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**Advances and Slowdowns in
Carbon Capture and Storage
Technology Development**

Aurora D'Aprile, Fondazione Eni
Enrico Mattei (FEEM) and Centro
Euro-Mediterraneo sui Cambiamenti
Climatici (CMCC)

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Advances and Slowdowns in Carbon Capture and Storage Technology Development

By Aurora D'Aprile, Fondazione Eni Enrico Mattei (FEEM) and Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC)

Summary

With the long term goal of holding the increase in the global average temperature to well below 2°C and "to pursue efforts to limit the temperature increase to 1.5°C", the Paris Agreement puts renewed attention on the portfolio of technologies needed to achieve consistent emission reductions and reach "a balance between anthropogenic emissions by sources and removals by sinks" in the second half of this century. Carbon capture and storage (CCS) technology, after having been hailed as a promising mitigation option around a decade ago, is undergoing a gruelling path to stay on top of the expectations. The opportunities and constraints in deploying large-scale carbon capture and storage systems are of the utmost actuality, as the technology promises to get rid of up to 90% of the most common greenhouse gases produced in industrial and energy plants before they reach the atmosphere (or even to achieve "negative" emissions, if combined with biomass). Despite potential benefits, CCS development and deployment proceeded at a far slower rate than what was expected and are struggling to emerge as a sound low-carbon choice for governments and investors. Based on recent existing literature, this reflection explores the main progress and deadlocks in CCS's difficult path.

Keywords: Climate Change, Carbon Sequestration, CCS, Carbon Mitigation, Low-carbon Technology

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Address for correspondence:
Aurora D'Aprile
Fondazione Eni Enrico Mattei
Isola di San Giorgio Maggiore
30124 Venice
Italy
E-mail: aurora.daprile@feem.it

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Aurora D'Aprile, ICCG

Introduction

With the long term goal of holding the increase in the global average temperature to well below 2°C and "to pursue efforts to limit the temperature increase to 1.5°C", the Paris Agreement puts renewed attention on the portfolio of technologies needed to achieve consistent emission reductions and reach "a balance between anthropogenic emissions by sources and removals by sinks" in the second half of this century.

Renewable energy sources are experiencing a "golden age", with cheap prices and mature development leading to a record high in global investment of USD328.9 billion in 2015, largely driven by increasing investments in China, Africa, the US, Latin America and India¹. By contrast carbon capture and storage (CCS) technology, after having been hailed as a promising mitigation option around a decade ago, is undergoing a gruelling path to stay on top of the expectations.

The opportunities and constraints in deploying large-scale CCS systems are thus of the utmost actuality, as the technology promises to get rid of up to 90% of the most common greenhouse gases produced in industrial and energy plants before they reach the atmosphere, and even to achieve "negative" emissions if combined with biomass.

Enter Carbon Capture and Storage

CCS includes a range of technologies to sequester carbon dioxide from fossil fuel plants and industrial facilities (blast furnaces, cement plants, steel mills, fertilizer production and gas-processing units), transport it to a designated storage site and bury it in onshore or offshore deep geological formations (depleted oil and gas fields or saline formations), in a way that guarantee it will remain trapped permanently. Each of the three stages encompasses technical options that are at different levels of development, testing and implementation.

The potential of CCS is widely recognized: many global climate models cannot reach concentrations of about 450 ppm CO₂eq by 2100 (corresponding to the 2°C target) without CCS. According to IPCC, "scenarios that are likely to maintain warming at 2°C include more rapid improvements in energy efficiency and a tripling to nearly a quadrupling of the share of zero- and low-carbon energy supply from renewable energy, nuclear energy and fossil energy with CCS, or bioenergy with CCS (BioCCS) by the year 2050".² Moreover, IPCC scientists observed that mitigation costs become consistently higher if CCS is excluded from the mitigation scenarios. The new IPCC Chair, Hoesung Lee, remarked that it will be very difficult to reach zero carbon emissions without CCS.³

CCS is crucial not only for reducing power generation emissions but also in the industrial sectors, as it is currently the only technology, together with energy efficiency improvements, that could achieve large reductions in emissions from industrial processes such as manufacturing iron and steel, chemicals and cement. The issue is acknowledged by companies and stakeholders. For instance, a report by the UK Task Force on Shale Gas said that "if a shale gas industry begins to develop at scale, CCS will become essential, and a CCS industry should be developed and grown concurrently."⁴ Similar conclusions were drawn by another UK research centre that published a study highlighting that, without CCS, natural gas can play only a limited role as a "bridging fuel."⁵

After having being hailed as a promising mitigation option around 15 years ago, CCS development and deployment proceeded at a far slower rate than what is needed to emerge as a sound low-carbon choice for governments and investors. In absence of a strong and coherent international action to reduce GHG emissions in the past years, and with low carbon prices, enhanced oil recovery (EOR) remains the main commercial rationale for deploying CCS. EOR, the injection of CO₂ into depleting oil fields to increase the pressure and drive the oil towards the production wells, has driven the majority of large scale CCS projects currently in operation.

¹ BNEF, Clean energy investment by the numbers – End of Year 2015, January 2016

² IPCC, Synthesis Report, Fifth Assessment Report (AR5), 2014

³ World Energy Focus : Interview Hoesung Lee, new Chairman IPCC: "There is enormous value in carbon capture and storage"(November 16, 2015)

⁴ Task Force on Shale Gas, Assessing the Impact of Shale Gas on Climate Change (September 2015)

⁵ UK Energy Research Centre, The future role of natural gas in the UK (February 2016)

The reasons behind CCS's difficult path are multiple, ranging from financial and technical aspects to legislative and political issues. On the one hand, the slow deployment and limited results have led to calls to dismiss CCS efforts in favour of supporting other, more mature, low-carbon options (renewables, nuclear, energy efficiency, afforestation). On the other hand, the huge contribution that, if developed at scale, CCS can bring to climate action (as long as fossil fuels and carbon-intensive industries play dominant roles the global economy) is still keeping it among the critical topics in the climate agenda. Past years have seen progress and stalemates, both scrutinized by scientists, operators and experts.

