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The contribution of CO_2 capture and storage to a sustainable energy system

Policy brief in the CASCADE MINTS project

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CASCADE MINTS

Preface

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More information on the project can be found on www.e3mlab.ntua.gr/ cascade.html.

The following partners are involved in Part 2 of the CASCADE MINTS project:

- Energy research Centre of the Netherlands (ECN) (The Netherlands); coordination/MARKAL model.
- ICSS/NTUA - E3MLAB (Greece); PRIMES and PROMETHEUS models.
- The International Institute for Applied Systems Analysis (IIASA) (Austria); MESSAGE model.
- IPTS (Institute for Prospective Technological Studies), Joint Research Centre, EC (Spain); POLES model.
- Paul Scherrer Institute (PSI) (Switzerland); GMM model.
- The Centre for European Economic Research GmbH (ZEW) (Germany); PACE model.
- The Institute for Energy Economics and the Rational Use of Energy (IER) (Germany); TIMES-EE and NEWAGE-W models.
- ERASME-Équipe de Recherche en Analyse des Systèmes et Modélisation Économiques, University of Paris (France); NEMESIS model.
- International Energy Agency (France); ETP model.
- U.S. DOE/EIA Energy Information Administration of the U.S. Department of Energy (USA); NEMS model.
- Research Institute of Innovative Technology for the Earth (Japan); DNE21+ model.
- National Institute for Environmental Studies (Japan); AIM model.
- Natural Resources Canada (Canada); MAPLE model.

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Abstract

This report addresses the prospects of CO_2 capture and storage (CCS) technologies in the power sector. Based on the results of 10 advanced energy models, it provides an overview of the results of the scenarios analysed in the CASCADE MINTS project. Three policy approaches are compared in order to address the question how to achieve significant CO_2 emission reductions through the application of CCS technologies. The analysis shows that CCS can provide an important contribution to mitigating climate change. Up to 30% of global CO_2 emissions could be captured in 2050, while for Europe, due to a more limited growth of the power sector than in some other world regions, this would amount to some 22% of total CO_2 emissions. The carbon constraint policies not only induce the large-scale introduction of CCS systems in the electricity sector, but they also accelerate the penetration of renewable energy sources and nuclear. Policies that provide flexibility, for instance through emission trading, are more cost-effective than those obliging CCS to be installed with all new fossil power plants. Therefore, it is recommended to employ mixes of the different CO_2 emission reduction options available, also depending on regional circumstances. The uncertainties, particularly in storage capacities, are large. Using conservative estimates in line with the IPCC Special Report, the CASCADE MINTS project arrives at the conclusion that the availability of storage capacity does not impose limits to the amount of CO_2 stored in the time frame to 2050. Being a new technology, the actual deployment of CCS will also depend on public perception and on how legal and regulatory aspects related to risks and liabilities are addressed.

Contents

List of tables

List of figures

Policy brief

Fossil fuel fired power plants play an important role in current global and European energy systems. Alternatives, such as renewables, are currently more costly than the more mature fossil technologies. Due to their 'add-on' nature, CO_2 capture and storage (CCS) technologies could work as transitional technology, reducing the CO_2 emissions from the energy sector before a transition to less carbon-intensive energy system is achieved. However, CCS still needs a price on carbon or another CO_2 reducing policy in order to be deployed.

This policy brief focuses on the role of CO_2 capture and storage technologies in the power sector, and provides an overview of the main results from a number of models used in the CASCADE MINTS project. The models used are: POLES, MARKAL and TIMES-EE for the European impacts, GMM, MESSAGE, ETP, DNE21+ and PROMETHEUS to illustrate global developments, the global economic model NEWAGE-W, and finally NEMS for the US. Three policy approaches (CCS standards, a CO_2 cap, and a CO_2 cap combined with a CCS subsidy) are analysed through these advanced energy-environment-economy models to address the question how to achieve significant CO_2 emission reductions through the application of CCS technologies. The models do not take into account non-economic aspects of CCS that may inhibit the deployment, such as public acceptance, risks and safety regulations and upstream environmental impacts.

