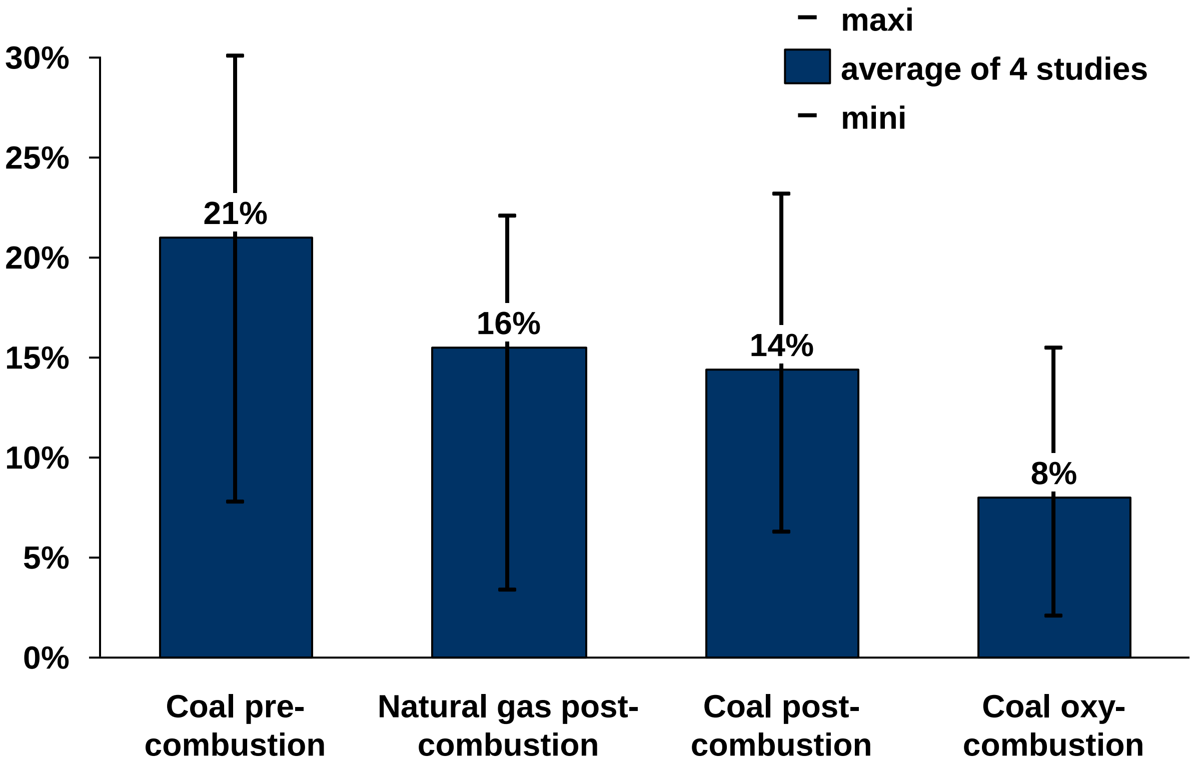
- Over two-third of the increase in LCOE comes from capture
- An energy penalty of 16% to 43% is incurred by the capture system

Notes: *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: Bloomberg New Energy Finance (2012);

CCS costs will fall as installed capacity rises, and as transport and storage infrastructure are shared

RANGE OF REDUCTION IN LCOE AFTER DEPLOYMENT OF 100 GW CAPACITY



- In addition, CCS projects grouped in clusters would save transport costs and storage risks

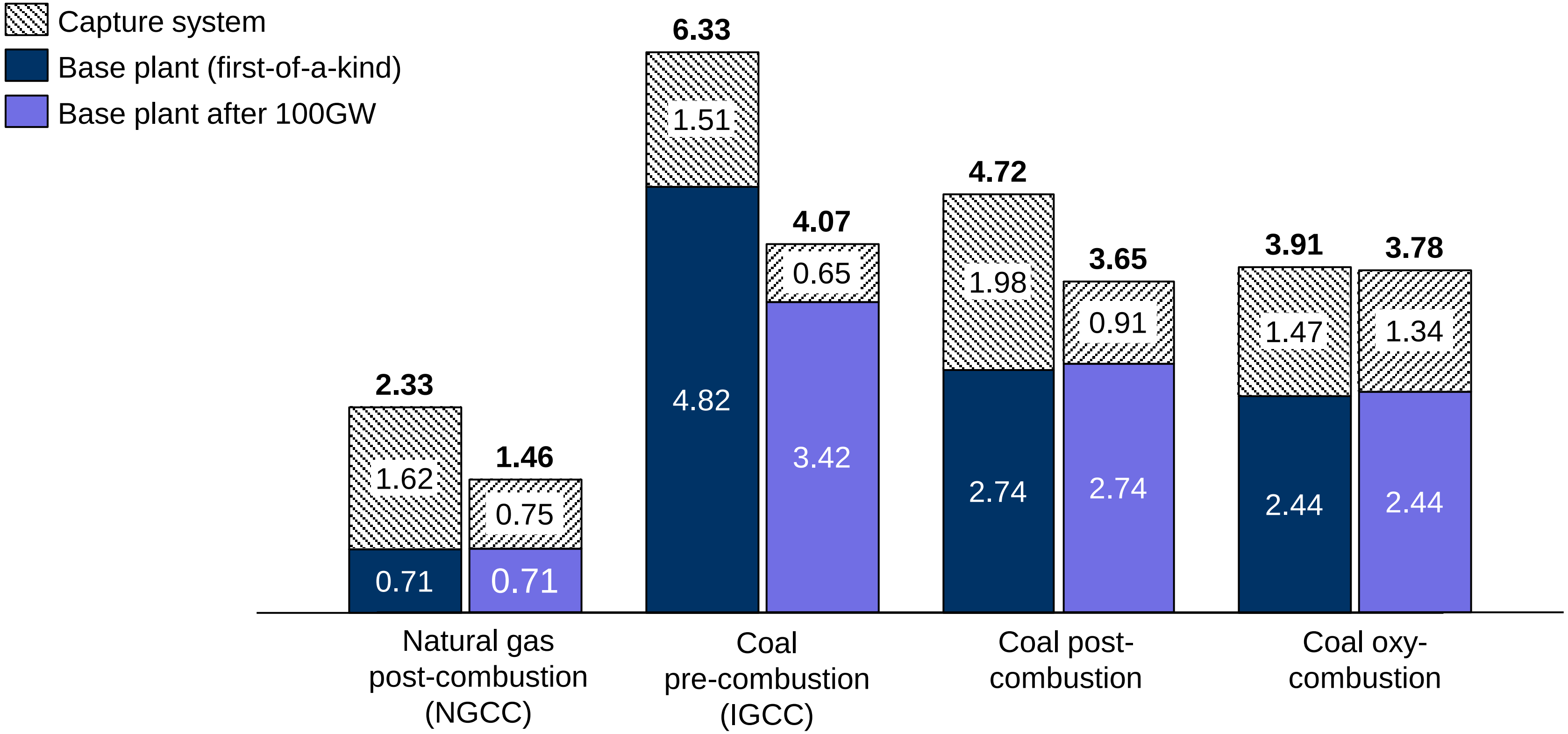
Notes: LCOE for levelized cost of electricity

Source: Average of four existing studies: Rubin 2007, EPRI 2008, US DOE 2009, Bloomberg New Energy Finance 2012

Declines in costs will come from improvements in the capture process and cheaper coal-gasification power plants (IGCC)