The CCS deployment landscape

Large-scale integrated CCS projects are defined as systems involving CO₂ capture, transport, and storage at a scale of at least 800,000 tons annually for a coal-based power plant, or at least 400,000 tons annually for other emissions-intensive industrial facilities (including natural gas-based power generation).⁶

According to the latest annual report by the Global CCS Institute, there are currently 15 CCS projects in operation worldwide that captured 28 million tonnes of CO₂ in 2015, mainly from industrial plants.⁷ The world's first large-scale, commercial CCS project is located at the gas processing site of Sleipner, Norway, where capture and storage operations initiated in 1996. It captures about 1 million tonnes of CO₂ per year and stores it in an offshore deep formation.⁸

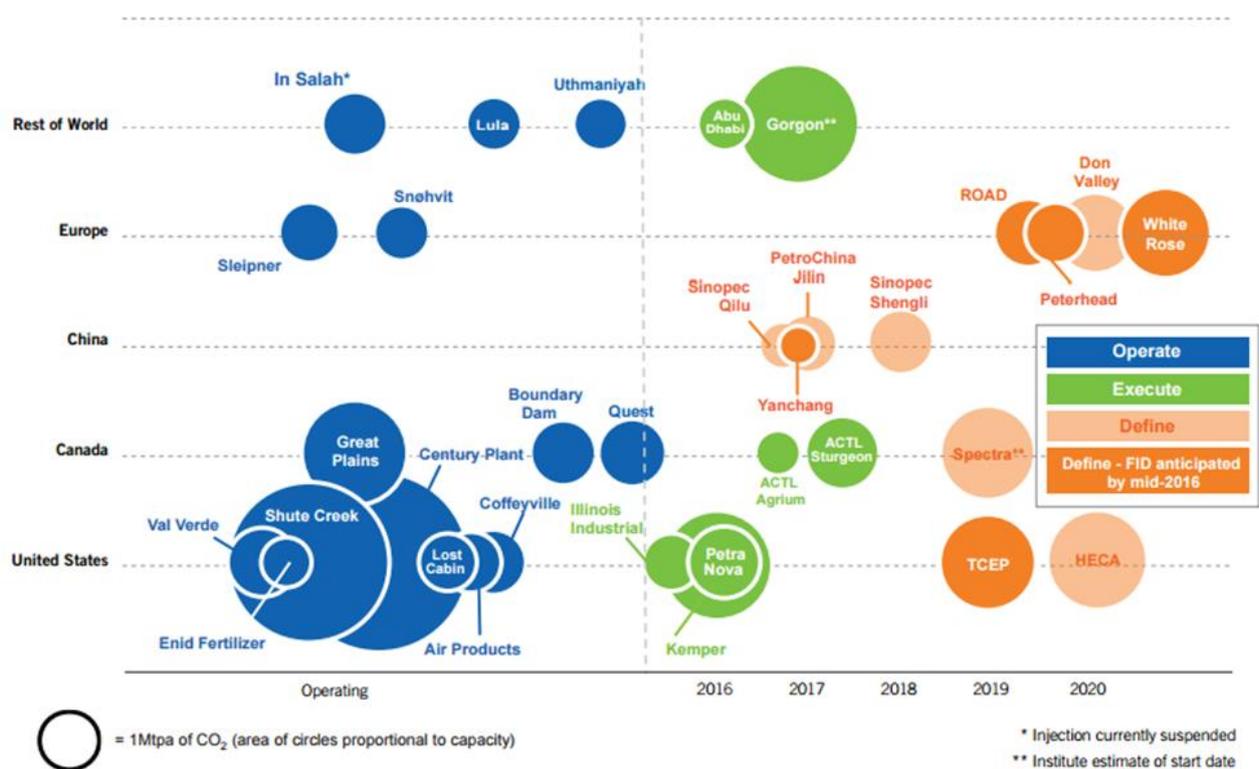


Figure 1: Actual and expected operation dates for large-scale CCS projects in the Operate, Execute and Define stages by region and project lifecycle stage. Source: Global CCS Institute, The global status of CCS 2015: summary report, Fig. 4

The latest large-scale system to capture and store CO₂ is the Quest project in Alberta, Canada, which became operational in November 2015. It captures 1.08 Mtpa of CO₂ from the manufacture of hydrogen for upgrading bitumen into synthetic crude oil, and stores it in a deep saline formation. The other CCS project launched in 2015 is the Uthmaniyah CO₂-EOR Demonstration Project in Saudi

⁶ Global CCS Institute, Large-Scale CCS Projects – Definitions, online at: <http://www.globalccsinstitute.com/projects/large-scale-ccs-projects-definitions>

⁷ Global CCS Institute, The global status of CCS (2015)

⁸ Global CCS Institute, Sleipner CO₂ Storage Project, online at: <http://www.globalccsinstitute.com/projects/sleipner%2%A0co2-storage-project>

Arabia, which reportedly captures around 0.8 Mtpa of CO₂ from a natural gas liquids recovery plant and injects it into the Uthmaniyah gas production unit, operated by Saudi Aramco, for enhanced oil recovery (EOR).⁹

While the above mentioned projects, as the majority of operational CCS projects to date, are in the industrial sector, the first and so far only large scale CCS project in the energy sector is the Boundary Dam power station in Canada. Having entered into operation in October 2014, it captures CO₂ from a retrofitted coal-fired power station and uses it for enhanced oil recovery (EOR) in the nearby oil fields in southern Saskatchewan. It was announced to capture one million tons of CO₂ per year, but in its first year of operation the CO₂ captured was around 400,000 tons.

The other most advanced CCS projects in the energy sector are the Kemper County Energy Facility in Mississippi, and the Petra Nova Carbon Capture Project in Texas, both planned to become operational in 2016.

With seven projects due to become operational in 2016-2017 and a further 23 in different stages of planning, the total potential number currently amounts to 45, with an estimated capture capacity of 80 Mtpa.¹⁰

Steps forward

In the last decade (and since the publication of IPCC's landmark Special Report on CO₂ Capture and Storage in 2005) CCS technologies have been increasingly addressed by **academic research**, with a consistent acceleration in recent years, bringing CCS out of the domain of climate "science fiction" to be properly explored among all low-carbon solutions on the table.