The main results and conclusions in this policy brief reflect the consensus among the modellers. Although all models confirm these messages, there are sometimes significant differences among individual model results, reflecting the different dynamics and assumptions and indicating the impact of uncertainties in the future energy system. The graphs presented in this paper show projections from different models, and should be regarded as illustrative of the discussed trends, by no means the only possible paths.

Earlier scenario work in the CASCADE MINTS project has again underlined the challenges faced by Europe's energy system in the decades to come. Most of these are related to the continuing worldwide reliance on fossil fuels, which is likely to contribute 70-75% to the primary energy mix in 2030. This would lead to a worldwide doubling in CO_2 emissions in 2030 compared to 1990, with a particularly large expected growth in Asia. Although CO_2 emissions in Western Europe show moderate growth as compared to the global trend, they are not on track towards the target agreed under the Kyoto Protocol. Beyond 2012, assuming that some climate policy is in place in Europe, reflected in a moderate carbon tax of 10 €/tonne CO_2, emissions are expected to continue their growth with ca. 0.4% per year. Furthermore, Europe's dependence on oil from the Middle East is expected to increase to 85%, and for natural gas, external dependency will also grow in the next decades. A continuing growth in gas consumption combined with a decrease of gas production in the UK, the Netherlands and Norway, will lead to a higher share of imports, probably still from the two current main suppliers Russia and Algeria.

P.1 What is CO_2 capture and storage?

CO_2 capture and storage is increasingly mentioned as one of the options in the portfolio to mitigate climate change. CCS involves the capture of CO_2 from a large point source, compression, transport and subsequent storage in a geological reservoir, the ocean, or in mineral carbonates.

As illustrated in Figure P.1, capture can be done at large point sources of CO_2 such as electricity plants, refineries, hydrogen production units, or cement and steel factories. Several capture processes are available or are being developed. Post-combustion systems separate CO_2 from the flue gases after combustion, while pre-combustion systems extract the C as CO_2 from the fossil fuel and combust or use the resulting hydrogen. Oxyfuel combustion, which involves combustion with pure oxygen as opposed to air, is still in the demonstration phase. In most cases, the capture and compression step represents the bulk of the total energy use and cost of a CCS operation.

