Model-based evaluation of European carbon capture and storage – policy options

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Abstract

This paper investigates the prospects of carbon capture and storage (CCS) in the European energy system, as a mean of supporting the climate mitigation efforts of the EU. It examines the economic, environmental and social impacts of CCS deployment under different supporting policy schemes. The analysis is based on a combination of a systems approach, using the large scale partial equilibrium energy systems model PRIMES, and some further ex-post analysis of the model's results. The study suggests that under the European – Emission Trading Scheme (EU-ETS), CCS deployment could reduce the cost of meeting the emission reduction targets with small impacts on total employment. Additional policies for promoting and supporting CCS lead to higher overall costs that do not seem to be compensated by benefits in terms of security of energy supply, innovation and competitiveness.

1. Policy background

In the context of a 50% global reduction of CO_2 emissions by 2050, necessary to meet the 2°C target, a 30% reduction in emissions in the developed world by 2020 is required, rising to 60-80% by 2050. This reduction is technically feasible but for its achievement all mitigation options must be harnessed, among them carbon capture and storage (CCS). To enable the use of CCS, two problems have to be solved. The first is to manage the environmental risks of the technology, in order to ensure that stored CO_2 remains isolated from the atmosphere and biosphere, and so the technology is environmentally secure and effective as a climate change mitigation option. The second is to address commercial barriers to the deployment of CCS for new power plants, assuming that the technology will reach progressively commercial maturity in the future depending on market penetration prospects$_i$f. However, if entirely left to the market, investment expectations in CCS technology development may be insufficient to enable maturity early enough in the future, for several reasons. First, the positive CO_2 reductions from CCS are currently not rewarded since CCS is not enabled as part of the EU-Emission Trading Scheme (EU-ETS) nor the Clean Development Mechanism (CDM). If included, the CO_2 reduction through CCS would be valued at the carbon price which is a significant motivation for CCS investment. In addition, any positive impacts from developing the technology relative to cost and efficiency, so called the learning-by-doing effect, are not generally captured by the market (positive externalities) (Jaffe et al., 2005). Furthermore, investment in common infrastructure for CO2 transportation and storage involve risks and burden that cannot be addressed purely on a private basis. Finally, reductions in non-CO_2 pollutants in the long term due to the deployment of CCS are not yet internalised, because of uncertainty about persistence of climate policies in the long term. All these reasons justify that public policy interventions are needed to support the maturity process of CCS technology and infrastructure.

The objective of this paper is to give an overview of the major economic, environmental and social impacts of a range of policy options aiming at internalising externalities related to CCS that are being discussed in the EU. In particular the policies considered are:

- not enabling CCS
- enabling CCS under the EU-ETS

– imposing obligations for mandatory CCS on new and/or existing power plants
– subsidising CCS deployment.

2. Methodology and data

The impacts of the various policy options were assessed using the PRIMES model which simulates the European energy system and markets on a country-by-country basis and provides detailed results about energy balances, CO_2 emissions, investment, energy technology penetration, prices and costs by 5-years intervals over a time period from 2000 to 2030. While the modelling provides useful quantitative indications of the scale of potential impacts, predictions of the behaviour of a complex system decades in advance are inevitably uncertain, and the main uncertainties and sensitivities are identified hereafter. Deployment scenarios were run for each of the above options using the PRIMES model (Capros et al. 2007). The impacts on employment were assessed by using the GEM-E3 general equilibrium model and the impacts on air quality by IIASA's GAINS model.

The PRIMES model incorporates a large variety of power generation technologies including future power plants with carbon capture capabilities. Three technologies of carbon capture are considered, namely pre-combustion, post-combustion and oxy-fuel technology. The model represents optional CCS retrofitting of old plants as well as candidate investment in new plants with CCS technologies. In addition, the model includes the costs of transportation and storage of CO_2 through dynamic cost-supply curves based on geological and engineering data. The cost structure includes recovery of investment in CO2 transport network and in geogological storage. PRIMES assesses the direct and indirect impact of policy options by simulating the impacts on the market, thus taking into account the reaction of market agents such as power plants operators. The model establishes a complete linkage between supply and demand for energy and hence takes into account the impacts of CCS policies on market prices (electricity, carbon price). Alternative policies and regulations that promote CCS deployment may be assessed by the PRIMES model.

Technical and economic data on power generation technologies have been recently updated and revised. The revised data reflect new information generated from the EC Technology Platforms (the "Zero Emission Platform") (ZEP 2006) (SAPIENTIA 2005) (VGB Powertech 2004). The model simulates the investment and plant operation choices of power producers within the electricity market, in interaction with consumers' behaviour and with upstream suppliers of fuels, given the price-quantity relationships of the CO2 transportation and storage service. The decision on whether to deploy CCS is part of the endogenous investment choice of the power producer.