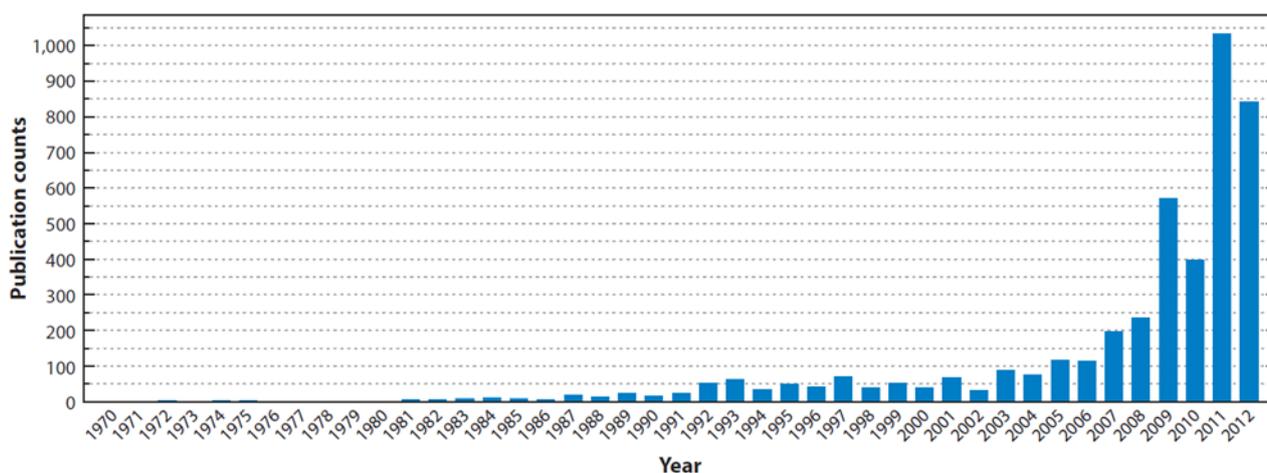


Figure 2: Publication counts related to CCS (search terms: CO₂ capture and storage) from the Web of Science 1970–2012. Source: H. C. de Coninck and S. M. Benson: Carbon Dioxide Capture and Storage: Issues and Prospects in Annual Review of Environment and Resources 2014. 39. Note from original source: The peak figures in 2009 and 2011 are due to conference papers at the Greenhouse Gas Control Technologies (GHGT) conferences in 2008 and 2010, respectively.

The greater attention paid, mainly driven by government spending on CCS R&D, have led to both technical and non-technical advancements and strengthened the scientific basis essential to assess the potential and the weak points of CO₂ capture and storage.¹¹

Running almost parallel to the diffusion of CCS research, also the establishment of **bilateral and multilateral initiatives**, from both governments and private actors, has seen some substantial steps forward worldwide.

The latest and probably most significant advancement is the increasingly closer cooperation between the United States and China. The two top global GHG emitters deepened their collaboration on climate-related issues, including CCS, in 2013 with the creation of the US-China

⁹ Global CCS Institute, The global status of CCS (2015)

¹⁰ Ibidem

¹¹ H. C. de Coninck and S. M. Benson, : Carbon Dioxide Capture and Storage: Issues and Prospects, in Annual Review of Environment and Resources 2014. 39, pp. 243–270

Climate Change Working Group. Through this institution, the United States and China in July 2014 signed eight partnership agreements to increase their climate cooperation, half of which concern the launch of CCUS (carbon capture, utilization, and storage) demonstration projects.¹² The two countries are the top ranking worldwide per number of large scale CCS projects in operate, execute or define stages: United States currently features 13 projects and China 9 (although none of the Chinese projects are in operation yet).¹³

One of the largest and most long-running multilateral governmental initiatives on CCS is the Carbon Sequestration Leadership Forum (CSLF). Formed in 2003, the CSLF is the only international ministerial body focused on fostering the development and deployment of CCS technologies. With the addition of Romania and Serbia in 2015, it currently involves 24 member nations (including US, China, India and many other G20 countries) and the European Commission. During the latest annual CSLF gathering, held in Riyadh, Saudi Arabia, in November 2015, ministers recognized the advances made since the previous meeting in 2013, highlighting that "R&D portfolios have grown, international collaboration has expanded, and the world's first large-scale CCS project in the power sector commenced operation."¹⁴

Well aware that the progress made so far is not sufficient, CSLF members are focusing on strategies and initiatives designed to "move beyond the first wave of CCS demonstrations" and meet existing challenges, including capacity-building for CCS in developing countries and methods for financing CCS projects. The CSLF also launched a new initiative, the "Large-Scale Saline Storage Project Network", to facilitate collaborative testing of advanced CCS technologies at real-world, saline storage sites.¹⁵

Technologies required for capture and transport of CO₂ are generally well understood and, in some cases, technologically mature.¹⁶ Uncertainties surrounding the storage phase (especially the identification of proper storage sites) are among the major concerns for CCS deployment (as discussed in the next section).

According to experts from several research fields, **technical and operational progress** has been made in the last decade concerning CO₂ capture, transport, storage efficiency, and methods to assess leakage impacts and risks of induced seismicity.¹⁷

Separation and capture of CO₂ from natural gas sweetening and hydrogen production is generally considered technically mature and commercially practiced, and the most common and tested technology to separate CO₂ from a gas stream today is absorption into amine chemical solvents. Other approaches include adsorption onto solid substrates (under testing on small scale systems), oxygen combustion (mature but very energy intensive), cryogenic separation and transport of pressurized gas stream through CO₂ selective membranes (both deployed on a limited basis in industrial plants).¹⁸ The key challenges concerning CO₂ capture are the high costs and high energy penalties of the process (discussed below).

Transporting CO₂, mostly through pipelines, is the most technically mature phase in CCS. The key issue to be addressed in the next years is the massive scale up of infrastructure required to cope with a large-scale deployment of the technology. For instance, estimates for the US are around 37,000 km needed between 2010 and 2050, up from a current 6,500 km of operational CO₂ pipelines, and 150,000 km in the European Union. Other challenges include the creation of trans-boundary and shared networks in order to optimize transport and costs, and the development of

¹² U.S. Department of State, Media note: Key Achievements of U.S.-China Climate Change Cooperation Under the Strategic and Economic Dialogue (July 9, 2014)

¹³ MIT Carbon Capture and Sequestration Technologies Program, CCS Project Database, online at: <https://sequestration.mit.edu/index.html>

¹⁴ CSLF, final communiqué of the 6th Carbon Sequestration Leadership Forum Ministerial Meeting: "Moving Beyond the First Wave of CCS Demonstrations" (November 4, 2015)