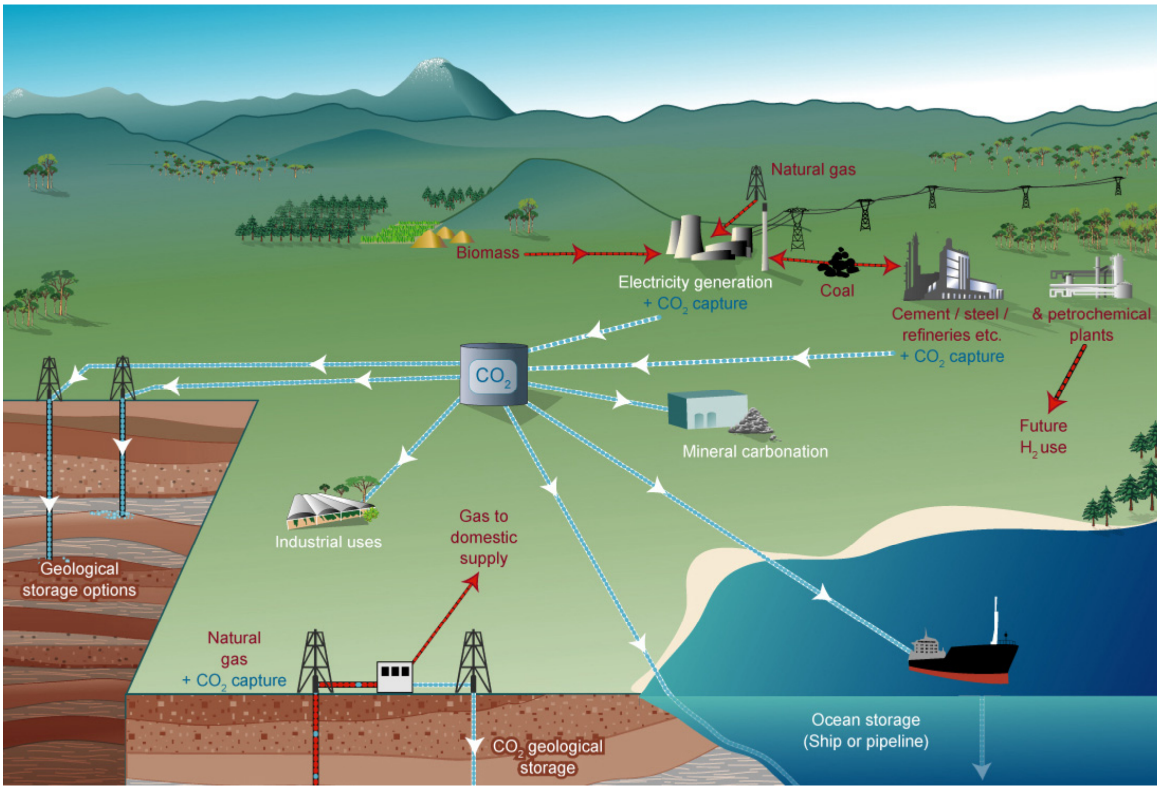

Figure P.1 *Overview of CO_2 capture, transport, and storage options*
Source: IPCC, 2005.

The captured CO_2 is compressed and transported to a storage location, normally by pipeline, but in case of over-sea transport and large distances, transport by ship could become more attractive. The CO_2 is normally injected in a supercritical state. Once in the reservoir, the CO_2 is slowly immobilised through several trapping mechanisms, such as dissolution, residual gas saturation, and mineralisation.

Underground storage of CO_2 can be done in geological formations such as oil or gas fields, saline formations, or coal beds. The oil and gas fields could be depleted, but much is expected from enhanced hydrocarbon recovery by injecting CO_2 in a producing field, which would generate additional revenues.

P.2 Assumptions in the models

As a background to the description of the model results, Table P.1 gives an overview of the models involved, classified along their methodology. Generally, energy system models have a detailed technology representation and these have been used to analyse the impact of CCS technologies. Still, a variety of methodologies, including 'hybrid' modelling approaches is represented. The equilibrium model participating in the case study has made use of the results of one of the energy system models.

Table P.1 *Overview of the models participating in the CASCADE MINTS project*

<table>
<tr><th></th><th colspan="2">Top down</th><th colspan="2">Bottom up</th></tr>
<tr><th></th><th>Macro-economic</th><th>Computable General Equilibrium</th><th>Energy System Optimisation</th><th>Integrated Energy System simulation</th></tr>
<tr><td rowspan="2">Global,
US, Canada</td><td rowspan="2"></td><td rowspan="2">AIM*
NEWAGE-W
PACE*</td><td>DNE21+
ETP
GMM
MESSAGE</td><td>POLES
NEMS
MAPLE*</td></tr>
<tr><td colspan="2">PROMETHEUS
(stochastic)</td></tr>
<tr><td>Europe</td><td>NEMESIS*</td><td></td><td>MARKAL Europe
TIMES-EE</td><td>PRIMES*</td></tr>
</table>

Note: Models marked with * were not involved in the analysis of the CCS scenarios.

Assumptions on costs of CCS technologies are highly determining for their penetration into the energy system. All models have made assumptions regarding variables like investments costs, O&M costs, the energy penalty, the CO_2 capture efficiency, and the learning rate of CCS technologies for power plants, which are documented in this report.

Most models have applied approximately the same set of capture technologies. There are differences in how transportation and storage of CO_2 is modelled. Some models have a wide array of storage options with capacities whereas others have a generic storage technology with infinite capacity. This does have an effect on the results, since for some models, the revenues related to hydrocarbon recovery greatly contribute to making CCS viable. The modelling of transportation costs also varies.

The CCS policy cases are compared to a common, harmonised baseline scenario, characterised by a moderate economic and demographic growth, and based on the IPCC B2 scenario[1]. Oil prices reflect assumptions of low to moderate resource availability. In the period 2000-2050, the world oil price is projected to increase from ca. 26 to 38 $US\$_{95}$/barrel (4.2 to 6.2 €/GJ)[2]. Obviously there is a great deal of uncertainty to this assumption. Natural gas prices within Europe, although not explicitly harmonised among the models, are projected to increase from on average 2.3 to 5.4 €/GJ in 2000-2050. Finally, some representation of climate policy or emission trading for the region of Europe has been included, reflected in a generic carbon tax of 10 €/tonne CO_2 from the year 2012 onwards.

