

OVERVIEW

The IEA World Energy Outlook (WEO) Reference Scenario projects that, based on policies in place, by 2030 CO₂ emissions will have increased by 63% from today's level, which is almost 90% higher than 1990 levels. Even in the WEO 2004's World Alternative Policy Scenario – which analyses the impact of additional mitigation policies up to 2030 – global CO₂ emissions would increase 40% on today's level, putting them 62% higher than in 1990. Hence, to avoid substantial increases over the next few decades, stronger actions than those currently being considered by governments must be taken, including the development and deployment of technology options that have the potential to cut emissions significantly. One such option is to capture the CO₂ produced from fuel use at major point sources and prevent it from reaching the atmosphere by storing it.

This study shows that CO₂ capture and storage (CCS) is a promising emission reduction option with potentially important environmental, economic and energy supply security benefits. But more research and investment into CO₂ capture and storage is required. This study highlights the fact that large-scale uptake of capture and storage technologies is probably 10 years off and that, without a major increase in RD&D investment, the technology will not be in place to realise its full potential as an emissions mitigation tool from 2030 onwards.

This study compares CCS and other emission mitigation options and assesses its prospects. It describes the challenges that must be overcome for a CCS strategy to reach market introduction by 2015 and achieve its full potential over the next 30-50 years. It identifies the major issues and uncertainties that should be considered when deploying CCS as part of an emission mitigation strategy.

This analysis is in three parts. The first provides a comprehensive overview of the prospects, costs and R&D challenges of CO₂ capture, transportation and storage technologies. The second quantitatively tests the hypothesis that CCS is a viable and competitive strategy for cutting emissions and that it is worthwhile accelerating RD&D and international efforts to advance CCS to the levels required. The third highlights the priority actions that would need to be taken for the timely deployment of CCS as an emissions mitigation tool.

What is CO₂ capture & storage?

CO₂ capture and storage (CCS) involves three distinct processes, shown in the figure below: first, *capturing* CO₂ from the gas streams emitted during electricity production, industrial processes or fuel processing; second, *transporting* the captured CO₂ by pipeline or in tankers; and third *storing* CO₂ underground in deep saline aquifers, depleted oil and gas reservoirs or unmineable coal seams. All three processes have been in use for decades, albeit not with the purpose of storing CO₂. Further development is needed, especially on the capture and storage of CO₂. While pipeline transport is an established technology, the siting of CCS projects can reduce the need for an extensive transportation system. The challenge, cost and environmental impact of such a CO₂ pipeline system should not be underestimated.

What are the current and planned CCS projects?

An overview of CCS projects is provided in the table below. In most CO₂ capture demonstration projects, existing technologies are applied. Various small-scale pilot plants based on new capture technologies are in operation around the world. Only one power plant demonstration project on a megatonne-scale has so far been announced: the FutureGen project in the US. This is a coal-fired

CO₂ Capture, Transport and Storage Concept

CAPTURE
for example



Power plants

Illustration: BÜG, Statoil



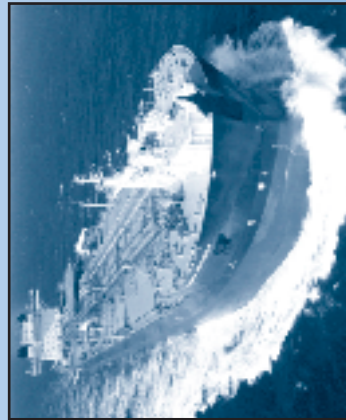
Gas processing

TRANSPORT



Pipelines

Photo: Sealand, Statoil



Ships

STORAGE
for example



Illustration: D. Fierstein, Statoil

Storage in saline aquifers

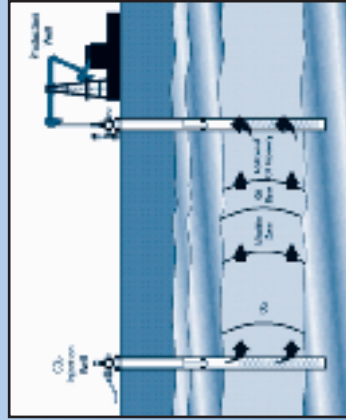


Illustration: IEA GHG R&D Programme

Enhanced oil recovery

advanced power plant for cogeneration of electricity and hydrogen. Its construction is planned to start in 2007. Other demonstration projects are planned in Canada, Europe, and Australia.