¹⁵ U.S. Department of Energy, Media release: Secretary Moniz Announces New CO₂ Storage Network at Multinational Carbon Sequestration Forum (November 4, 2015)

¹⁶ H. C. de Coninck and S. M. Benson, : Carbon Dioxide Capture and Storage: Issues and Prospects, in Annual Review of Environment and Resources 2014. 39, pp. 243–270

¹⁷ International Journal of Greenhouse Gas Control Volume 40, September 2015: Special Issue commemorating the 10th year anniversary of the publication of the Intergovernmental Panel on Climate Change Special Report on CO₂ Capture and Storage

¹⁸ H. C. de Coninck and S. M. Benson, Carbon Dioxide Capture and Storage: Issues and Prospects, in Annual Review of Environment and Resources 2014. 39, pp. 243–270

appropriate regulations, standards and operational frameworks to minimize risks of leakage or accidents, especially in densely populated areas.¹⁹

Safe and effective storage of CO₂ has been demonstrated in smaller projects but the results cannot be automatically translated to large-scale projects, where different factors intervene. Due to the small number of large-scale systems currently in operation, future, on-the-ground assessment of storage operations in the planned CCS systems will be essential to gather more robust knowledge in the coming years.

Overall, individual components and phases have been studied and upgraded, but they need to be tested and evaluated on the ground, at an integrated level, in far more cases in order to provide better knowledge and substantially, and to move to a more efficient, cost-effective and better designed next generation of CCS systems.

In its latest assessment of low-carbon technologies, the IEA recognized that CCS has seen some positive developments (“a slow but steady increase in the number of CCS projects under construction”), but not enough to be on track with the levels required.²⁰

What is lagging behind?

IEA estimates CCS could deliver around 13% of the emissions reductions needed by 2050 to limit the temperature increase to 2°C, with the removal of around 6 billion tonnes of CO₂ per year in 2050.²¹

In order to achieve such levels the IEA Technology Roadmap states that by 2020 the capture of CO₂ should be successfully demonstrated in at least 30 projects across many sectors, including coal- and gas-fired power generation, gas processing, bioethanol, hydrogen production for chemicals and refining, with over 50 MtCO₂ safely and effectively stored per year. By 2030, CCS should be routinely used in power generation and industry, and be demonstrated also in cement manufacture, iron and steel blast furnaces, paper production and second-generation biofuels, with the storage of over 2,000 MtCO₂ per year. In the period 2015-2050, approximately 120 GtCO₂ would need to be captured and stored across all regions of the globe.²²

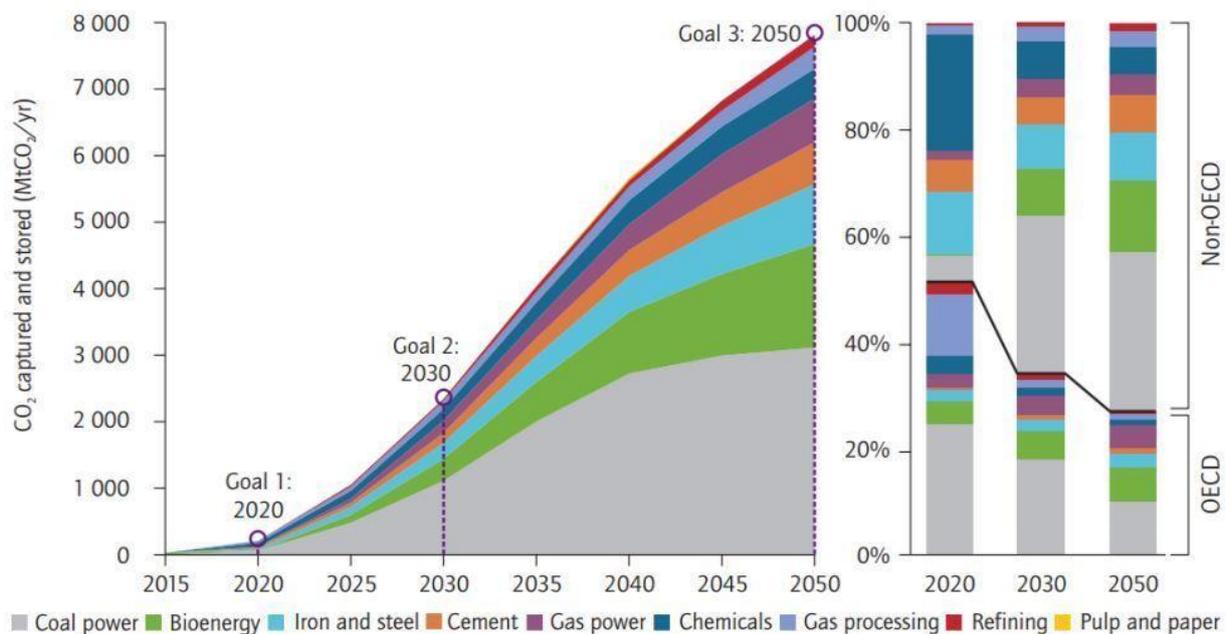


Figure 3: CCS in the power and industrial sectors in the 2DS. Source: IEA CCS Technology Roadmap 2013, Fig. 4

¹⁹ Ibidem

²⁰ IEA, Tracking Clean Energy Progress (2015)

²¹ IEA, Carbon Capture and Storage: The solution for deep emissions reductions, (2015)

²² IEA, Technology Roadmap: Carbon Capture and Storage (2013)

Despite progress, CCS is currently “well below the trajectory required to match the 2DS” and “will have to increase markedly, particularly in OECD non-member economies.”