P.3 How much can CCS contribute to mitigating climate change?

The first policy case analysed, ‘CCS standards’, requires that from 2015 onwards, all new fossil fuelled power plants have to be equipped with a CO_2 capture facility. These standards are not applied to peaking plants with an utilisation rate of up to 20% and small CHP-plants. Due to the exclusive nature of the standards, this policy shows the largest CCS penetration. This section focuses on the results of this scenario, because it indicates how much CCS deployment could be achieved until 2050.

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1 More information on key assumptions, ‘business as usual’ trends and developments for Europe can be found in the CASCADE MINTS baseline report on http://www.ecn.nl/library/reports/2004/c04094.

2 This is in line with results of the European WETO project, although it is relatively low in comparison to current prices. A forthcoming scenario in the Cascade Mints project will include higher oil and gas price projections.

P.3.1 Up to 30% of global CO_2 emissions captured

Under the assumption of the regulatory CCS standards, 16% to 30% of global CO_2 emissions can be captured in 2050, as illustrated in Figure P.2. According to the different global models used, this corresponds to a range of 7 to 19 Gton CO_2 captured and stored in 2050. One of the factors underlying this range is the large variation in emissions projections among the models, which is related to the differences in the projected primary energy mix, particularly the share of fossil fuels. Other important explanatory factors are the assumptions related to technology learning and future costs of CCS technologies and renewables, as well as the growth constraints or potentials of the main carbon-free energy sources, nuclear and renewables.

The CCS standards not only induce the large-scale introduction of CCS systems in the electricity sector, but they also accelerate the penetration of nuclear and renewable energy sources. This 'substitution effect' is due to the fact that the application of CCS makes electricity generation more expensive and therefore other options become more competitive. For this reason, the emission reduction compared to the baseline is even larger, up to 40%, in most models. Generally, it more than compensates the 'energy penalty', e.g. the energy use and related emissions due to the additional energy needed for the CO_2 capture and storage processes themselves. However, one of the models (MESSAGE) points out that imposing CCS standards within the power sector may lead to a considerable shift ('leakage') of emissions to other sectors. The increase of biomass use for power production, for instance, induces more use of fossil methanol instead of bio-ethanol in the transport sector.

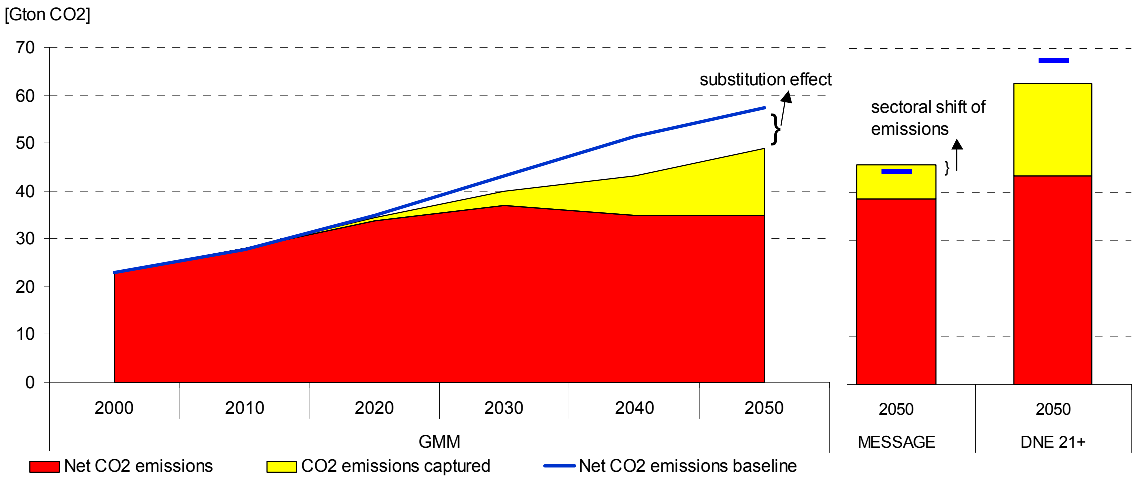

Figure P.2 *Global net CO_2 emissions and amount of CO_2 captured in the CCS Standards case compared to net CO_2 emissions in the baseline*

For Europe, comparable emission reductions can be achieved through the CCS standards. By 2050, approximately 21%-23% of total CO_2 emissions would be stored. Compared to the baseline, the reductions are higher due to the shift to renewables and nuclear. Model analysis for the US, with a time horizon until 2025, shows that CCS technologies remain largely uneconomic within this period. The technologies that gain most from the obligation to install CCS with new fossil power plants are those not affected by the CCS standards - peak production gas turbines and renewables.