There are one hundred ongoing and proposed geologic storage projects. Two of these projects deserve special mentioning because of their scale. Storage in deep saline aquifers has been demonstrated in one commercial-scale project, at the Sleipner site in Norway (sub-sea storage). About 1 Mt of CO₂ per year has been stored since 1996. This project is important as it proves that storage in aquifers can work in practice. No leakage has so far been detected. Using CO₂ to enhance oil recovery and CO₂ storage underground have been demonstrated at the Weyburn project in Canada. About 2 Mt of CO₂ per year has been stored since 2001. In both projects the behaviour of the CO₂ underground has corresponded to what models had predicted, and important progress was achieved in the monitoring of CO₂ underground. Pilot projects suggest that CO₂-enhanced coal-bed methane (ECBM) and enhanced gas recovery (EGR) may be viable but the experience so far is not sufficient to consider these two as proven options. Encouraged by these promising results, many more storage demonstration projects have been started or are planned.

Overview of worldwide CCS projects

	No. of projects
CO ₂ capture demonstration projects	11
CO ₂ capture R&D projects	35
Geologic storage projects	26
Geologic storage R&D projects	74
Ocean storage R&D projects	9

Where could CO₂ capture technology be applied?

In principle, CO₂ can be captured from all installations used to combust fossil fuels and biomass, provided that the scale of the emissions source is large enough. In practice, only three areas are suitable: electricity generation (including district heating and industrial combined heat and power generation), industrial processes, and fuels processing. Emissions from other sources – such as the transport, agriculture, service and residential sectors – are too dispersed to make capture viable. Alternative measures, such as enhancing energy efficiency, renewables, CHP and increased use of hydrogen produced at centralised facilities fitted with CO₂ capture technology, may be better options for these sectors.

Since power production is responsible for over 29% of global CO₂ emissions, capturing from electricity plants offers the best initial potential for capturing the CO₂ generated from fossil-fuel use. To a lesser extent, CO₂ can also be captured during the production of iron, steel, cement, chemicals and pulp, and from oil refining, natural gas processing and the production of synthetic fuels (such as hydrogen and liquid transportation fuels from natural gas, coal or biomass).

Which CO₂ capture technologies are most promising?

CO₂ can be captured either before or after combustion using a range of existing and emerging technologies. In conventional processes, CO₂ is captured from the flue gases produced during combustion (post-combustion capture). It is also possible to convert the hydrocarbon fuel into CO₂ and hydrogen, remove the CO₂ from the fuel gas and combust the hydrogen (pre-combustion capture).

In pre-combustion, physical absorption of CO₂ is the most promising capture option. In post-combustion capture, options include processes based on chemical absorption or oxyfueling (combustion using oxygen separated from air, which generates nearly pure CO₂ flue gas). Chemical and physical absorption are proven technologies. Longer-term, gas separation membranes and other new technologies may be used for both pre- and post-combustion capture.

In electricity generation, CO₂ capture is most effective when used in combination with large-scale, high-efficiency power plants. Indeed, the success of a CCS strategy could depend on the use of such plants. For coal-fired plants, Integrated Gasification Combined Cycle (IGCC) fitted with physical absorption technology to capture CO₂ at the pre-combustion stage is considered to be promising. Coal-fired Ultra Supercritical Steam Cycles (USCSC) fitted with post-combustion capture technologies or various types of oxyfueling technology (including chemical looping, where the oxygen is supplied through a chemical reaction), may emerge as alternatives. For natural gas-fired plants, oxyfueling (including chemical looping), pre-combustion gas shifting and physical absorption in combination with hydrogen turbines, or post-combustion chemical absorption are promising options. At a later stage, fuel cells may be integrated into high-efficiency coal- and gas-fired power plants fitted with CCS. Capturing CO₂ from plants which co-generate electricity and synthetic fuels could have additional cost savings compared to stand-alone power production with CO₂ capture.