Even though the potential **capacity** of current projects in operation, under construction or in advanced stage of planning has been estimated at 63 MtCO₂/y by 2025 (thus roughly in line with the IEA roadmap), shortcomings and deadlocks cast doubts on the development of additional projects in the coming years.²³

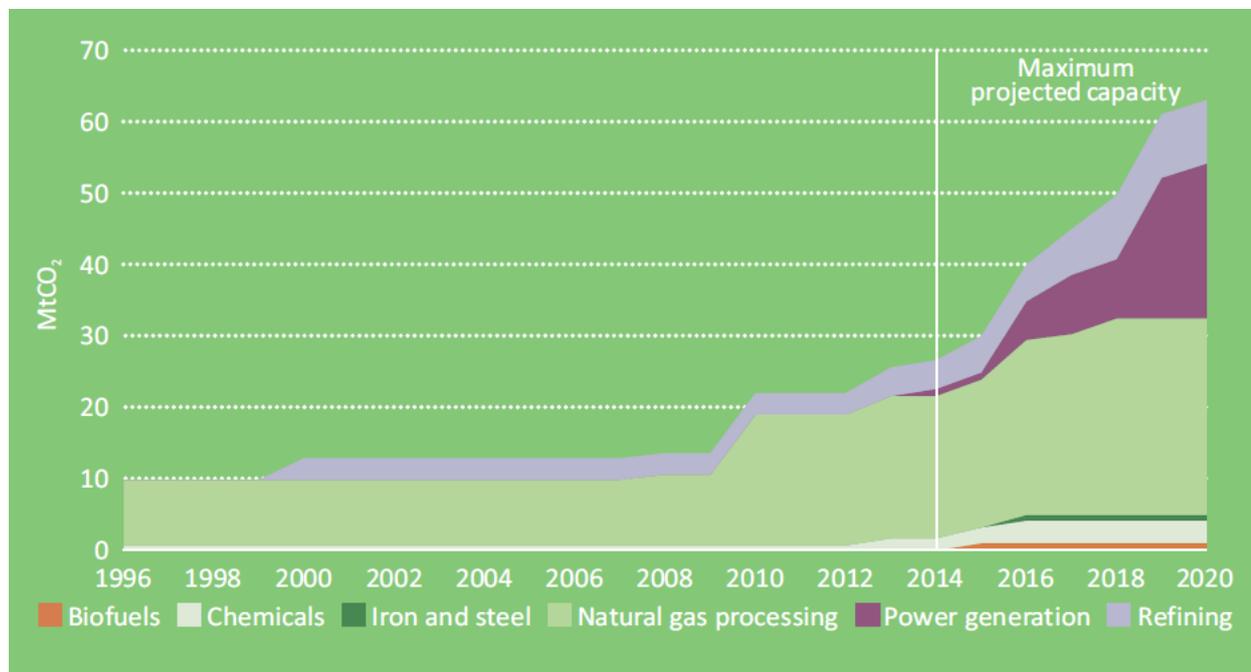


Figure 4: IEA Tracking Clean Energy Progress. Source: IEA Tracking Clean Energy Progress 2015 report, Fig. 1.17

In addition, it is important to handle projections of future capacity with due caution, as the majority of the estimates concern projects that have not been initiated nor tested yet. For instance, the Boundary Dam system in Canada captured 400,000 tonnes of CO₂ in its first year of operation, falling short of the announced design capacity of one million tonnes per year. At COP21 in Paris, SaskPower president Mike Marsh declared himself confident that the project was back on track, with a scaled-down target of capturing 800,000 tonnes in 2016.

Moreover, some planned CCS projects may not be completed due to changes in the political or economic context. It is the case of two planned projects in UK, the Peterhead Project by Shell in Scotland and the White Rose site in North Yorkshire. Their fate is on hold after the UK government in November 2015 unexpectedly announced that it was withdrawing its £1bn CCS Commercialisation Programme as part of a spending review. The decision, which drew broad criticism in UK, was motivated by economic reasons, as the projects were estimated to deliver energy at a price of £170 per MWh, much higher than the cost of new nuclear and offshore wind capacity.

The UK case is not an isolated one. Dozens of CCS projects have been dismissed or postponed due to investment shortages and government U-turns, such as the FutureGen CCS-equipped coal plant in Illinois, from which the US government pulled out in early 2015.

The **economic case** is the Achilles' heel of CCS and the current situation looks like a real conundrum. In the absence of predictable government support, emission limits or a strong carbon price, private investors and utilities are reluctant to build new CCS-equipped plants or to retrofit the existing ones due to the high costs and high energy penalties. At the same time, governments cannot entirely finance projects whose financial viability, especially in the power sector (where the majority of GHGs are produced), is unclear. But without new investment, deployment and testing, it is unlikely to achieve the progress needed to reduce costs and increase efficiency.

²³ IEA, IEA Tracking Clean Energy Progress (2015)

Bringing CCS in line with a 2°C scenario would require a total undiscounted investment of USD 3.6 trillion until 2050.²⁴ Current cumulative investment in large-scale CCS has amounted to USD 12 billion since 2005, and while OECD governments have made available USD 22 billion, much of this has not yet been spent.²⁵

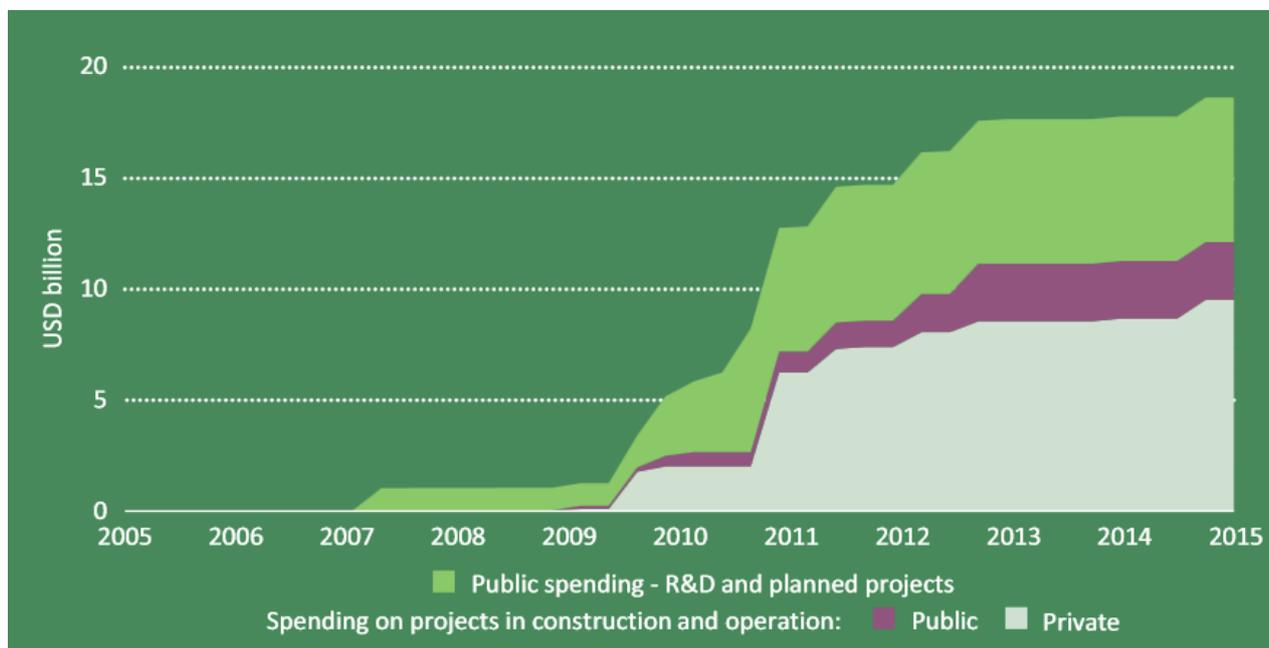


Figure 5: Cumulative spending on CCS projects. Source: IEA Tracking Clean Energy Progress 2015 report