P.3.2 More CCS with coal than with gas-fired power plants

Most of the models indicate that coal-based power plants with CCS dominate, particularly Integrated Gasification Combined Cycle (IGCC) plants with pre-combustion capture, implying more limited CO_2 capture at gas-fired power plants. This is related to the high costs associated with capture technology applied to gas-fired power plants. It should also be noted that IGCC itself (even without CO_2 capture) is currently not a fully developed technology; there are only a couple of commercial IGCC plants operational in the world today. There are exceptions in specific policy cases and specific regions, where CCS applied to gas-fired power plants has a relatively large role. This is the case in Europe, as illustrated in Figure P.3. Biomass gasification combined with CCS offers prospects for negative emissions. However, it is the least likely option for a major CCS introduction because of the considerable risks of high capital cost.

The addition of CCS only to new plants slows down CCS penetration, pointing at the inertia in the power sector. Even in 2050, sizeable capacities without capture technologies remain in the system. They consist of gas-fired, peak-load capacities excluded from the standard and remaining coal capacities close to the end of their lifetime.

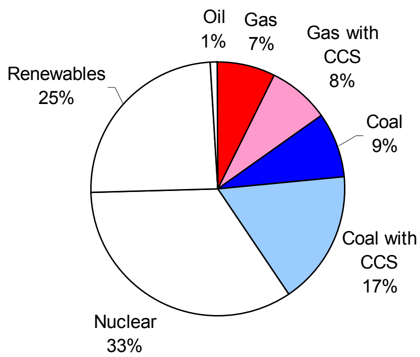

Figure P.3 *European electricity generation mix in 2050 in the CCS Standards case*
Source: POLES (EU-30).

P.3.3 Storage potentials appear to be more than sufficient in 2020-2050

There is an ongoing scientific debate on how the CO_2 storage capacity should be estimated. Any site needs a detailed geological survey in order to make a reliable estimate of the suitability of the reservoir for storage of CO_2. Although acknowledging the controversies in the scientific literature on this issue, the CASCADE-MINTS project used conservative estimates in line with the IPCC Special Report, and arrives at the conclusion that the availability of storage capacity does not impose limits to the amount of CO_2 stored in the time frame to 2050.

The global models report that under the CCS standards policy for new fossil power plants, the global, cumulative amount of CO_2 captured and stored in 2020-2050 is in the range of 170 - 260 $GtCO_2$. Acknowledging that the power plants built towards 2050 will need enough storage capacity for the decades to come, this still seems well below IPCC estimates (IPCC, 2005) of 675-900 $GtCO_2$ of cumulative potential for CO_2 storage in global gas and oil fields. Only one of the global models (DNE21+) has reported on the type of reservoir used. Geological storage in saline formations and oil fields combined with EOR prevails, while ocean storage is mainly utilized in Japan. This is related both to physical storage potentials and to the political acceptance of this option.

As far as the regional distribution is concerned, the global models suggest that although in 2030, comparable amounts of CO_2 are captured in Asia and the OECD, the emphasis shifts to Asia after 2050, due the large expansion of new power plants in this region, which would be equipped with CCS technologies as a result of the standards policy.

Also in Europe, storage potentials appear to be sufficient. There are differences among the models in what kind of reservoirs are used. These differences are closely related to the uncertainties in storage potentials as a result of the huge variety in local geological circumstances.

The TIMES-EE model has projected the amount of CO_2 to be captured and stored for individual EU Member States under the different policies, see Figure P.4. Most CO_2 is expected to be stored in Germany, followed by Poland and Spain. The country differences are explained by regional storage potentials, the contribution of coal in the electricity production of individual Member States, and differences in the extent to which countries can shift to nuclear or renewables. The total amount is a factor 4-5 lower than what is expected by the other European models POLES and MARKAL, because this model 'anticipates' on the standards by projecting an increase in natural gas capacity in the years before the CCS standards become binding. Although the latter effect is related to the modelling methodology ('perfect foresight'), it does suggest that market actors may try to circumvent anticipated policy measures.