CAPITAL COST REDUCTION AFTER 100 GW FOR POWER PLANTS WITH CAPTURE SYSTEMS

$/MW



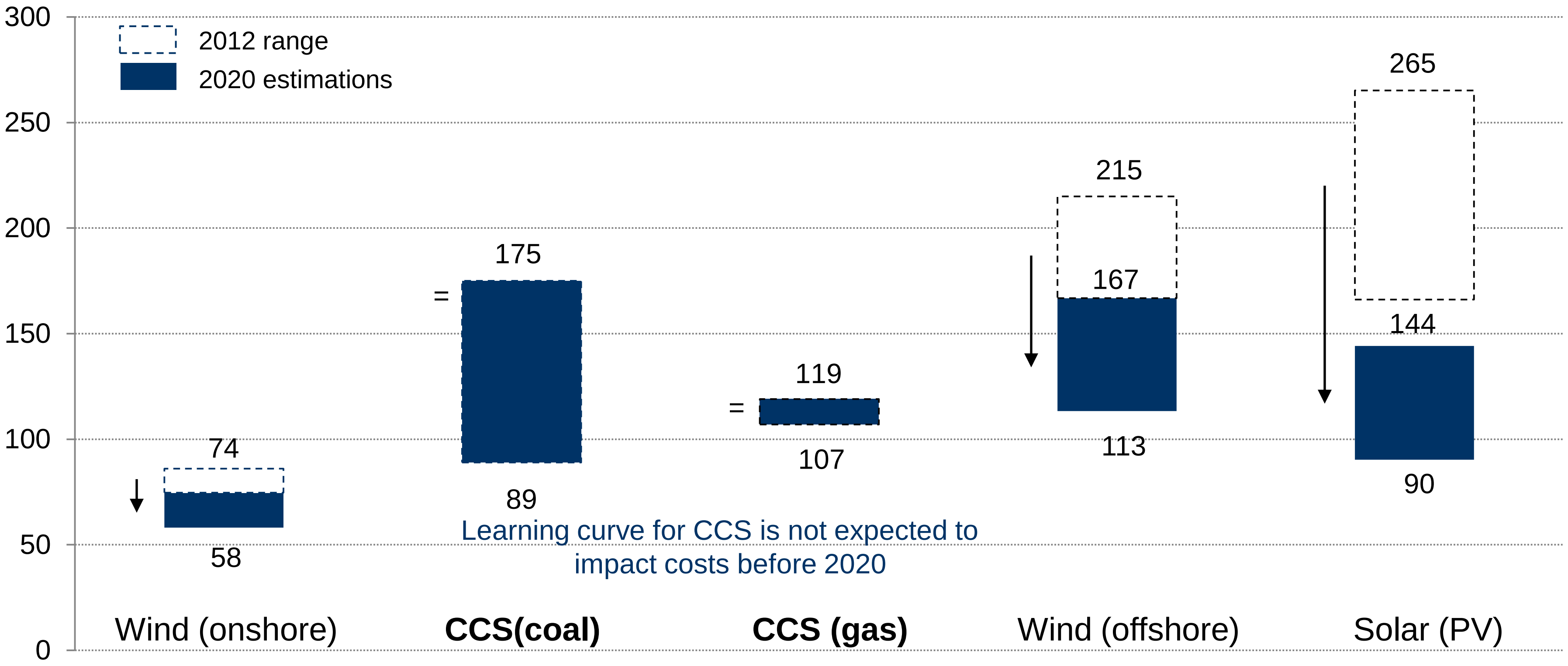
Note: Costs are based on 250 MWe base plant and capture. In the IGCC case, plant includes gasification and SO2 removal. Capture systems refer to all additional equipment needed for CCS at the plant (air-separation units, gas-separation systems, solvents, oxy-combustion boilers, purifiers, compressors…).

Source: Carbon capture & storage – Research note, Bloomberg New Energy Finance 2011

In contrast to the cost of renewables, the cost of CCS is unlikely to decrease before 2020 because of the limited number of demonstration projects

RANGE OF LEVELIZED COST OF ELECTRICITY IN THE UNITED STATES IN 2020

$/MWh



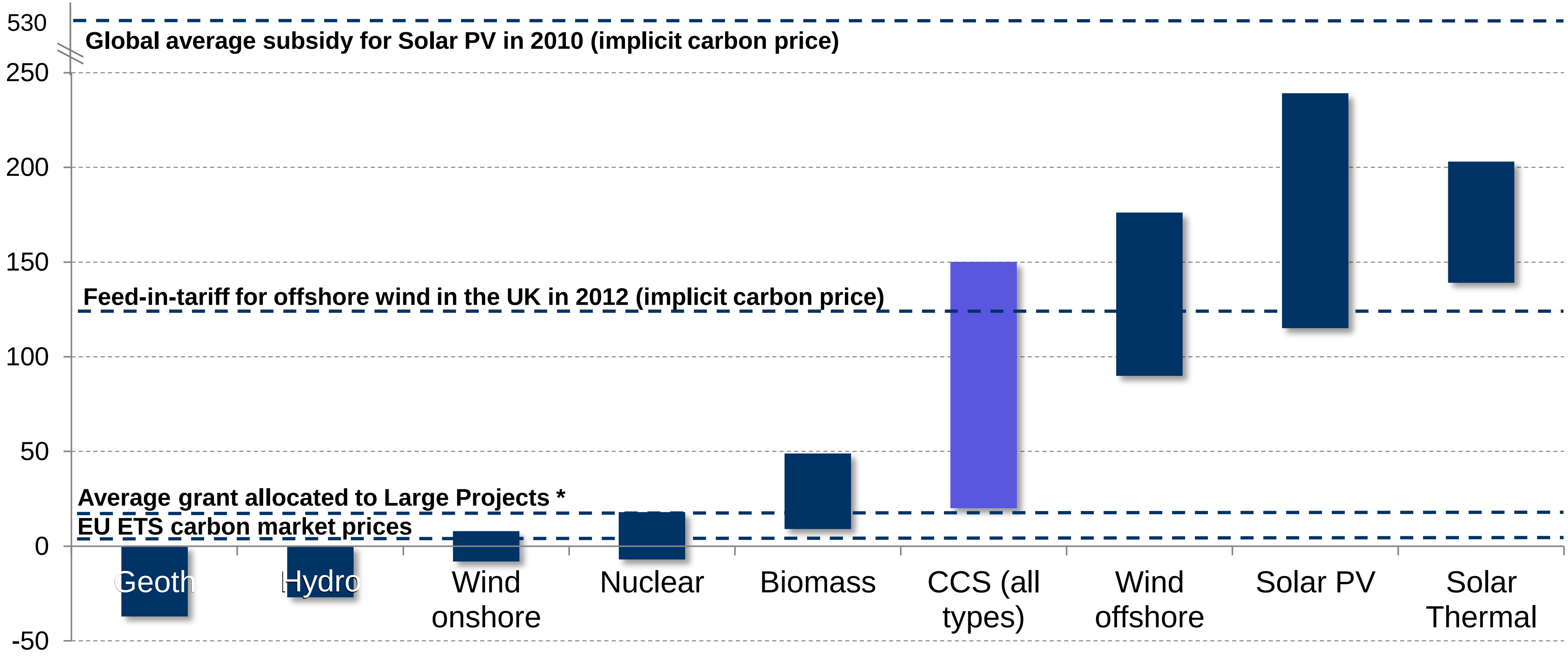
Note: Forecasts are based on BNEF estimates for LCOE reductions from 2011 to 2020, applied to ranges taken from the sources listed below. The LCOE of CCS has not been reduced, as “learning” has yet to start for this technology.

Source: Estimates are ranges of LCOE in the United States with current available technologies, and are derived from 19 international studies gathered by the Global CCS Institute in “The costs of CCS and other low-carbon technologies – issues brief 2011, No.2”. Estimates for EGS are highly hypothetical and derive from models from MIT, 2006; and Huenges and Frick, 2010.