The cost of producing electricity with CCS has been estimated at 60–100 USD/tonne CO₂, of which 70–80% is made up of the CO₂ capture phase burdened by high energy penalties.²⁶

In an efficient CCS-equipped power facility the energy used for CO₂ capture should be 2-3% of the output of the power plant, but in the real world this figure is 5 to 10 times higher, and additional energy is required to compress the CO₂ in order to transport and store it. According to experts, the total energy requirements could be reduced to about 10% of the plant's output by optimizing the most advanced options for both capturing and compressing the CO₂.²⁷

Waiting for R&D and demonstration projects to reduce cost and increase efficiency, using CO₂ for enhanced oil recovery remains the main driver for CCS deployment, especially in the United States and Canada. In fact, more than half of the CCS power plants currently under construction and planning are EOR-oriented. But CO₂-EOR projects are not generally required to undertake the same monitoring, measurement and verification as injected CO₂ that is permanently stored. Although in the short term EOR is considered an important non-climate benefit to facilitating CCS development and reducing costs, in the long term it is essential to make CO₂-EOR plants comply with the same performance standards as projects storing CO₂ purely to prevent the release in the atmosphere.²⁸

With the exception of Norway, whose CO₂ tax introduced in 1991 created the incentives to start the Sleipner and Snøhvit CCS projects in 1996 and 2008 respectively, attempts to link CCS deployment to carbon pricing systems have delivered poor results to date, due to low carbon prices. The prime example is the European Emissions Trading Scheme experience. The NER300 programme was launched in 2011 to provide funding to renewable energy and CCS projects in EU member states by setting aside 300 million allowances (EUAs) in the New Entrants' Reserve for the third phase of the ETS (2013-2020). It was expected to earn around €6-9 billion from the EUAs sold but the collapse in

²⁴ IEA, Technology Roadmap (2013)

²⁵ IEA Tracking Clean Energy Progress (2015)

²⁶ D. Y.C. Leung, G.Caramanna, M. Mercedes Maroto-Valer, An overview of current status of carbon dioxide capture and storage technologies, in Renewable and Sustainable Energy Reviews, Volume 39, November 2014, Pages 426–443

²⁷ H. C. de Coninck and S. M. Benson: Carbon Dioxide Capture and Storage: Issues and Prospects, in Annual Review of Environment and Resources 2014. 39, pp. 243–270

²⁸ IEA Tracking Clean Energy Progress (2015)

EU carbon prices resulted in a significant reduction of expected returns.

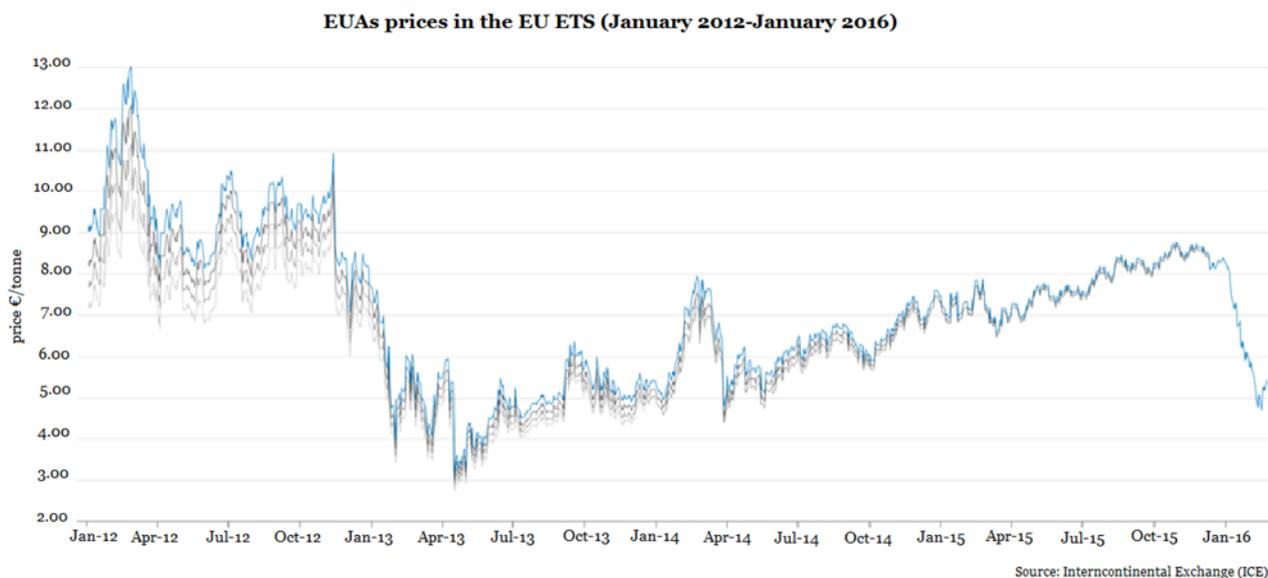


Figure 6: EUAs prices in the EU ETS (January 2012-January 2016). Source: ICE

Under the first call for proposals (covering 200 million EUAs) the European Commission assigned a total of €1.1 billion to 20 renewable energy projects. Under the second call for proposals (covering 100 million EUAs) in July 2014 it granted a total of €1 billion to 18 renewable energy projects and one carbon capture and storage project.²⁹

The only CCS proposal selected for NER300 funds was the UK White Rose project, which was also in the recently repealed UK CCS Commercialisation programme. Without government support it is now unclear whether the White Rose project will receive the EU funding.