Power operators are assumed to maximize profits over time, which drives plant investment and operation. The optimisation is constrained by existing capacities, technical restrictions and policy obligations. Cost supply curves of resources, for example fuels, renewables, sites for nuclear investment, cost of storage of CO_2 captured, etc are also taken into account. These cost supply curves incorporate information about the maximum potential of the resources and their decreasing returns of scale associated with their rate of use. The dynamics of investment are flexible and the model provides multiple alternatives, as for example the retrofitting of old plants, the replacement of an old plant on an existing site, the capacity extension of existing plants, and of course the possibility to build new plants in new sites. The model represents more than 200 typical alternative technologies for power generation. Power system decisions are followed by computation of electricity, steam and heat tariffs, according to an extended Ramsey-Boiteux methodology. These tariffs influence energy demand; hence a closed loop is established between demand for energy and supply of energy, which corresponds to market clearing via energy prices. A multitude of factors affect directly or indirectly CCS deployment in the PRIMES model: fuel prices and price-volume relationships, cost and potential of renewable energy, cost-potential curves of CO_2 storage, old capacities and investment commitments, potential of developments in existing sites, current and future costs of candidate power technologies (including learning effects) and government policies (e.g. on nuclear power plants, emission restriction, etc.).

The PRIMES baseline scenario[1], which does not include climate policy targets, projects the trends in energy markets and technologies without assuming any new policy beyond those put in place in the past (and thus in particular without the 2020 GHG or renewables targets). It assumes

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[1] Extended review on http://ec.europa.eu/dgs/energy_transport/figures/trends_2030_update_2007/index_en.htm

gradually increasing carbon prices in the EU-ETS market reaching 22 €[2]/tCO_2 in 2020. In the baseline scenario, CCS is not found economic to deploy since carbon prices of the EU-ETS market are not sufficiently high.

In this paper the Council Conclusions objectives of 20% reduction in GHGs and a 20% share of renewables in total energy consumption by 2020 are taken as the reference case for assessing the CCS policies, instead of the baseline scenario. To reach this renewables target the model projects that 30 to 25% of electricity would be produced by means of renewable energy forms. To meet these targets, the model computed that the carbon price would have to increase to around 40 €/tCO_2 in 2020 and some 45 €/tCO_2 in 2030. No specific emission reduction target was defined for 2030, however the scenarios have been designed so as to deliver a reduction of approximately 30% by 2030 as compared to 1990. In addition, to meet the 20% renewables share, the model computed a renewable shadow price of around 40 €/MWh in 2020 and almost 50 €/MWh in 2030.

In all scenarios it is assumed that nuclear policies of the Member-States remain as in the Baseline scenario, namely that nuclear phase-out is followed in three Member-States (Germany, Belgium, Sweden), no extension of life time of old nuclear plants beyond their current licenses and no development of nuclear energy in ten Member-States. However, nuclear is considered among the investment options in the remaining Member-States. Given that trade of electricity among the member-states is endogenously projected by the model, it is possible that nuclear develops in a country and also contributes to increase exports of electricity addressed to other countries.

3. Results

3.1. Introduction

All the policy options considered are based on meeting the EU's agreed climate objective of 20% GHG reduction by 2020. Moreover a 20% share of renewable energy (in total final energy consumption) by 2020 is also set as mandatory target. These options are the following:

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[2] All monetary figures are in constant Euros of 2005.

Option 0: Achievement of climate objectives without the deployment of CCS

Option 1: Enable CCS under the EU-ETS

Option 2: In addition to enabling CCS under the ETS, obligatory enforcement of CCS from 2020 onwards and consideration of four sub-options:

a) Making CCS mandatory only for new coal-fired power from 2020 onwards
b) Making CCS mandatory for new coal- and gas-fired power from 2020 onwards
c) Making CCS mandatory only for new coal-fired power from 2020 onwards, but also enforce retrofit of existing plants (built between 2015 and 2020) from 2020
d) Making CCS mandatory for new coal- and gas-fired power from 2020 onwards, but also enforce retrofit of existing plants (built between 2015 and 2020) from 2020.

Option 3: In addition to enabling CCS under the ETS, application of a subsidy so as to internalise the positive externalities not captured by the market

Option 0 was examined in depth in the Impact Assessment for the Sustainable Fossil Fuels Communication. It reflects a scenario with no CCS uptake, because legislative barriers to CCS deployment will remain in place (in particular Directives 2000/60/EC and 1999/31/EC) and there will be no incentive to pay the additional generation cost entailed by CCS, since no credit for the associated reductions will be given under the EU-ETS. This option is used to provide an indication of the viability of CCS by allowing an assessment of how much more expensive it would be, under the carbon market, to achieve the climate objectives with CCS.