High up front costs make it difficult for governments to allocate funds

COSTS OF CO_2 AVOIDED IN THE US BY VARIOUS TECHNOLOGIES, RELATIVE TO COAL

$/t$CO_2$ avoided



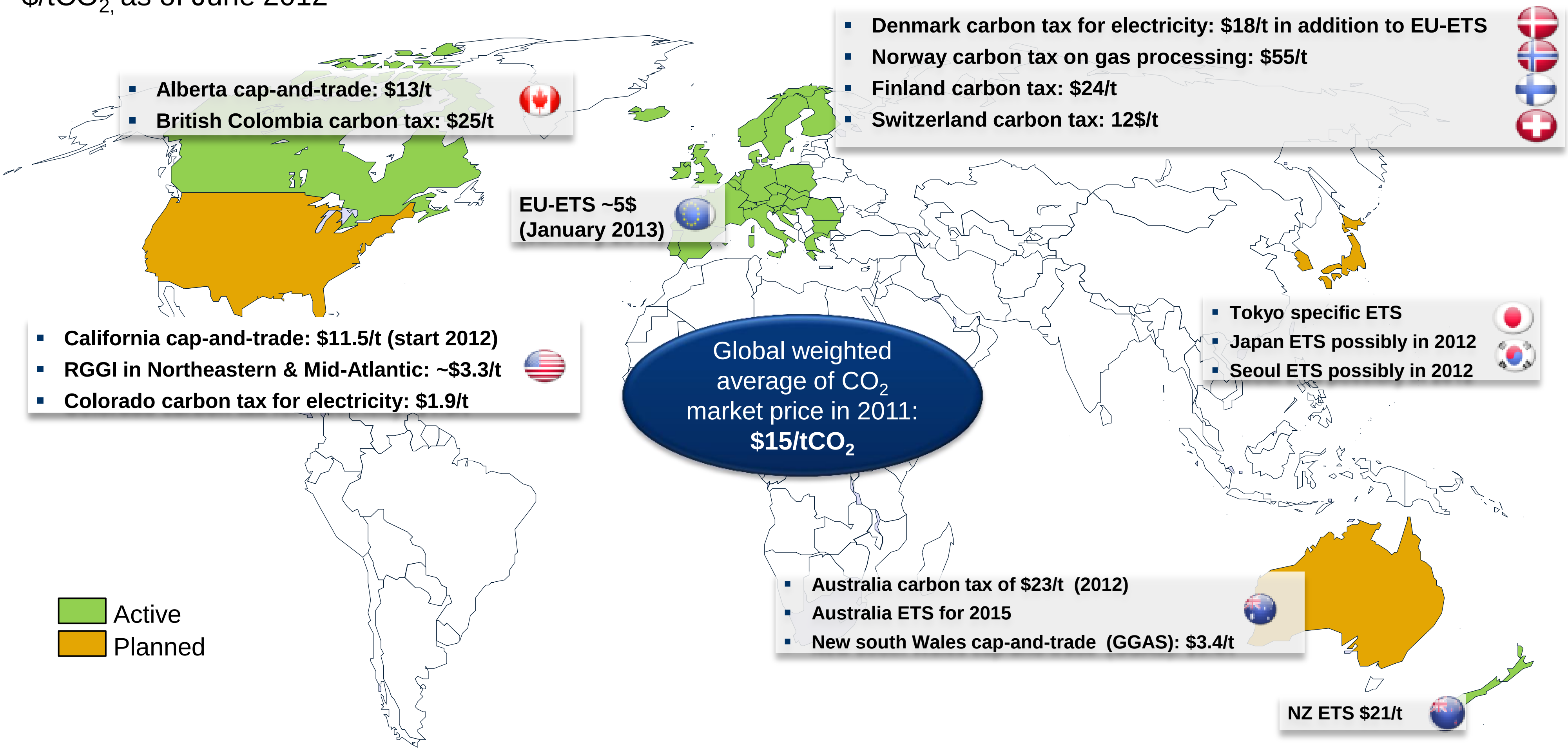
Notes: * Sum of all allocated grants over the cumulated CO_2 abatement of all Large Projects subsidized
For CCS, costs of CO_2 avoided are for first-of-a-kind plants, relative to the same plant without CCS. Estimated costs in the United States with current available technologies.

Source: SBC Energy Institute. Global average subsidy for Solar PV are from IEA (2011). Offshore wind feed-in tariffs in UK is from UK Department of Climate Change. CO_2 market price for EOR is from Bloomberg New Energy Finance (2012).
Costs in are derived from 19 international studies gathered by the Global CCS Institute in “The costs of CCS and other low-carbon technologies – issues brief 2011, No.2”. Other dataset includes Bloomberg New Energy Finance; IEA “Industrial Roadmap for CCS”, 2011; Global CCS Institute, “Economic assessment of CCS technologies”

Globally, environmental carbon prices are generally below $\$25/tCO_2$

EXPLICIT CARBON PRICE APPLIED TO CCS (CAP-AND-TRADE OR CARBON TAX)

$\$/tCO_2$, as of June 2012



- **Denmark carbon tax for electricity: $18/t in addition to EU-ETS**
- **Norway carbon tax on gas processing: $55/t**
- **Finland carbon tax: $24/t**
- **Switzerland carbon tax: 12$/t**

- **Alberta cap-and-trade: $13/t**
- **British Colombia carbon tax: $25/t**

EU-ETS ~5$ (January 2013)

- **California cap-and-trade: $11.5/t (start 2012)**
- **RGGI in Northeastern & Mid-Atlantic: ~$3.3/t**
- **Colorado carbon tax for electricity: $1.9/t**

Global weighted average of CO_2 market price in 2011: **$\$15/tCO_2$**

- **Tokyo specific ETS**
- **Japan ETS possibly in 2012**
- **Seoul ETS possibly in 2012**

- **Australia carbon tax of $23/t (2012)**
- **Australia ETS for 2015**
- **New south Wales cap-and-trade (GGAS): $3.4/t**

NZ ETS $21/t

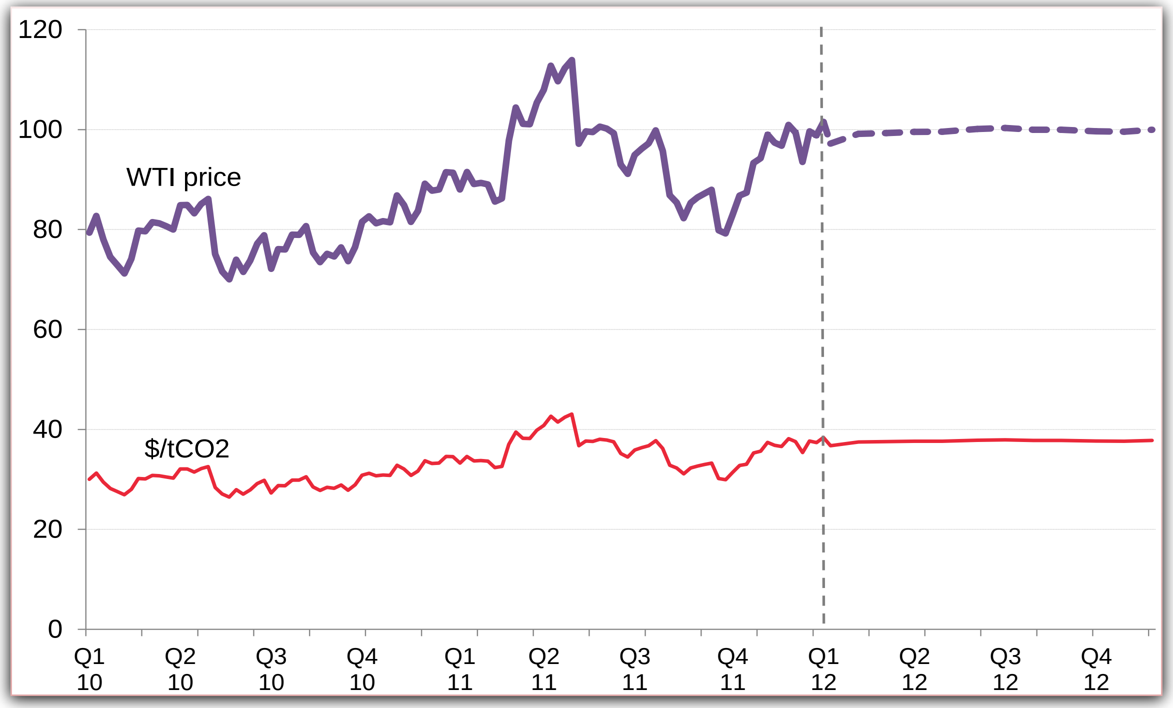
🟩 Active
🟧 Planned

Source: IEA, Carbon Tax Center, OECD, Global CCS Institute.