A legislative proposal for reforming the EU ETS after 2020 is under discussion and includes a renewed program to award returns from the selling of 400 million EUAs to low-carbon projects, extending the scope to innovation in industrial sectors as well as to CCS and renewables. The EU Commission estimated the new “NER400” program would raise around €10 billion assuming a €22 average EUA price in ETS Phase 4 (2021-2030).³⁰ Even in the case that this assumption proves to be correct, the assumed price will be inadequate to develop CCS at the level required by the EU long-term goals. According to a study from the UK’s Grantham Research Institute, EUA prices need to be around €35-60 for coal-fired power stations and €90-105 for gas-fired plants to make CCS competitive with unabated thermal power generation. The cost of installing 11 GW of CCS electricity generation by 2030, as envisioned in the EU Energy Roadmap, could cost between €18-35bn.³¹

At a global level, current decline in fossil fuel prices has been highlighted as an opportunity to ease the financial barriers to CCS development, allowing governments to reduce or phase out fossil fuel subsidies, introduce measures that raise the costs and risks of using fossil fuels without CCS (such as robust carbon pricing or emissions standards) and drive investments in research, development, demonstration and deployment.³²

The key role of governments in CCS deployment is not limited to making available funds and economic incentives but also to provide the adequate **legal and regulatory framework**.

Also this aspect is far from being well established at the international level. A sound national policy framework should comprehend laws and regulations covering all aspects and phases of CCS

²⁹ EU Commission, NER 300 programme, online: http://ec.europa.eu/clima/policies/lowcarbon/ner300/index_en.htm

³⁰ Carbon Pulse, EU ETS Innovation Fund could raise €10.7 bln to clean up industry, online: <http://carbon-pulse.com/7369/>

³¹ S. Bassi et al., Bridging the gap: improving the economic and policy framework for carbon capture and storage in the European Union (2015)

³² IEA, Energy Technologies perspectives (2015)

lifecycle: technology research and development, demonstration support, emissions pricing or limits, incentives for deployment, permitting rules for resource management and safe storage. So far the most advanced and comprehensive legislative frameworks concerning CCS are in place in the United States, Canada, Australia, United Kingdom and in the European Union. In the rest of the world, where some advancement has been made, governments are still implementing policies related to the R&D phase.³³

Sub-national governments are playing a key role, with Canadian provinces and Australian states leading the development of specific regulatory frameworks.

The transposition of the 2009 European Directive 'on the geological storage of carbon dioxide' in the 28 countries' national jurisdictions is almost complete (transposition measures are under discussion only for one member state). It covers CO₂ capture, transport and storage and guarantees flexibility for EU member states on storage regulation (leading to very different choices for EU countries on allowing, limiting or prohibiting storage operations in their territories³⁴).

Despite its theoretical completeness, the EU CCS Directive is still lacking a sound test as normative tool. In its 2014 review, the EU Commission acknowledged the fact that the number of CCS installations had been much fewer than expected when the law was passed in 2009 and that "the lack of practical experience of projects going through the regulatory process precludes a robust judgment of the performance of the Directive."³⁵

Given the relative infancy and slowness of large-scale CCS deployment at the global level, the institutional and regulatory path faces several gaps and uncertainties.

First, there is a general geographical diffusion gap, as the action to provide R&D support, regulate and (where suitable) incentivize CCS is concentrated in the richest and most-established industrialized nations. In emerging and developing countries (where the majority of future emissions are projected to occur) the process is almost non-existent, with the notable exception of China. In recent years governments and stakeholders in Indonesia, Malaysia, South Africa and Turkey have started discussing options and the potential for CCS.³⁶

Second, the conditions for trans-boundary transportation of CO₂ are currently limited. The 2009 amendment to the London Protocol allowing for trans-boundary CO₂ transport for offshore storage requires ratification by two-thirds of the parties in order to come into force.³⁷ So far only two countries (Norway and UK) out of the 47 Parties to the Protocol have ratified the amendment, while another five (Australia, Canada, the Netherlands, South Korea and Sweden) have started the ratification process. Until the amendment enters into force, multilateral or bilateral cooperation on offshore storage is restricted, thus limiting the possibility for countries to develop CCS networks and international hubs through use of shared infrastructures.

The third and probably most arduous regulatory challenge concerns the final phase of CCS projects: the **CO₂ storage** permitting frameworks and long-term liability.

All countries leading the development of CCS regulation have implemented key arrangements to allow safe and effective storage of the CO₂ captured. Nonetheless, the overarching rules in place generally lack the on-the-ground tests and feedbacks necessary to consolidate a sound CO₂ storage permitting framework, tailoring rules on the specific national and local conditions. For instance, in 2012 the Canadian province of Alberta concluded a review assessment of its regulatory framework that resulted in 71 recommendations for improvement across 21 regulatory issues, showing that after the key regulatory elements are in place, additional work is required to finalize the legislation.³⁸ This case excluded, the pace of policy action has slowed in the past years, likely reflecting the fact that there is the little impetus to develop large-scale demonstration

³³ IEA, Carbon Capture and Storage: Legal and Regulatory Review, Edition 4 (2014)

³⁴ Finland, Luxembourg and Belgium did not allow CO₂ storage on their territory or part of it due to unsuitability of their geology. Some other Member States have also not allowed geological storage of CO₂ (Austria, Estonia, Ireland, Latvia, Slovenia, Sweden) or restricted it (Czech Republic, Germany).

³⁵ European Commission, Report on review of Directive 2009/31/EC on the geological storage of carbon dioxide (2015)

³⁶ IEA, Carbon Capture and Storage: Legal and Regulatory Review, Edition 4 (2014)

³⁷ In 1996 the London Protocol was agreed to modernize the London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter of 1972. Under the Protocol all dumping is prohibited, except for possibly acceptable wastes on the so-called "reverse list". The Protocol entered into force in 2006 and there are currently 47 Parties.

³⁸ IEA, Carbon Capture and Storage: Legal and Regulatory Review, Edition 4 (2014)

projects, and thus little pressure to implement and finalise CO₂ storage permitting frameworks in many jurisdictions.³⁹

Also the rules concerning the long-term liability associated with a storage site are not well established. They regulate whether the responsibility of the CO₂ stored underground (onshore or offshore) should be transferred to the government after a certain period of time from the project closure, or retained by the CCS project's operators indefinitely. The risk of CO₂ leakage from a storage stage decrease after injection ends, but monitoring and verification must continue for some time to demonstrate long-term security.