Advances in capture technology are needed to reduce the cost of CO₂ capture from power generation. Given the range of ongoing R&D efforts, it is not yet possible to pick a 'winning' capture technology. It is likely that several will be used in future. All require further improvements to cut costs and improve capture efficiency before they can be applied on a commercial scale, a process which is likely to take years. RD&D must be accelerated if CCS is to play a substantial role in the coming decades and have a significant impact on emissions.

How much CO₂ storage capacity is available?

Deep saline aquifers, depleted oil and gas reservoirs and unmineable coal seams offer the best option for underground CO₂ storage. This includes sub-sea reservoirs. Oceanic storage (*i.e.*, CO₂ storage in the water column) is problematic given the unknown environmental impacts. Surface mineralization is still at a conceptual stage.

In underground reservoirs, CO₂ is stored as a bubble under an impermeable caprock at a depth of more than 800 meters, in the top part of a water-filled reservoir rock. Deep saline aquifers offer potentially decades or hundreds of years' worth of storage capacity with between 1,000-10,000 Gt of capacity available, possibly even more. This is the single most important underground storage potential. Around 920 Gt of CO₂ could be stored in depleted oil and gas fields. The storage capacity of unmineable coal seams, where CO₂ is absorbed on the coal surface, is an order of magnitude smaller. While the absolute value of the potentials are uncertain as of yet, it is clear that they are large. CO₂ storage may be combined with enhanced oil recovery (EOR), enhanced coalbed methane recovery (ECBM), and enhanced gas recovery (EGR). Such combinations could create revenues that may offset part or even all of the capture and transportation cost.

Many storage sites are far from large emission sources. Coupled with the fact that long-range intercontinental transportation of CO₂ would incur significant additional cost, this means that the economic storage potential is country and region specific and smaller than the total geologic storage potential. However, in most world regions storage capacities do not pose a constraint for widespread CCS use for decades to come.

What is the risk and effect of CO₂ leakage back into the atmosphere?

All three storage options – deep saline aquifers, depleted oil and gas reserves and unmineable coal seams – need more proof on a large scale. The technology to store CO₂ underground should be considered proven technology. The problem is whether the CO₂ will leak from underground storage sites back into the atmosphere. The leakage discussion can be split into two parts: the question to what extent leakage can reduce the emissions reduction effectiveness of CCS, and public concerns that CO₂ leakage can be dangerous.

Small leakages of CO₂ may occur over a long period of time, which could reduce the effectiveness of CCS as an emission mitigation option. This so-called permanence problem is currently dealt with through field tests and through modelling studies. Depleted oil and gas fields have contained hydrocarbons for millions of years. This makes them a relatively safe place to store CO₂. The problem for such reservoirs is mainly if the extraction activity has created leakage pathways, and if abandoned boreholes can be plugged properly so the CO₂ cannot escape. The only existing large-scale aquifer storage demonstration project has shown no leakage since it started eight years ago. Many projects for natural gas storage and acid gas storage have worked well. Progress in modelling allows increasingly accurate forecasts of the long-term fate of the CO₂, which cannot be tested in practice. Several natural phenomena, such as CO₂ dissolution in the aquifer water, will reduce the long-term risk of leakage. The understanding of these phenomena is improving gradually.