Assuming that the EU-ETS is designed and implemented so as to deliver the EU's climate objectives, Option 1 fully integrates the positive climate externality of CCS. Options 2 and 3 show increased penetration of the CCS technology, however both are more expensive ways of meeting the 20% GHG reduction target than Option 1. These extra costs shall be partly or totally compensated by expected additional positive externalities due to enhanced, but policy driven, deployment of CCS. These positive externalities are related with learning-by-doing, security of supply, any positive impact on global market share for CCS technology, any positive impact on achieving global climate objectives, and non CO_2 atmospheric pollution reduction.

Option 3 is based on a subsidy which should, in theory, reflect all the positive (external) effects of increased CCS deployment in addition to the climate benefit. In economic theory, subsidy should be a more efficient means of internalising these externalities than mandating CCS. Subsidies could be given for the investment or operating costs. The latter include subsidies for additional fuel, storage and capture costs and are difficult to measure and monitor. Such costs can make up roughly half of the additional cost (25 to 45 €/tCO_2) of CCS. Including CCS in the EU-ETS (current Phase II price 23 €/tCO_2) would cover these costs. A subsidy on investment on the other hand, would cope with the additional capital costs. As a first approximation, the innovation benefit from the mandatory scenario was used to set the subsidy level. The innovation benefit is estimated at around 10% reduction in investment costs and so for the analysis a subsidy of 10% of the investment cost is used. This level might not suffice for reflecting any positive, external effects on the externalities not captured by the market.

3.2. Deployment of CCS

Table 1 summarises the model results of the impact of the policy options on total CO_2 capture. If enabled under the EU-ETS (option 1) CCS would be gradually picked up by the market in the reference case since a price of 40 €/tCO_2 in 2020 (increasing to around 45 €/tCO_2 in 2030) would be enough for some (coal-based) CCS to be deployed by the market. The volume of CO_2 captured would increase from 7 MtCO_2 in 2020 to 161 MtCO_2 in 2030 in line with the increase in carbon price over time and the gradual maturity of the CCS technology. The model projects that 21 GW of CCS-equipped power plants will produce in 2030 170 TWh of almost carbon free electricity which represents 10.2% of electricity produced by fossil-fuel plants. Under this option, 13% of CO_2 emissions from power and steam production would be captured in 2030 (equal to 5% of total CO_2 emissions from the whole energy system).

Under option 3, which in addition to option 1 policies, involves a subsidy of

10% on investment costs for new plants with CCS, it is found that this would induce power plant operators to invest in CCS on new coal fired plants rather than retrofitting old plants, which was among the outcomes of option 1. Hence CCS would be stimulated under option 3 but with a time delay (related to construction of new plants).

Making CCS mandatory for new coal fired plants built from 2020 onwards (option 2a) initially only slightly increases the amount of carbon captured since power operators would shift to existing coal fired plants by extending their lifetime and operating hours in 2020, and later (2025-2030) shift to natural gas. However, in 2030 the volume of CO_2 captured is found higher than under option 1 despite power operators partly shifting power generation from coal to gas. Making CCS mandatory also for new gas fired plants (option 2b) does not allow this shift and results in a higher volume of CO_2 captured from 2025 onward. Making CCS mandatory for new and existing coal plants (2c) will further increase the amount captured since a shift of power generation to existing coal plants is no longer possible and leads to a further increase of power generation from gas. Conversely, making CCS mandatory for new and existing coal and gas (2d) leads to shift to power generation from gas to renewables (2020-2025) but, nevertheless in 2030 coal generation is found to get a higher market share than under option 1.

Table 1. Impacts of options in terms CO_2 captured by CCS (in Mt CO_2)

	Option 0: No CCS	**Option 1: ETS**	**Option 2: ETS + mandatory**				**Option 3: ETS + subsidy**
			New coal 2a	**New coal + gas 2b**	**New + old coal 2c**	**New + old coal + gas 2d**	
2020	0	7	7	7	37	75	0
2025	0	20	21	27	118	177	22
2030	0	161	267	391	326	517	211

Options 2a and 2b hardly have an impact on the carbon price in 2020 but lead to a somewhat higher carbon price in 2030 since all scenarios aim at delivering significant reduction in CO_2 emissions in 2030 (higher than in 2020). Options 2c and 2d lead to lower carbon prices since old plants are prevented from lifetime extension. Under all the options involving CCS deployment, the model projects that a significant part of the coal- and gas-firing power capacity would have CCS equipment and that given the carbon price these plants will be extensively operated to produce electricity. The carbon prices are computed by the model to accommodate overall emission reduction.

Table 2 summarises the impact of the options on total CCS power capacity. In all options, CCS power capacity by 2020 is small as the technology is not yet mature enough. By 2030, the options involving mandatory CCS lead to substantially large CCS power capacity. Imposing the obligation also on gas plants has significant impacts in favour of CCS power capacity. Imposing in addition obligation to retrofit old plants lead to further increase of CCS total capacity. Most of the CCS capacity is for coal-fired plants except in case 2d. The investment cost subsidy of 10% under option 3 would increase CCS capacity by 50% in 2030 as compared to option 1. The total public costs of the subsidy would be 5.5 billion € and the additional private investment in CCS induced would be around 27 billion €.