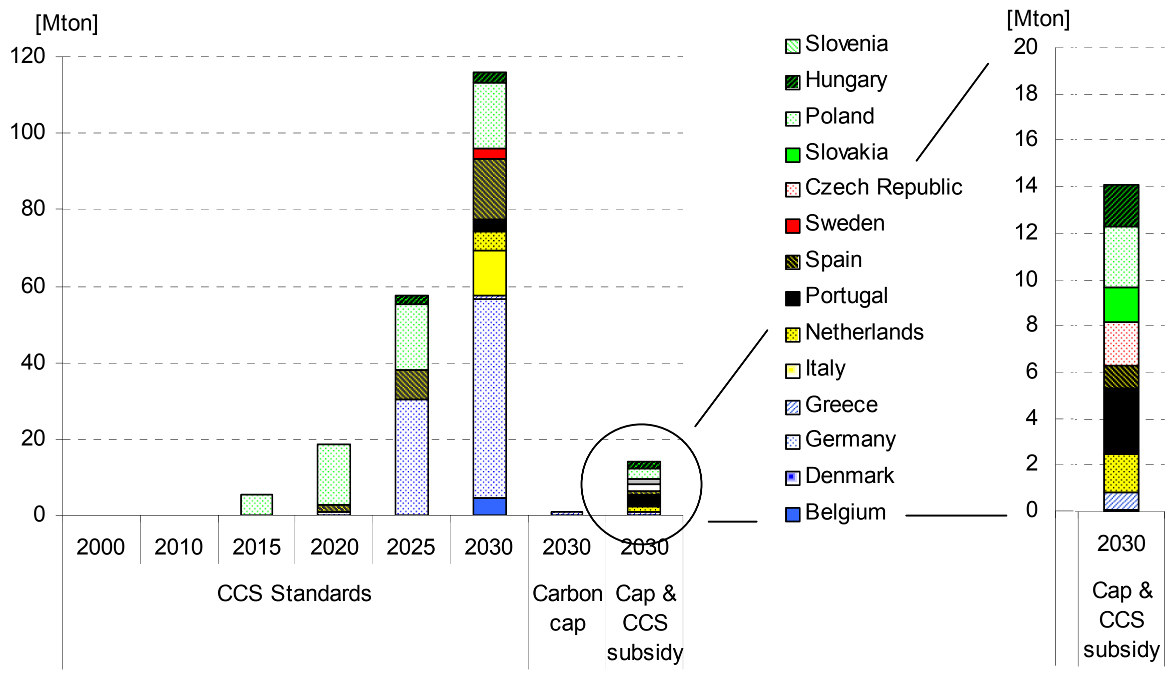

Figure P.4 *CO_2 storage in the EU-25 by country and policy case (Member States where no storage takes place omitted from the graph)*

Source: TIMES-EE.

P.4 Which policy instruments are most effective?

Three policy approaches are compared in order to address the question how to achieve significant CO_2 emission reductions through the application of CCS technologies. The first case, 'CCS standards' has already been described. The second case, 'CO_2 cap' takes the emission level from the CCS standards case as an upper bound for the overall emissions, but allows flexibility as to which technologies in which sectors are used to achieve this emission reduction. The third case, 'CCS subsidies' uses the same CO_2 emission cap as in case 2. In addition, a subsidy on CO_2 capture technologies is given. This subsidy is 35% of the investment cost at its introduction in 2015 and is reduced by one percent each year until it is zero in 2050.

P.4.1 A standards policy leads to highest CCS penetration

Figure P.5 presents the cumulative amounts of CO_2 stored under the different policy cases, for the three world models that have reported on this. As discussed before, obliging CCS for new fossil fuelled power plants, as in the CCS Standards case, is focused on the power sector, where it does lead to the highest CCS penetration among the cases analysed.