CO₂ is not toxic, but CO₂ can be dangerous in high concentrations as it can cause suffocation due to lack of oxygen. Accidents where significant amounts of CO₂ are released from underground reservoirs, with potential risk for local residents, are highly unlikely. The storage under more than 800 metres of sediment excludes sudden eruptions of massive amounts of CO₂. However, there are cases where natural CO₂ emissions from underground have created locally dangerous situations. Proper CO₂ monitoring systems and remediation measures can prevent such problems.

While the RD&D results are encouraging, more pilot projects are needed to better understand and validate the permanence of underground storage in various geological formations and develop criteria to rank appropriate sites. Too strict criteria for leakage could unnecessarily reduce the potential for aquifer storage.

What is the cost of capturing, transporting and storing CO₂?

The future cost of capturing, transporting and storing CO₂ depends on which capture technologies are used, how they are applied, how far costs fall as a result of RD&D (innovation) and market uptake (learning-by-doing), and fuel prices. Since applying capture requires more energy use and leads to production of more CO₂, the cost per tonne of CO₂ emission mitigation is higher than the per tonne cost of capturing and storing CO₂. The gap between the two narrows as capture energy efficiency increases.

At this stage, the total cost of CCS could range from 50 to 100 USD per tonne of CO₂. This could drop significantly in future. In most cases, using CCS would cost 25-50 USD per tonne of CO₂ by 2030, compared to the same process without. Certain early opportunities exist with substantially lower cost, but their potential is limited.

The cost for CCS can be split into cost of capture, transportation and storage. Current estimates for large-scale **capture** systems (including CO₂ pressurization, excluding transportation and storage) are 25-50 USD per tonne of CO₂ but are expected to improve as the technology is developed and

deployed. If future efficiency gains are taken into account, costs could fall to 10-25 USD/t CO₂ for coal-fired plants and to 25-30 USD/t CO₂ for gas-fired plants over the next 25 years.

With CO₂ **transportation**, pipeline costs depend strongly on the volumes being transported and, to a lesser extent, on the distances involved. Large-scale pipeline transportation costs range from 1-5 USD/t CO₂ per 100 km. If CO₂ is shipped over long distances rather than transported in pipelines, the cost falls to around 15-25 USD/t CO₂ for a distance of 5,000 km.

The cost of CO₂ **storage** depends on the site, its location and method of injection chosen. In general, at around 1-2 USD per tonne of CO₂, storage costs are marginal compared to capture and transportation costs. Revenues from using CO₂ to enhance oil production (EOR) could be substantial (up to 55 USD/t CO₂), and enable the cost of CCS to be offset. However, such potential is highly site specific and would not apply to most CCS projects. Longer-term costs for monitoring and verification of storage sites are of secondary importance.

Using CCS with new coal- and gas-fired power plants would increase electricity production costs by 2-3 US cents/kWh. By 2030, CCS cost could fall to 1-2 US cents per kWh (including capture, transportation and storage).

How does the cost-effectiveness of CCS compare to other emission reduction options? The model analysis

CO₂ emission reduction options in the energy sector include lower carbon fossil fuels, renewables, nuclear, energy efficiency and CCS. Outside the energy sector there are options such as afforestation and land-use change, and reduction of non-CO₂ greenhouse gases. Each option is characterized by a (marginal) cost curve that allows for a certain emission reduction potential at a given CO₂ price. Therefore different options co-exist in a cost-effective policy mix. The more ambitious the emission reduction targets, the more options will be needed, and the more effective and costly the options that will be needed. CCS can reduce emissions by 85 to 95% compared to the same processes without CCS but it is a relatively costly emission reduction strategy. Therefore the widespread use of CCS only makes sense in a scenario with significant emission reduction.

The Energy Technology Perspectives (ETP) model is an economic partial equilibrium model. The world energy system for the period 2000-2050 is optimized, based on least cost. The model is based on a detailed representation of the energy system in terms of energy flows and energy technologies. Cost-effective emission reduction options are chosen from a technology database that contains options such as CCS, nuclear, renewables and energy efficiency. The model is a suitable tool with which to identify the best set of options and to map uncertainties.