Table 2 Impacts in terms of CCS deployed capacity (in GW)

	Option 1: ETS	**Option 2: ETS + mandatory**				**Option 3: ETS + subsidy**
		New coal **2a**	**New coal + gas 2b**	**New + old coal 2c**	**New + old coal + gas 2d**	
2020	1	1	1	6	16	0
2025	2	3	4	19	42	3
2030	21	40	68	53	109	32

3.3. Economic impacts

3.3.1. Resource cost

Total resource costs to the energy sector were calculated by using the PRIMES model. These exclude costs incurred for purchase of CO_2 allowances (since this is not a cost to society as a whole but a transfer payment). The calculation includes all types of costs for the energy system as a whole. They include costs for CCS (investment, operating costs, transport of CO_2 and storage) as well as the indirect impact on costs of other power plants (e.g. making CCS mandatory for coal plants will increase electricity production from gas-fired plants and their costs). Costs are the sum of all changes in the energy system (including impact of increased electricity prices on demand and other costs incurred at the level of demand sectors). In all cases costs are showed as additional to the costs of option 1 (CCS included in ETS). Costs are not discounted but a weighted cost of capital of around 9% in real terms is assumed in the power sector to annualize investment costs and simulate investment decisions.

Table 4. Additional costs based on Option 1 (€billion/year)

	Option 0: No CCS	**Option 1: ETS**	**Option 2: ETS + mandatory**				**Option 3: ETS + subsidy**
			New coal 2a	**New coal + gas 2b**	**New + old coal 2c**	**New + old coal + gas 2d**	
2020	2.2	0	0.8	2.4	1.9	4.9	-0.2
2025	5.2	0	2.1	3.3	4.8	10.0	-0.1
2030	59.5	0	6.7	9.8	6.7	12.6	2.1

Under option 1 (CCS is enabled but only used if the ETS market drives it as being cost-effective), the model shows that effectively CCS develops among the means for meeting the 20% reduction in GHG and the 20% renewable targets. It would then be part of a package of measures such as additional renewables (e.g. wind turbines and biomass), energy efficiency measures and reductions in non_CO_2 Greenhouse Gases. If CCS were not enabled (Option 0) the additional costs of meeting the same 20% GHG and 20% renewable targets (and 30% GHG reduction in 2030) would be 60 billion per year in 2030 or 40% higher compared to Option 1. The additional costs correspond to the use of more expensive technologies (e.g. solar PV or more expensive biomass options) instead of the CCS. Option 3 would cost slightly more than option 1. The additional costs of mandatory CCS (options 2) are higher than those under option 1 (see Table 3) by 7 to 12 billion Euros per year in 2030. They differ depending on the specific option chosen. Generally, the options involving mandatory CCS both for coal and gas power generation lead to higher costs than options imposing mandatory CCS on coal alone. Also, the options involving mandatory retrofitting of old plants also lead to higher costs than for options without such an obligation.

As described above, the modelling was adjusted to simultaneously satisfy the 20% GHG reduction target and the mandatory CCS obligations, and so a reduction in the carbon price will in general result from making CCS mandatory. Since there is no official emission reduction target for 2030, the scenarios have not been fully adjusted to deliver exactly the same emission reduction by 2030. This implies that the options are not directly comparable to each other for the year 2030. To enable a comparison of the options the additional costs corresponding to any extra reduction from reference are valued at the average reduction costs (see Table 5). Thus it should be noticed that, for example, of the additional cost of option 2d in 2030 (shown as €12.6bn in Table above) €6.7bn relates to an additional CO_2 reduction over and above the 20% GHG reduction target.

3.3.2. Impact on electricity price

The impact of the options on EU average electricity price was also assessed as competiveness indicator. Option 3 (subsidy + ETS) would not change electricity prices significantly (unless subsidy cost recovery is effected through higher electricity prices). The same applies for Options 2a and 2b that lead only to minor differences in electricity prices compared with Option 1 in 2020. However, the mandatory application of CCS on coal and gas fired plants would leave little flexibility to generate electricity in 2020 and would initially lead to additional increases, particularly significant for Option 2d. In 2030 the impacts of the mandatory cases are less pronounced since they lead to a shift in generation from coal to gas or the other way around. Case 2b leads to less gas and relatively more coal use in 2030 for power generation. Since the coal price is relatively low in 2030 versus the gas price overall generation costs in 2030 can be lower. Up-front costs (in 2020) are higher since investments have to be made early and coal/gas price ratio differ in 2020.