A global CO_2 emission cap results in a lower penetration of CCS technologies, but reaches the same emission reduction at lower costs. A cross-sectoral policy scheme may also prevent 'carbon leakage' among sectors. Generally, this policy instrument induces a stronger increase in the contribution of renewable energy sources and nuclear power. There are clear differences between the models concerning the timing and extent of CCS penetration, related not only to the differences in projected fuel mix, but also to the severity of the CO_2 cap, which is derived from the emission reduction realised in the CCS standards case.

The third policy instrument analysed, is a combination of the CO_2 cap with a direct subsidising of capture technology. According to most of the models, the subsidy does have a strong impact on short-term investments, and thus does speed up the introduction of CCS. However, by 2050, the difference with the previous policy case - CO_2 cap alone - is small, so this decreasing subsidy scheme appears not to be sufficient to have a very lasting effect on CCS technology development and cost reduction. This is mainly due to the limited uptake of CCS under the carbon cap. Still, subsidies may have an effect on the choice of CCS technologies.

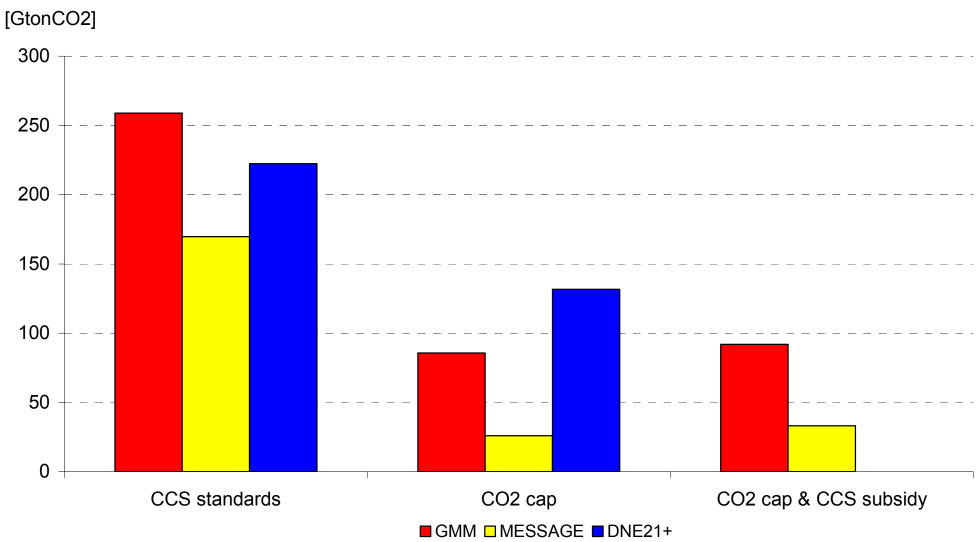

Figure P.5 *Cumulative amount of CO_2 stored in 2020-2050*[3]

P.4.2 A carbon cap is more cost-effective

The CCS standards case is for most models the most expensive one and the CO_2 cap case, where it is left to the market to find the most cost-effective way of reducing CO_2-emissions, the cheapest. Generally, the latter case has 7-8% lower system costs than the CCS Standards case.

One of the models, PROMETHEUS, explicitly takes uncertainties into account, and points out that there is a probability that climate policy in future years becomes sufficiently ambitious to make large scale application of CCS cost-effective without the additional policies considered here.

Furthermore, the general equilibrium model NEWAGE-W reports that the obligation to use CCS technologies for conventional fossil power plants leads to a decrease in GDP. By 2030, the gross domestic product for Western Europe would be approximately 1.5% lower than in the Business as Usual scenario without a CCS standard, not taking into account indirect effects on GDP such as the export of CCS-related technologies to other countries.

[3] Cumulative CO_2 storage in the CO_2 cap & subsidy case is *not* zero according to the DNE21+ model; this model has not calculated the CO_2 cap & CCS subsidy case.

P.5 Other issues determining the prospects of CCS

CO_2 capture and storage is a new technology and faces barriers to implementation. It is important to realise that the actual deployment of CCS depends on how risks and environmental impacts, public perception, and the legal and regulatory framework are addressed. The outcomes of the models reported here assume perfect storage and do not take into account any potential barriers to CCS (or other mitigation options).