CO₂ capture and storage (CCS) could potentially allow for the continued use of fossil fuels while at the same time achieving significant reductions in CO₂ emissions. Indeed, the results of IEA analysis show that CCS could even play a key role in a scenario where global CO₂ emissions are roughly stabilized at 2000 level by 2050. This would require significant policy action, however, equivalent to a CO₂ penalty level of 50 USD per tonne of CO₂. This scenario would halve emissions by 2050 compared to a scenario where no additional policy action was taken. CCS technologies contribute about half of the reductions achieved by 2050.

By 2050, 80% of the captured CO₂ would come from electricity production, particularly coal-fired generation. At a penalty level of 50\$/t CO₂, power plants with CO₂ capture would represent 22% of total global installed generation capacity by 2050 and produce 39% of all electricity. Within the electricity sector, coal-fired IGCCs fitted with CCS that co-generate hydrogen and other

transportation fuels would play an important role. Capture from coal-fired processes would represent 65% of the total CO₂ captured by 2050, the remainder coming from gas, oil- and biomass-fired processes, and from cement kilns.

Up to 2025, CCS would mainly be applied in industrialized countries. By 2050, almost half of total capture activity could be rolled out in developing countries, mostly China and India. Technology transfer from industrialized countries (particularly of efficient power-generation plants) could help to realize the full potential of CCS in developing countries. If CO₂ policies were limited to industrialized countries, the role of CCS would be significantly reduced. This finding emphasizes the importance of international co-operation.

What would be the environmental benefits of CCS?

The potential benefits of CCS can be further illustrated by considering a scenario without CCS but with the same emission penalty level (50 USD/t CO₂). In this case, emission levels in 2050 would increase by over a quarter compared to the scenario in which CCS was included. In fact, without CCS, the CO₂ penalty imposed would need to be doubled before the same reductions could be achieved.

Additional scenarios were analysed that combine various key uncertainties such as the policy ambition level, the extent of international co-operation to mitigate emissions and the prospects for technological change. These scenarios suggest CCS potentials are between 3 Gt and 7.6 Gt CO₂ in 2030, and between 5.5 Gt and 19.2 Gt CO₂ in 2050. This compares to 38 Gt CO₂ emissions by 2030 under the WEO Reference Scenario. The fact that all scenarios show a potential on a Gt-scale suggests that CCS technologies constitute a robust option for emissions reduction.

Such results are sensitive to assumptions about future technology development, not only for CCS, but also for other mitigation options such as renewables and nuclear. More optimistic assumptions for the future cost reduction of renewables and the potential for expanding nuclear would considerably reduce the future role of CCS.

One important finding of this analysis is that renewables, nuclear and CCS technologies can co-exist as part of a cost-effective portfolio of options for reducing CO₂ emissions from energy production. However, the relative role of each would vary from region to region. It would also depend on policy efforts and cost developments for all technologies, the extent to which promising technology options actually work, institutional and legal barriers, and public acceptance (relevant for all three technology options). Investing in CCS RD&D could be a good 'insurance policy' for the future. Such a hedging approach would reduce the risk of failure.

What would be the fuel market consequences of CCS?

CCS would result in a significant increase in the use of coal compared to a scenario where CCS is not considered, but the same CO₂ policies are applied. As coal is considered a more secure fuel than oil and gas, the fact that coal remains a viable energy option increases supply security. CCS would have a limited impact on the use of oil and natural gas. CCS would result in a lower use of renewables and nuclear and increase clean fossil energy availability. However, this model result does not account for the uncertain growth potential of cost-effective renewables. Coal on the other hand is an established fuel. As CCS makes coal a more sustainable option, it increases the security of supply, even in regions where the actual investments in coal are of a limited scale.

For regions with ample coal reserves, such as North America, China and India, CCS could result in lower imports and increased reliance on domestic energy sources. For a number of countries such

as Australia, coal exports would be higher if global coal consumption were higher. This could have economic advantages that need to be analysed in more detail.