3.3.3. Innovation (dynamic efficiency)

As suggested by Jaffe et al (2005) a potentially positive impact of mandatory CCS requirements is the additional learning-by-doing from the early deployment thus stimulated. Greater deployment might lead to additional reductions in costs, dependent on the cumulative capacity build.[3] Learning will also depend on the time interval between deployment phases in order to

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[3] Note that there is some debate over the direction of causation in the relation between cost and deployment scale. The Stern Review puts it as follows: 'There is a question of causation since cost reductions may lead to greater deployment; so attempts to force the reverse may lead to disappointing learning rates. [The available] data shows technologies starting from different points and achieving very different learning rates. The increasing returns from scale shown in these curves can be used to justify deployment support, but the potential of the technologies must be evaluated and compared with the costs of development.' (Chapter 16 p. 362.)

absorb the lessons of previous effort, but a provisional estimate of the benefits of learning can be made assuming that cost reductions are sensitive only to the cumulative capacity. (All other things being equal, this will overestimate the learning benefits.)

Table 5 Additional CO_2 emission reduction from energy in EU27(in $MtCO_2$, in % in brackets)

	Option 1: ETS	**Option 2: ETS + mandatory**				**Option 3: ETS + subsidy**
		New coal 2a	**New coal + gas 2b**	**New + old coal 2c**	**New + old coal + gas 2d**	
2020	0	5 (0%)	-6 (0%)	-20 (-1%)	-20 (-1%)	6 (0%)
2025	0	-48 (-1%)	-43(-1%)	-118 (-4%)	-130 (-4%)	+1 (0%)
2030	0	-27 (-1%)	-94 (-3%)	-63 (-2%)	-157 (-5%)	-51 (-2%)

Table 6 Additional costs (bn €/year) due to CO_2 reduction exceeding the 20% GHG target

	Option 1: ETS	**Option 2: ETS + mandatory**				**Option 3: ETS + subsidy**
		New coal 2a	**New coal + gas 2b**	**New + old coal 2c**	**New + old coal + gas 2d**	
2020	0	-0.2	0.3	0.8	0.8	-0.2
2025	0	2.1	1.8	4.8	5.2	0
2030	0	1.2	4.3	2.7	6.7	2.0

Table 7. Impacts on average generation costs (%-point change compared to option 1)

	Option 2: ETS + mandatory				**Option 3: ETS + subsidy**
	New coal 2a	**New coal + gas 2b**	**New + old coal 2c**	**New + old coal + gas 2d**	
2020	0.2%	0.6%	0.9%	1.9%	0.1
2025	0.6%	1.0%	0.7%	1.8%	0.1
2030	-0.1%	-0.1%	-0.2%	0.0%	0.3

In line with the above mentioned ideas, it is assumed that for each doubling of installed capacity a cost reduction occurs. The model's database quantifies cost reduction potential on the basis of common agreement by major experts on CCS technology. The basic components of CCS correspond to established technologies. Cost savings are possible mainly in the assembly of components, the optimization of the system as a whole and the scaling up of their dimension. For CCS these cost reductions are expected to be limited to 3% for each doubling of capacity.[4] Thus it is assumed that cost reduction occurs after a minimum volume of capacity (2 GW each of coal and gas, in line with 10 to 12 demonstration plants) is installed to close the R&D phase, and that for every doubling of capacity beyond 2 GW a reduction in costs of 3% is entailed. The table below shows that the options 2a to 2d might lead to slightly higher cost reductions (for coal) than assumed in the model. For gas-CCS this is only the case for option 2d. For each of the options, the extra reduction in costs (over and above that assumed in the model) is calculated and multiplied by the relevant investment cost (797€/kW for coal (IGCC-coal post combustion) and 500€/KW for gas (gas combined cycle post-combustion)). This is then multiplied by the deployment in 2030 to give total investment cost reduction, which is then annualized over the economic lifetime of the plant (20 years for coal, 10 years for gas). (See Table 3.) The difference between Option 1 and Option 2d is around €0.8bn/year in 2030, compared with the additional resource costs (net of additional CO_2 reduction) of around €6bn. In conclusion, learning effects might lead to bigger cost reductions than assumed for the mandatory cases and including these cost reduction will lower the additional resource costs by a maximum of around 10%. An additional subsidy of 10% (Option 3) would have only a marginal impact on learning.

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[4] IEA (2006) Estimating the future trends in the costs of CO2 capture technologies, Technical Study, Report Nr. 2006/6, IEA Greenhouse Gas R&D program, Paris.