There are risks associated with CO_2 storage. Although it is likely that certain trapping mechanisms are more effective over long timescales, the possibility cannot be excluded that a reservoir may become leaky due to an unforeseen event, with consequential damage to humans or the environment, and to climate change. These risks should be quantified and a framework needs to be developed to qualify the risks and to determine which risks are acceptable. As a new option, with risks possibly extending over long timescales, CCS needs a legal framework that takes into account long-term liability for the storage reservoir. It is likely that a distinction will be made between offshore storage, under jurisdiction of international legal treaties, and onshore storage, mainly within the scope of national legislation.

The direct environmental impacts of CO_2 storage in suitable reservoirs are expected to be low. The environmental impacts of capture and compression of CO_2, apart from that capturing CO_2 means building a middle-sized chemical factory, are mainly found in the extra energy requirements and the associated upstream impacts of additional fossil fuel use.

Public acceptance of CCS is uncertain, but it is clear that the public is not well informed on CCS. The initial response of environmental non-governmental organisations to CCS was reserved, but several have expressed support, although concerns are voiced that CCS diverts resources from renewable energy sources and energy efficiency, therefore slowing the R&D or deployment of those options. The model results, by the way, do not confirm this, depending on the policy choice.

In the Kyoto mechanisms and the EU Emissions Trading Scheme, CCS is currently not included, although efforts are underway to address this. To account for the reductions in CO_2, methodologies should be developed and eligibility of CCS under the policy instruments currently in place should be confirmed.

P.6 Conclusions and recommendations

From a comparison of the policies adopted and results obtained, a number of conclusions can be drawn. The most general observation is that the models investigated are broadly in agreement: they confirm that CCS is likely to play a role in cost-effectively reducing CO_2 emissions. However, the actual deployment of CCS not only depends on its technical and economical characteristics, as taken into account by the models, but also on several other important aspects. The importance of the availability of reservoirs near a point source of CO_2 was already mentioned. The potential and characteristics of CO_2 storage reservoirs remain uncertain, although several studies aim at reducing this uncertainty. Furthermore, several legal and regulatory issues, related to risks and liabilities still need to be dealt with, and not much is known yet about public acceptance. Finally, CCS has not yet established itself in the climate change negotiations, and it needs an accepted accounting methodology in the Kyoto regime.

The main policy instrument analysed, which obliges new fossil power plants to install CCS technologies as of 2015, shows that 16% to 30% of global CO_2 emissions could be captured in 2050, while for Europe, due to a more limited growth of the power sector than in some other world regions, this would amount to some 21%-23% of total CO_2 emissions. These amounts could be regarded indicative of the maximal CCS penetration achievable by 2050, as the more flexible global CO_2 emissions cap induces a much lower CCS uptake, while at the same time there are several mechanisms limiting the effectiveness of any policy focusing exclusively on CCS.

First, the inertia in the power sector will slow down the penetration of CCS technologies, as plants built before the introduction of the standards regime are allowed to operate until the end of their lifetime. Secondly, imposing a strict standard requirement on one sector alone leads in some cases to moving the carbon intensive fuels to sectors where no such requirements are imposed. Third, it is difficult to target such a policy well, as it may easily provide an incentive for fossil-based technologies not covered by the standard, such as peak-load gas plants. Finally, the introduction of a CCS standards policy is often much more costly than imposing a CO_2 cap that reaches the same emission reduction.

Therefore, a prerequisite for the implementation of this type of regulatory measure is that CCS technologies are both available and affordable for large-scale application. It is recommended to gradually adopt such a policy, in order to reduce the associated cost penalty.

Although a global CO_2 emissions cap, that reflects the same emissions reduction scheme across all sectors and options combined, is a more flexible, and therefore more cost effective policy instrument, implementing this type of policy, particularly globally, clearly faces many barriers. Still, it demonstrates that while CCS may be an important option for cost-effectively reducing CO_2 emissions, it is no 'silver bullet'. Therefore, it is recommended to continue considering other CO_2 reduction options and employ mixes between the different options available, also depending on prevailing regional circumstances.

CCS on coal-based power plants, notably IGCC, is preferred over gas-fired plants. This implies that especially for countries with a booming demand for cheap (often coal-based) energy, CCS could still allow for a low-carbon energy supply. The application of CCS could lead to an increased reliance on coal, thus increasing security of energy supply. Still, the single motivation for CCS is the mitigation of climate change.