Is CCS relevant for all countries and all regions?

The relevance of CCS differs by region. Model analysis suggests that CCS can become an important option in North America, Australia and parts of Europe. While the CCS potentials in China and India are important as well, the realization of these potentials will depend on the extent of global efforts to reduce CO₂ emissions. If CO₂ policies are limited to industrialized countries, the role of CCS is significantly reduced on a global scale. This finding emphasizes the importance of technology transfer and international co-operation on both technology and policy.

Given that long-range transportation of CO₂ seems an unlikely option given its high cost, for countries without sufficient storage potential close to their emission sources, it may be more cost effective to consider alternative emission reduction strategies. While having CCS in a CO₂ policy portfolio is certainly attractive, the issue of its application will require a careful case-by-case project evaluation. This evaluation must account for the energy system characteristics on the continental, the country and the local scale.

What will it take to bring CO₂ capture & storage to market?

There is a 'window of opportunity' for CCS to compete as a technology option, starting from around 2020 and peaking in the second half of the 21st century. Beyond that, CO₂-free alternatives would make CCS redundant. In other words, CCS should be considered an essential 'transition technology' to a sustainable energy system for the next 50 to 100 years.

The single most important hurdle which CCS must overcome is public acceptance of storing CO₂ underground. Unless it can be proven that CO₂ can be permanently and safely stored over the long term, the option will be untenable, whatever its additional benefits.

The potential for 2030 is two to three orders of magnitude greater than the projected Mt-scale demonstration projects for 2015. This indicates the need for significantly increasing both investment in RD&D and the scope of projects, if a CCS strategy is to succeed. Taken together, all the planned CCS projects in the coming decade will barely reach the 10 Mt per year scale. If the full emission mitigation potential of CCS is to be realized, RD&D activities need to be scaled up and accelerated significantly.

Achieving this will require increasing the number of commercial scale storage pilot projects over the next 10 years and ensuring that the general public is consulted throughout. RD&D should initially focus on storage projects which enhance fossil-fuel production and those which advance knowledge on sub-sea underground storage, and aquifer storage in locations with low population density, in order to minimize planning hurdles. Processes which consult, review, comment and address stakeholder concerns should be built into all pilot projects. Procedures for independently verifying and monitoring storage and related activities should also be established. Finally, a regulatory and legal framework for CO₂ storage projects must be developed to address issues around liability, licensing, leakage, landowner, royalty and citizens rights.

Governments must address the present shortage of sizeable RD&D projects in order to advance technological understanding, increase efficiency and drive down costs. This will require increasing RD&D, investment into CCS demonstration projects, and power-plant efficiency improvements. By 2015 at least 10 major power plants fitted with capture technology need to be operating. These

plants would cost between 500 million and 1 billion USD each, half of which would be additional cost for CCS. The current CCS budget is over 100 million USD per year. The needed RD&D would represent a fivefold increase. While the amount required is challenging, it is not insurmountable given the scale of past energy RD&D budgets. It would represent a 30% increase of the current total RD&D budget for fossil fuels and power & storage technologies. Leveraging the funds in private/public partnerships is essential.

Creation of an enabling environment to ensure technology development must be accompanied by the simultaneous development of legal and regulatory frameworks. In the interests of time, and given the diversity of institutional arrangements and policy processes between countries, working at the national level using existing frameworks may be the best short-term option.

Finally, countries should create a level-playing field for CCS alongside other climate change mitigation technologies. This includes ensuring that various climate change mitigation instruments, including market-oriented trading schemes, are adapted to include CCS. The future role of CCS depends critically on sufficiently ambitious CO₂ policies in non-OECD countries. Therefore, outreach programmes to developing countries and transition economies and international commitment to reduce CO₂ emissions are a prerequisite. The maturation of a global emissions-trading scheme, a meaningful price for CO₂ and a predictable return on investment are important factors that could stimulate the timely deployment of CCS.