Table 8. Possible innovation impacts on investment costs in 2030 (% reduction in investment costs to 2020)

SOLID FUEL (Coal + Lignite)	**Option 1: ETS**	**Option 2: ETS + mandatory**				**Option 3: ETS + subsidy**
		2a	**2b**	**2c**	**2d**	
GW CCS installed	21	40	58	49	69	31
Number of capacity doublings	4.30	5.30	5.90	5.60	6.00	5.00
Cost reduction (% from 2020)	13	16	18	17	18	15
Additional cost reduction compared to PRIMES (%)	6	9	11	10	11	8
Investment costs savings (€/KW)	53	80	96	88	98	71
Total investment cost savings (bn €)	1.1	3.2	5.5	4.3	6.8	2.2
Annualized investment cost savings (bn €)	0.1	0.3	0.5	0.4	0.6	0.2
GAS	**Option 1: ETS**	**Option 2: ETS + mandatory**				**Option 3: ETS + subsidy**
		2a	**2b**	**2c**	**2d**	
GW CSS installed	0	0	10	0	35	0
number of capacity doubling	0.00	0.00	3.30	0.00	5.12	0.00
Cost reduction (% from 2020)	0	0	10	0	15	0
Additional cost reduction compared to PRIMES (%)	0	-3	7	-3	12	0
Investment costs savings (€/KW)	0	-16	36	-16	64	-0
Total investment cost savings (bn €)	0.0	0.0	0.4	0.0	2.2	0.0
Annualized investment cost savings (bn €)	0.0	0.0	0.0	0.0	0.2	0.0
Solid & Gas: Sum of annualized investment cost savings (bn €)	0.1	0.3	0.6	0.4	0.9	0.2

3.3.4. Export potential

Additional cost reductions achieved through learning might open opportunities for exporting the technologies to markets that are expected to expand in the future (China and USA) (c.f. experience with stimulating wind turbines in the EU in the past). The impact of such cost reductions on export opportunities is difficult to quantify since those opportunities will depend on future international agreement on reducing greenhouse gas emissions, the cost of other GHG technologies in other countries and the extent to which other countries can produce CCS technologies domestically. There is a wide range of estimate of the potential global market for CCS in 2030 assuming that the 2°C target is translated into a binding international agreement including major developing countries. Some estimates put the potential as high as 600-700 GW (half of which coal) with more than 1/3 of the market in China and 10% in Europe.[5] But there are other estimates that the market could be lower by around 300 GW (based on IPCC scenarios that stabilise GHG concentrations while making different assumptions on energy prices, energy efficiency improvements and penetration for gas). If 20-40% of the global market (ex EU) could be captured by European companies, exports would increase by 0.2 to 0.6 billion €/year.[6] The case where the potential for coal-based CCS is low leads to gas generation substituting for coal which further leads to lower fuel consumption. In that case the prospects for gas-based CCS are bigger and might range from 40 to 300 GW in 2030 depending on the scenario.

A proper comparison between the options on this count would require a quantitative assessment of the effect of the differential learning between Options 1, 2 and 3 on the share of the global market the EU could capture, which is very difficult to do with any confidence. In the context also of the uncertainty about the scale of the market, it is hard to differentiate meaningfully between the options with regard to their impact on export potential.

3.4. Social impacts

3.4.1. Impact on employment

The expected impacts on employment and GDP of Option 1 are addressed in the report on impact assessment of effort sharing for meeting the 20% GHG and 20% renewables targets. In general these impacts are expected to be small (+/- 0.1% of total employment) and their sign, either negative or positive, depends on the degree at which the revenues of auctioning the allowances are efficiently recycled in the economy. The employment effects

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[5] Result POLES model IPTS for 2 degrees Celsius communication plus personal communication K. Riahi (IIASA) on IPPC scenarios B1+B2 with 480 ppmv.

[6] Personal communication F Bauer (VGB Powertech), October 2007.

within the EU27 are expected to be negative for coal mining because of the shift towards renewables and lower overall energy demand as consequence of emission reduction targets.

The analysis, based on general economic equilibrium, compares the differential impact on employment of the mandatory options (Option 2) and the subsidy option (Option 3) taking option 1 as a reference[7]. The impacts on employment were decomposed in the following categories:

a) direct effects on coal mining
b) effects from reducing the overall energy import bill
c) effects from increasing total domestic energy system costs
d) effects from shifting capital investment from non energy on energy-related direct investment and
e) other effects mainly through competitiveness of the EU economy due to change of relative to abroad general level of prices.

As already mentioned, option 1 (allowing CCS in the EU-ETS) is the most cost-effective scenario as far as the energy system is concerned. It follows that the mandatory cases (2) and the subsidy case (3) lead to higher overall energy costs. The additional costs for energy partially replace spending on other (eventually more labour intensive) commodities and services, and therefore overall employment is reduced, given that energy investments are generally less employment-intensive. These negative effects may be partially offset by decreased spending on energy imports (Option 2b, Option 3) and thus increased spending on domestic activities that produce goods and equipment needed for the energy sector activities, which involve more employment within the EU. However, this shift from imported goods (energy) to domestic goods (e.g. energy equipment) increases the general level of prices and the cost of capital, which has negative indirect effects on the economy, when assuming that general economic equilibrium prevails.