High oil prices are boosting CO_2 contract prices and improving CCS-EOR economics

ESTIMATED CO_2 CONTRACT PRICE IN THE US, Q1 2010-Q4 2012

\$/tCO_2



- **CO_2 prices are likely to be above \$30/t when oil price is above \$100/bbl**
  - Thanks to EOR revenues, CCS for natural gas processing and fertilizer plants is already commercial in North America
- **EOR reduces transport and storage costs**
  - 11%-30% reduction in additional CCS costs
- **EOR reduces storage risks**
  - Little public opposition for EOR
  - No liability nor monitoring requirement issue
- **Business models for CCS-EOR is easier to implement**
  - No need for vertical integration or joint venture
- **Multi-frac horizontal wells may become easier to implement than CO2-injections to enhance field's recovery factors**

Note: Costs are based on 250 MWe base plant and capture. In the IGCC case, plant includes gasification and SO_2 removal. Capture systems refer to all additional equipment needed for CCS at the plant (air-separation units, gas-separation systems, solvents, oxy-combustion boilers, purifiers, compressors…).

Source: Carbon capture & storage – Research note, Bloomberg New Energy Finance 2011

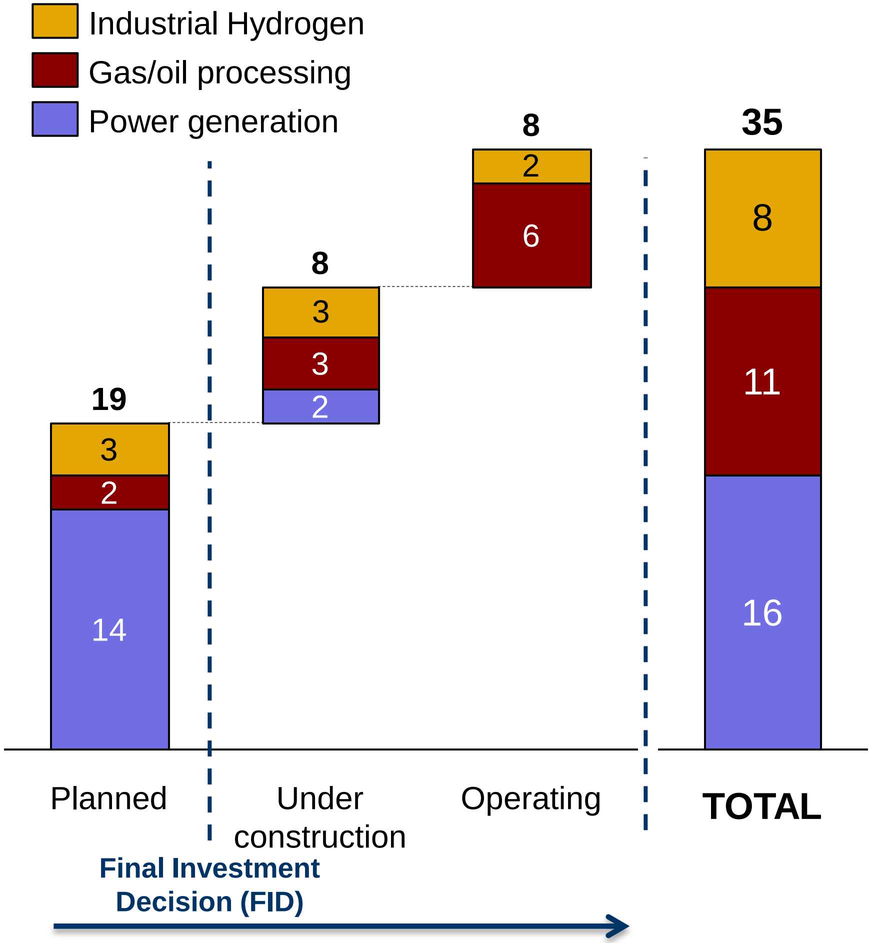
4. Perspectives

The pipeline of CCS projects remains encouraging

On paper, the list of project is encouraging, mostly for power generation and located in OECD countries

NUMBER OF REALISTIC LARGE PROJECTS CURRENTLY IN THE PIPELINE

As of October 2012



- Many power projects have been proposed
- Steel and cement are currently missing in the panel of CCS projects
- A growing number of companies are considering CCS-EOR, but projects are confidential until contracts are signed and many are missing in this list

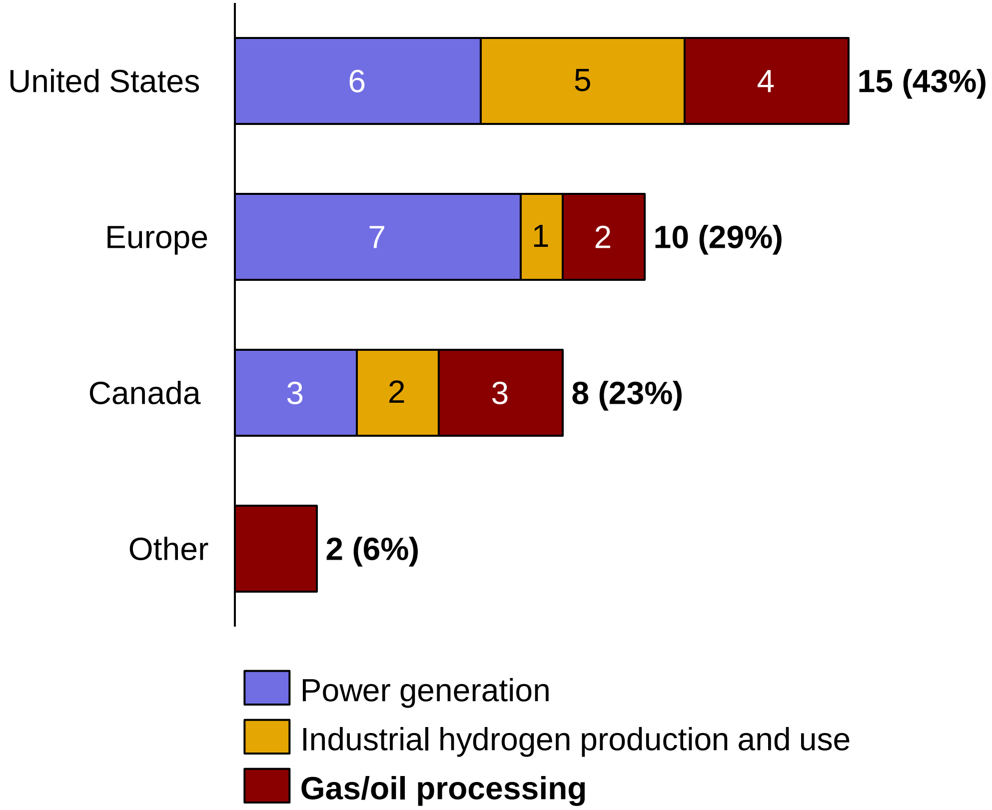
Notes: “Realistic” project: at a sufficiently advanced stage of planning to stand some chance of being built and operating before the end of the decade
Source: SBC Energy Institute analysis