Trends in the most advanced CCS regulations are oriented towards liability transfer, with Australia, the European Union and some Australian, Canadian and US states and provinces taking on the responsibility of the storage sites provided certain requirements, such as the absence of significant leakage risk and a financial contribution to the long-term stewardship of sites. However, some jurisdictions do not cover all the elements of long-term liability and the interpretation of the requirements that operator should comply with vary significantly.⁴⁰

Missing a clear political context and regulatory framework, investors and operators are reluctant to undertake CCS initiatives. The issues concerning storage operations, together with the economic viability, are the elements most affecting CCS development. While the characterization of depleted oil and gas fields for CO₂ storage is a relatively accessible process, the identification of a storage site in an underground geological formation (onshore or offshore) can take decades from exploration to operation. Without a sound strategy and information about where to store the captured CO₂, it is even less likely for a CCS initiative to attract the investment needed.

Worldwide, the technical potential of storage capacity has been estimated at about 2,000 GtCO₂.⁴¹ However, this figure can be limited by specific constraints at the local level, such as shortcomings in geological knowledge, restrictions related to injection technologies, costs, regulatory limitations and public opposition.⁴² National and regional assessments are uncertain due to lack of information and of a formally recognized international methodology and standards. For instance, storage capacity in the European Union has been estimated at 117 Gt of CO₂ (of which approximately 25% is offshore Norway),⁴³ while in the United States recent assessments found a potential of 3,000 Gt.⁴⁴

To allow CCS to be developed at scale, experts are calling on governments to invest quickly in characterizing actual storage capacity and ensuring appropriate monitoring and verifying rules for future storage sites.⁴⁵

Conclusion

Weighing the slow progress and the significant barriers that CCS is facing, a realistic approach includes downsizing the original expectations of CCS as being a "silver bullet" for climate change. Above all, it cannot be considered a convincing reason to delay the emissions cuts urgently needed in order to keep the global temperature increase at the safest possible level. Recent studies found a relatively small contribution of CCS in prolonging the currently intense use of fossil fuels, given the technology's costs, its relatively late date of introduction and the rate at which it can be built.⁴⁶ Other studies have brought attention to the uncertain (but potentially significant) consequences a widespread application of CCS and other "negative emissions" technologies may

³⁹ Ibidem

⁴⁰ IEA, Carbon Capture and Storage: Legal and Regulatory Review Edition 2 (2011)

⁴¹ IPCC Special Report on CCS, 2005

⁴² Wolf Heidug, The limits for CCS: gauging CO₂ storage potential, in IEA Energy: The Journal of the International Energy Agency, Issue 6, 2014.

⁴³ Rütters, H. and the CGS Europe partners (2013) - State of play on CO₂ geological storage in 28 European countries. CGS Europe report No. D2.10, June 2013, 89 p.

⁴⁴ U.S. Geological Survey (USGS), National Assessment of Geologic Carbon Dioxide Storage Resources, 2013.

⁴⁵ IEA, Tracking Clean Energy Progress (2015)

⁴⁶ C. McGlade and P. Ekins, The geographical distribution of fossil fuels unused when limiting global warming to 2 °C, in Nature 517, 187–190

have on natural resources, social and ecological systems.⁴⁷ These concerns should be taken into careful consideration by policy makers and specialists.

On the other hand, CCS should not (and will not) be dismissed for different, good reasons. First, it is so far the only technological breakthrough, together with efficiency improvements, that may significantly reduce emissions in the industrial sector. Second, fossil fuels are projected to remain abundantly available and relatively economical in the foreseeable future, and it is reasonable to think that they will continue to be used in significant quantities despite the increasingly important role of renewable sources. Third, CCS has been indicated as an integrating element to involve fossil fuel-rich countries in climate mitigation efforts, reducing the risks of carbon leakage via trade and intensified extraction in anticipation of stringent climate legislation.⁴⁸

Therefore, despite hurdles and delays, CCS is not going to leave the scene of low-carbon options. Recent developments in the international context may influence the technology's outlook. Weak international climate action has been considered one of the key reasons behind the slow pace of CCS deployment. In this sense, the Paris outcomes may represent a turning point, even if CCS explicitly mentioned in only three of the approximately 120 climate pledges, or INDCs, submitted by countries before COP21: Canada, Norway and China. Moreover, lower fossil fuel prices are seen as an opportunity to introduce carbon pricing mechanisms to support CCS without excessively impacting consumers.⁴⁹

In any case, the next, critical, phase of CCS deployment will see an increasingly important role played by public opinion and the media, which are often neglected elements among decision-makers, investors and traditional stakeholders. The role of the public opinion is linked both to financing issues and to storage challenges. Given that government support is needed to bring CCS systems from pilot testing to the commercial scale, decisions on where to allocate public investments will be taken according to economic and social priority that public opinion helps to define. At the same time, a well-informed public opinion is crucial at local level when new CO₂ transport routes and storage sites are to be planned and implemented. Clarity and transparency on a CCS project's operations, risks and safety requirements will become increasingly important to gain public acceptance, as the number of CO₂ transport and storage infrastructures is supposed to increase in the next years. Public perception has proven to be critical in the decision to cancel a CCS project, as happened with the Barendrecht project in the Netherlands and the Janschwalde project in Germany.⁵⁰

It will take a few years to understand if the Paris Agreement and evolving energy prices will become game changers in the next phase of CCS deployment. On the other hand, the pathway for CCS to become a solid climate mitigation strategy will take longer and it involves several complex and interconnected questions to which most answers are still uncertain.

⁴⁷ Pete Smith, Steven J. Davis, Felix Creutzig et al. : Biophysical and economic limits to negative CO₂ emissions in *Nature Climate Change* (2015)

⁴⁸ Tavoni, M., Carbon capture and storage: Promise or delusion? In Barrett, Scott and Carraro, Carlo and de Melo, Jaime, 2015: *Towards a Workable and Effective Climate Regime*, pp. 343-351

⁴⁹ IEA, *Energy Technology Perspectives* (2015)

⁵⁰ H. C. de Coninck and S. M. Benson, Carbon Dioxide Capture and Storage: Issues and Prospects, in *Annual Review of Environment and Resources* 2014. 39, pp. 243–270

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