The mandatory CCS options and the subsidy CCS option all show a reduction in total employment in 2030 compared to option 1, while employment in coal and lignite mining goes up or down depending on the particular option. Making CCS mandatory for new coal and new-and-existing coal will lead to an increase in gas-based power production and a smaller number of jobs in coal mining. Making CCS mandatory for coal and gas increases employment in coal mining since this increases cost of gas-

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[7] The analysis is based on Capros et al (2007).

based electricity production relative to coal, but has a net negative impact due to the additional energy costs. Adding a subsidy for CCS has a small positive impact on coal mining employment and small negative total impacts.

Note that a policy of not enabling CCS in the EU-ETS is the worst case. In that case 50 000 jobs would be lost in coal mining and over 300 000 jobs would be lost in total, because the overall energy costs of meeting the 20% GHG and renewable targets would increase by 40%. No information is available on the distribution of employment effects, but they are likely to be concentrated in those countries in which the effort is concentrated (for example Germany and Poland predominantly).

Table 9 Employment impact in 2030 (1000 jobs) compared to Option 1 (Enable CCS in ETS)

	Option 0: No CCS	**Option 2: ETS + mandatory**				**Option 3: ETS + subsidy**
		New coal 2a	**New coal + gas 2b**	**New + old coal 2c**	**New + old coal + gas 2d**	
Coal and lignite mining	-52	-7	+10	-8	+15	+1
Other sectors	-270	-52	-70	-62	-102	-12
Total	-322	-59	-60	-70	-87	-13

3.4.2. Distribution of efforts over the EU member states

In case CCS would be enabled in the EU-ETS market (option 1) more than half of the carbon captured would take place in Poland in 2030. Note that this result depends on a predicted low cost of carbon storage in Poland. Making CCS mandatory for new coal plants (option 2a) would imply that Germany and Poland would together account for 2/3 of the carbon captured. The rest would be split over Belgium, the UK, Spain and Italy in addition to Slovenia, the Czech Republic, Slovakia, Hungary, Romania and Bulgaria. Option 2c (making CCS mandatory also for existing coal plants) would add all other countries except Luxembourg, Sweden, Latvia, Lithuania, Cyprus and Malta to the list. The options (2b and 2d) involving CCS for gas-fired plants (of large-scale used by utilities) would lead to a slightly more even distribution. This result is attributed to the different structures of the energy system across the member-states and also to the existence of relatively lower cost of carbon storage possibilities in Central and Eastern Europe.

3.4.3. Security of supply

Insecurity of energy supply can be regarded as the exposure to interruption of imports of energy or strong fluctuations in energy prices due to the fact that supply is concentrated in a few countries with relatively high geopolitical risk. For the EU it concerns mainly reliance on gas and oil, and hence CCS policies could affect energy supply security by avoiding imports of oil and gas. Oil is of little relevance since the quantities are small, and hence the most significant issue is the impact on overall gas consumption. As a very rough rule of thumb, it could be stated that when gas consumption (and hence imports) increases security of supply decreases.

Table 10 shows the impact of options 0, 2 and 3 on primary fuel requirements of the EU as compared to Option 1 (enabling CCS in the ETS). Remarkably the extreme mandatory option (Option 2d) increases both the use of solids and gas in the power sector. In relative terms import dependency decreases, but in absolute terms more gas is imported. This takes place because the policy option imposes CCS on all coal and gas fired plants (new and old) which leads to a loss of efficiency (more fuel needed for same electricity output). Under such policy there is little flexibility to shift to other alternatives.

Making CCS mandatory for new coal and gas plants only (Option 2b) would increase energy supply security since the use of solids fuels would increase at the expense of gas in order to meet the GHG-reduction targets of the EU. The subsidy case would not affect energy supply security since gas consumption is not affected (CCS being mostly on coal-fired plants). Note that not enabling CCS under the EU-ETS at all would shift fuel use to imported gas mainly at the expense of coal. In conclusion, Option 2b increases energy supply security, 2a and 2c have a negative impact and 2d a marginal negative impact, and Option 3 is neutral compared to Option 1.

Table 10. Distribution of Mt CO_2 captured by Member State in 2030

Mt of CO_2 Captured in 2030	**Option 0: No CCS**	**Option 2: ETS + mandatory**				**Option 3: ETS + subsidy**
		New coal 2a	**New coal + gas 2b**	**New + old coal 2c**	**New + old coal + gas 2d**	
Ireland			2		5	2
United Kingdom		1	57	4	62	10
Belgium		17	27	22	50	
Luxembourg					1	
Netherlands			5	3	14	
Germany		74	115	135	186	56
France				3	3	
Spain		9	9	11	13	1
Portugal				2	2	
Denmark						
Sweden						
Finland				1	1	
Austria			7	1	11	
Italy		4	4	8	10	
Slovenia	5	5	5	5	5	5
Czech Republic	16	16	16	18	18	18
Slovakia	6	6	7	7	9	7
Poland	91	92	89	72	78	94
Hungary	8	8	9	7	12	8
Latvia						
Estonia					1	
Lithuania						
Romania	19	18	20	12	17	7
Bulgaria	15	15	15	14	16	3
Greece		1	3		3	1
Cyprus						
Malta						
EU27	161	267	391	326	517	211