Proposed plants would mainly be located in the US, Europe, Canada and Australia

REGIONAL DISTRIBUTION OF ALL 35 REALISTIC LARGE PROJECTS

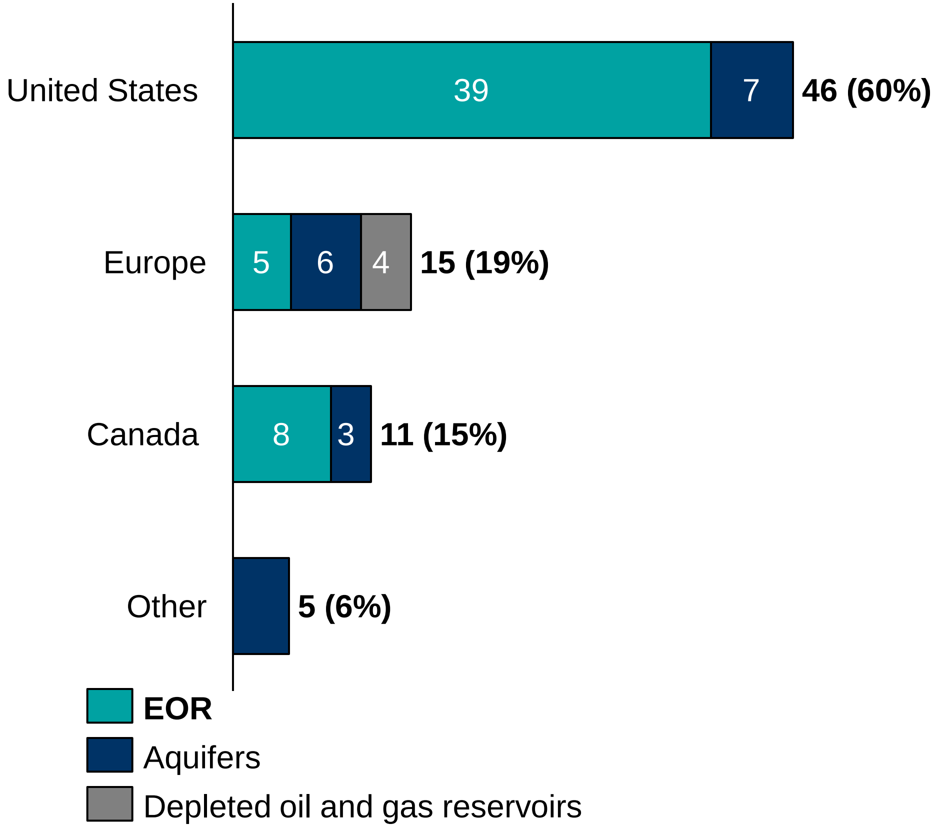
BY PLANT TYPE

Number of projects (% of total)



BY STORAGE SITE

Injection rate capacity in $MtCO_2$/year (% of total)

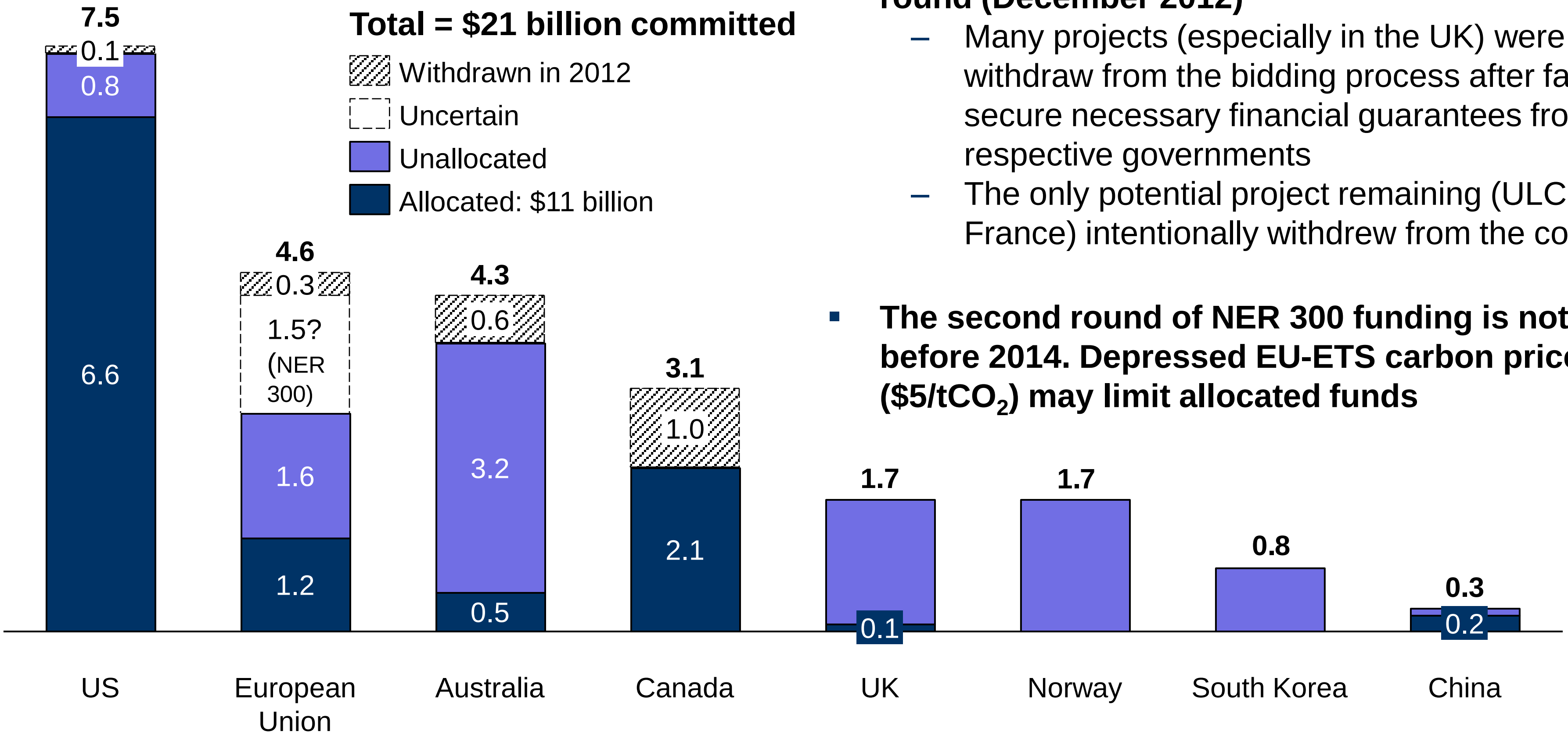


Source: SBC Energy Institute analysis

Governments have committed billions to demonstrate CCS but are struggling to allocate money to specific projects

GLOBAL PUBLIC FUNDS COMMITTED TO CCS

$ billion



- **The NER 300 has so far been a fiasco for CCS: No project has been selected for funding in the first round (December 2012)**
  - Many projects (especially in the UK) were forced to withdraw from the bidding process after failing to secure necessary financial guarantees from their respective governments
  - The only potential project remaining (ULCOS, France) intentionally withdrew from the competition
- **The second round of NER 300 funding is not expected before 2014. Depressed EU-ETS carbon prices ($5/tCO$_2$) may limit allocated funds**

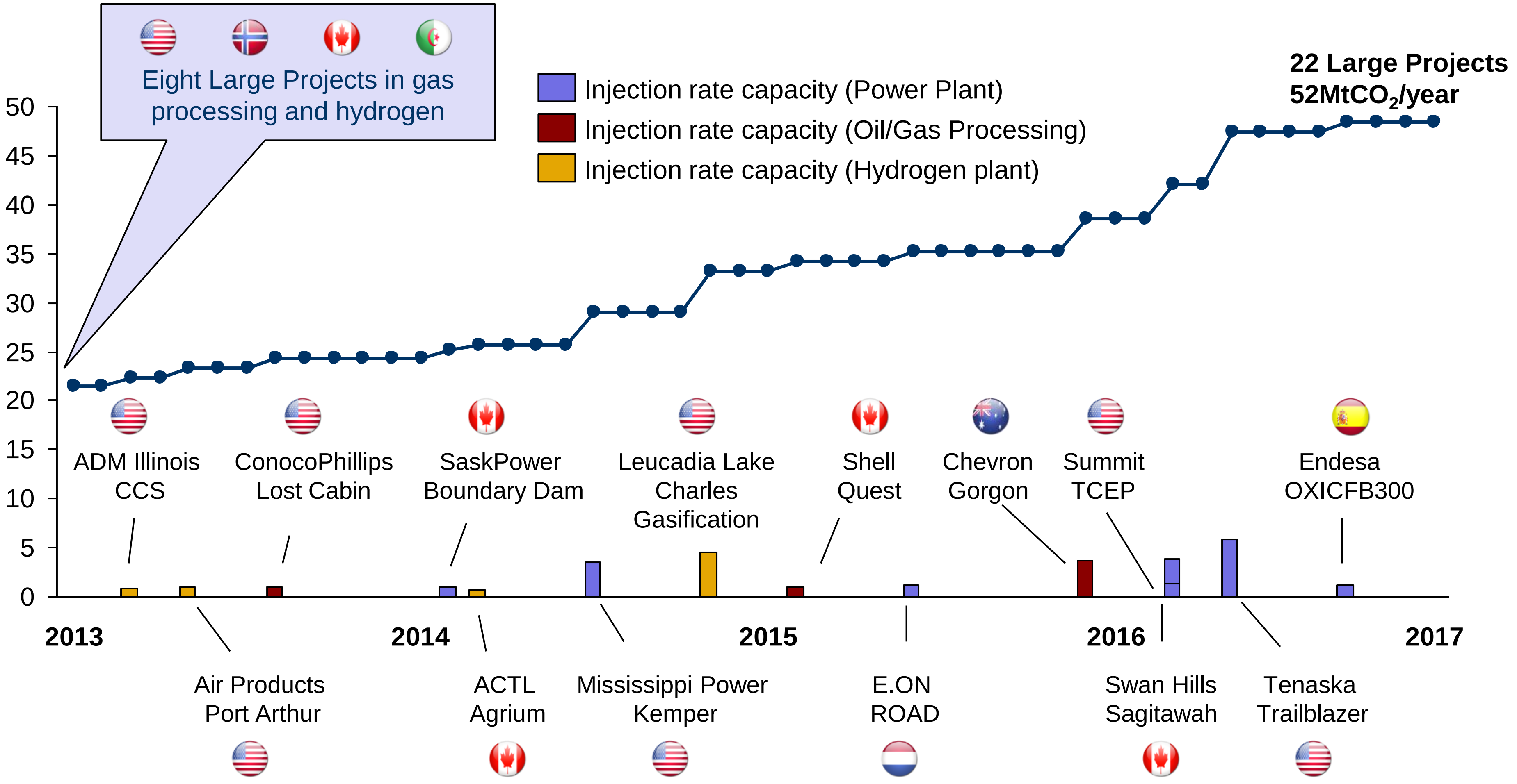
Note: Allocated category includes only funds for specific projects, and unallocated category includes all funds promised by governments, minus the funds that are uncertain. NER 300 is a funding process from the European Commission that aims at selling 300 million allowance units from the EU-ETS to subsidize CCS and other low-carbon technologies

Source: Global CCS Institute (2013)

By 2017, only 22 projects should be operating, 70% of them located in North America

CCS LARGE PROJECTS DEPLOYMENT FORECAST (2012-2017)

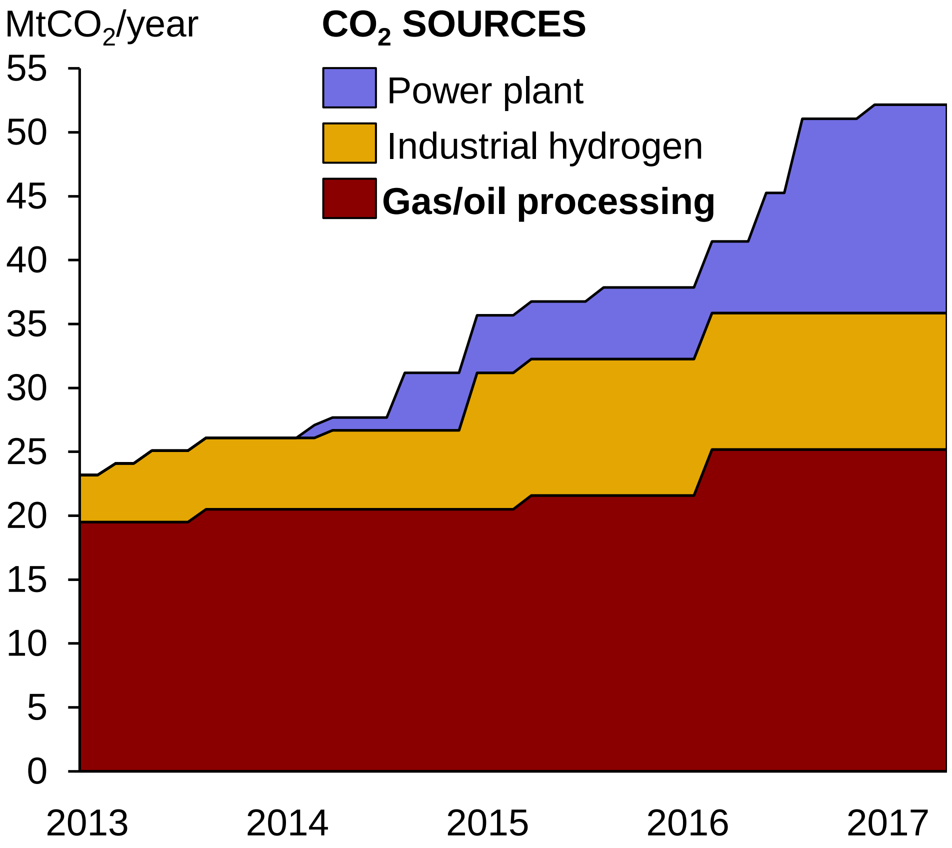
$MtCO_2$/year



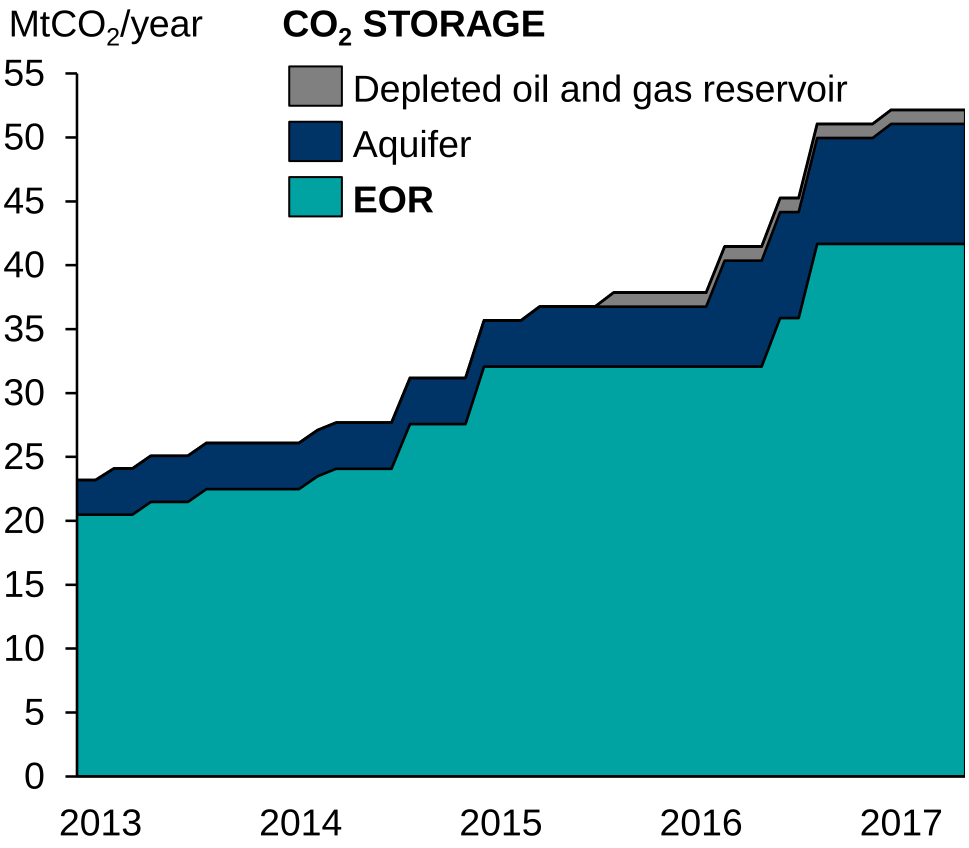
Source: SBC Energy Institute analysis

More than 90% of the installed CCS capacity will still be related to upstream oil & gas operations in 2017

CCS LARGE PROJECTS DEPLOYMENT FORECAST, 2012-2017



Power plants account for 30% of the operating capacity in 2017



EOR account for 80% of the operating capacity in 2017

Source: SBC Energy Institute analysis

China and the Middle-East will be of prime importance for CCS, but not before the end of the decade

CHINA: FOCUS ON CAPTURE, NOT ON PASSIVE CO_2 STORAGE

- Enormous potential for CCS (coal power plants)
- World leader in pilot-scale power CCS
- R&D on capture-ready plants should drive down costs
- Only interested in beneficial reuse of CO_2 (EOR, chemicals, algae biofuels…)
- Could rapidly deploy CCS to reduce CO_2 emissions after 2020, provided international emissions regulations are passed

MIDDLE-EAST: LARGE CO_2 STORAGE AND EOR POTENTIAL

- Region with the lowest abatement cost for CCS in the world (storage sites and gas-processing facilities)
- Large EOR potential, with projects planned (Aramco, Masdar…)
- Increasing governmental awareness of climate change in the region
- Limit: energy and water penalty are still seen as burden for CCS development in the region (opportunity cost)

Recommendations

Public authorities

- Leverage EOR projects to enable CCS to take off:
    - Reward for emissions avoided by storing CO_2 along with EOR
    - Promote collaboration in R&D and demonstration among major oil-producing countries
- Focus public support and investment incentives on overcoming hurdles to CCS:
    - Project type: large integrated demonstration
    - Sectors: power, steel and cement
    - R&D: capture processes
- Secure, stable regulation regarding long-term investment

Private sector

- Educate governments and the public on the potential of CCS technology in terms of decarbonisation
- Overcome knowledge-sharing issues by establishing consortia or industry alliances
- Explore new business models to ease partnerships in integrated projects (clusters)

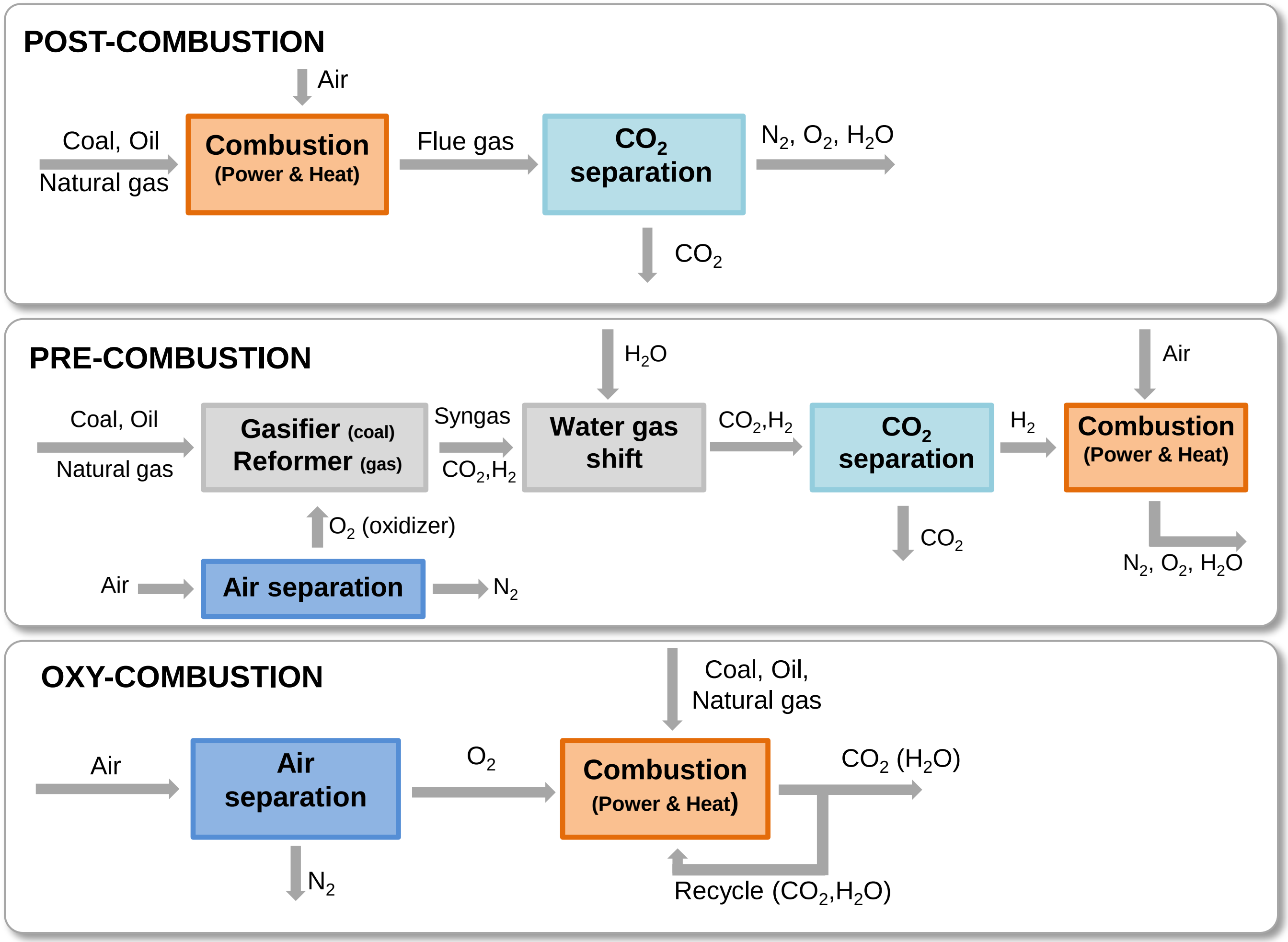
Conclusions

1. Meeting international CO_2 emissions-reduction targets will be extremely difficult to achieve without CCS
2. CCS projects are technically feasible at large scale and with moderate abatement costs per ton of CO_2 avoided. No R&D gap justify to wait before building demonstration projects
3. Demonstration projects are necessary to refine understanding of CO_2 sequestration mechanisms
4. R&D’s priority is reducing the cost of CO_2 capture
5. Projects associated with oil & gas production can be commercial. It will remain the main driver in the CCS industry in the current decade
6. Projects remain at a standstill for power generation and heavy industry when targeting passive CO_2 storage
7. Despite governments promises, demonstration is has been far slower than what was projected
8. IEA has just renewed its call for action to develop CCS, listing it in its 2013 priorities
9. Public stakeholders needs increase support for CCS and private-sector needs to develop overall awareness of the benefits of CCS

Appendix & Bibliography

Four main capture processes

FOR POWER GENERATION



POST-COMBUSTION

Air

Coal, Oil
Natural gas

Combustion
(Power & Heat)

Flue gas

CO_2 separation

N_2, O_2, H_2O

CO_2

PRE-COMBUSTION

Coal, Oil
Natural gas

Gasifier (coal)
Reformer (gas)

Syngas
CO_2,H_2

H_2O

Water gas shift

CO_2,H_2

CO_2 separation

H_2

Air

Combustion
(Power & Heat)

N_2, O_2, H_2O

CO_2

O_2 (oxidizer)

Air

Air separation

N_2

OXY-COMBUSTION

Coal, Oil,
Natural gas

Air

Air separation

N_2

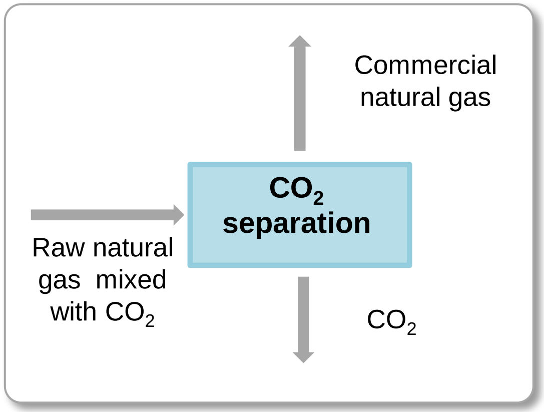
O_2

Combustion
(Power & Heat)

CO_2 (H_2O)

Recycle (CO_2,H_2O)

FOR NATURAL GAS PROCESSING



Commercial
natural gas

Raw natural
gas mixed
with CO_2

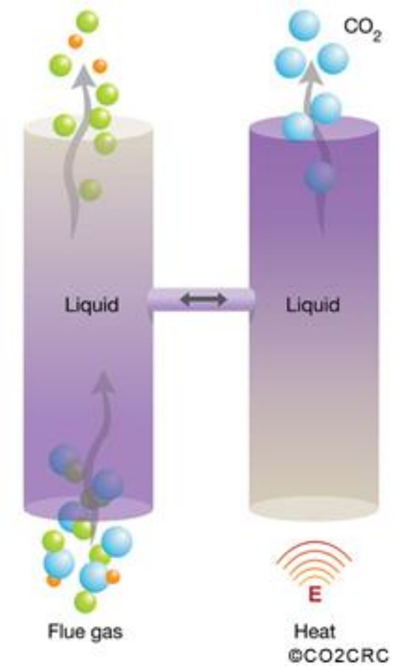
CO_2 separation

CO_2

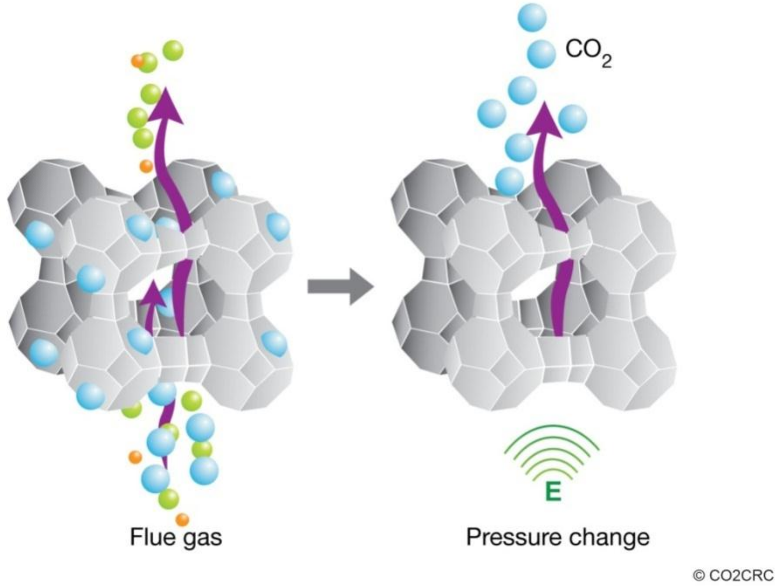
Source: SBC Energy Institute

Three main CO_2 separation technologies

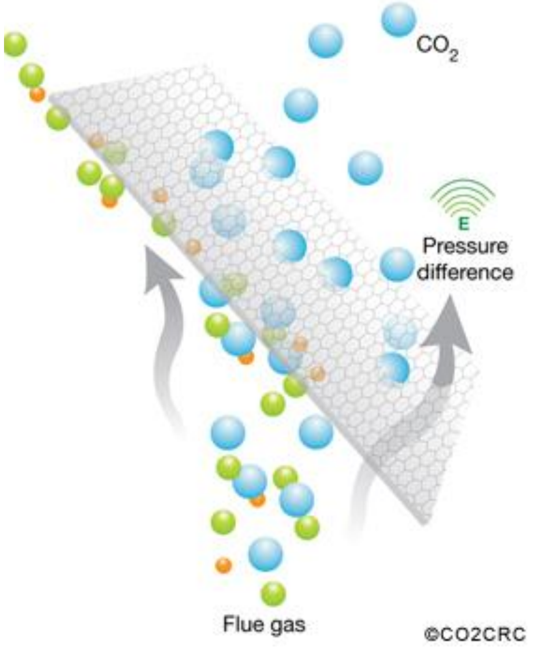
SOLVENT



SORBENT



MEMBRANE



Source: CO2COR, online public library

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 flight Paris to New York per passenger
  - The worldwide average CO_2 emissions per capita in 3.6 months
  - 1.35MWh of electricity produced with supercritical pulverized black coal power plant
- **What is the cost of CO_2 emissions?**
  - Carbon prices are generally below \$20 /tCO_2
  - Market prices for EOR have reached \$30 /tCO_2 with the oil price at \$100 /bbl.
  - Each tonne of CO_2 avoided by using CCS on a coal power plant is likely to cost \$53-\$92 /tCO_2.
  - Global average subsidy for solar PV in 2010 \$530/tCO_2 relative to coal
  - Carbon emissions intensity of developed economies ranges between \$2,000 and \$6,000 of gross domestic product per tonne of CO_2 emitted
- **Largest CCS integrated project in operation**
  - ExxonMobil Shute Creek CCS-EOR project in North America
  - Capture and store 6.5$MtCO_2$/year
  - Equivalent to ~1 million passenger vehicles taken off the roads
- **Standard coal power plant (supercritical pulverized black coal) without CCS**
  - Nominal capacity: 500MW
  - Load factor: 0.9 in average
  - Produces 4,000GWh of electricity per year
  - Emits 3$MtCO_2$/yr
- **Standard coal power plant with post-combustion CCS**
  - Produces 3,200GWh per year (CCS energy penalty: 20%)
  - Captures 90% of CO_2 emissions
  - Avoids 2.6$MtCO_2$/yr
- **Ways of producing 3TWh a year of low-carbon electricity**
  - One CCS power unit in a single location (though with extensive mining if powered by coal)
  - A 30km² PV farm with market-leading efficiency
  - A modern wind farm with 400 large turbines (2.5MW each) spread over more than 100km² (equivalent to the area of Paris)

Source: SBC Energy Institute

Acronyms

- **CAPEX**: capital expenditures
- **CCS**: carbon capture and storage
- **CDM**: clean development mechanisms
- **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**: levelised cost of electricity
- **Large Project**: integrated CCS projects of demonstration or commercial scale (above 0.6MtCO_2/year)
- **MtCO_2/yr**: million tonnes CO_2 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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Registered as follows: Stichting SBC Energy Institute, KVK 52935221, Parkstraat 83 -89, 2514JG's Gravenhage
Netherlands