Table 11. Change in fuel consumption in the power sector over option 1 (% in 2030)

	Option 0: No CCS	**Option 2: ETS + mandatory**				**Option 3: ETS + subsidy**
		New coal 2a	**New coal + gas 2b**	**New + old coal 2c**	**New + old coal + gas 2d**	
Solids	-38%	-6%	8%	-6%	12%	1%
Oil	-19%	4%	-3%	4%	0%	-3%
Gas	7%	15%	-6%	25%	4%	0%

Table 11 compares the impacts of the mandatory plus retrofitting policy option and the EU-ETS option on the emissions of SO_2, NOx and PM10 in 2030. Making CCS mandatory for coal only would increase the use of gas (and to a minor extent renewables) and would reduce SO_2 and increase NOx. Making CCS mandatory for both coal and gas and imposing a retrofitting obligation for existing plants (2d) would eliminate the possibility of operators to fall back either on existing coal plants, or on new gas plants without CCS. For this reason this option would lead to more CO_2 being captured in the power sector than if CCS were left alone to the market (EU-ETS).

3.5. Environmental impacts

3.5.1. Impacts on reduction in traditional air pollutants

Applying CCS may have direct and indirect impacts on air pollution (sulphur dioxide, nitrogen oxide and particulate matter). Directly, adding CCS to existing coal fired plants would lead to similar or lower concentration of most impurities in the flue gas of CCS-equipped plants, than in the case of plants without CO_2 capture. Overall, direct impacts would result in reductions in sulphur dioxide emissions and in minor increases in nitrogen oxide emissions in CCS plants by 2020, compared to coal fired plants without CCS.[8] Indirect impacts arise as a consequence of the combustion of fossil fuels in the extraction, processing and transport to the point of use, as well as emissions of dust from mining operations. When considering both direct and indirect impacts, the policy options (1, 2d and

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[8] Cofala, J., P. Rafal, W. Schoepp and M. Amann (2007), Impacts of options of CCS incentivisation. IIASA. Laxenburg. Final report to DG ENV. Monetary benefits based on standard estimates for the revision of the NEC Directive.

3) have comparable air pollution effects by 2020, with Option 2d being slightly more costly than Option 1 and 3.

A policy that reduces greenhouse gases emissions by 20% compared to 1990 (while increasing the share of renewables in final energy consumption to 20%) would reduce fuel use and prompt a shift towards less carbon-intensive fuels, resulting in a corresponding reduction in air pollution. Table 9 compares the impacts of the mandatory plus retrofitting policy option and the EU-ETS option on the emissions of SO_2, NOx and PM10 in 2030. Making CCS mandatory for coal only would increase the use of gas (and to a minor extent renewables) and would reduce SO_2 and increase NOx. Making CCS mandatory for both coal and gas and imposing a retrofitting obligation for existing plants (2d) would eliminate the possibility of operators to fall back either on existing coal plants, or on new gas plants without CCS. For this reason this option would lead to more CO_2 being captured in the power sector than if CCS were left alone to the market (EU-ETS).

A comparison of the two extreme policy options (1 and 2d) indicates that by 2030 Option 2d would achieve slightly better air pollution effects than Option 1. The mandatory plus retrofitting policy option (2d) would perform better in terms of reduced SOx, NOx and PM2.5 emissions. This is a consequence of faster learning processes for CO_2 capture technologies under the stringent CCS policy scenario (2d), which in turn would be conducive to a higher overall reduction of the energy penalty and emissions associated with CCS processes than under Option 1. Impacts for Option 3 are in between option 1 and 2d.

3.5.2. Other environmental impacts

As mentioned in the section regarding the economic impacts there might be some differences in impact on CO_2 emissions between the options (see Table 4). In addition accidental release of CO_2 might occur when storing and transporting CO_2. The accidental release of CO_2 would be around 0.1% of the total CO_2 captured.[9]

In brief, reducing CO_2 emissions by enabling CCS (either through Option 1,

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[9] Commission Staff Working Document, Impact Assessment Proposal for a Directive of the European Parliament and of the Council on geological storage of carbon dioxide, SEC (2007) X.

2d or Option 3) to meet the 20% GHG reduction target would have a positive effect in terms of significantly reduced atmospheric pollution control costs. Although it would lead to an additional reduction in non-CO_2 harmful substances, making CCS mandatory for existing plants through Option 2d would only decrease the air pollution control costs by circa 1.6 bn€ (2%) by 2030, as compared to incentivising CCS deployment only through the EU-ETS. Option 3 would also reduce air pollution control costs but to a smaller degree.

3.6. Major assumptions, uncertainty and sensitivities

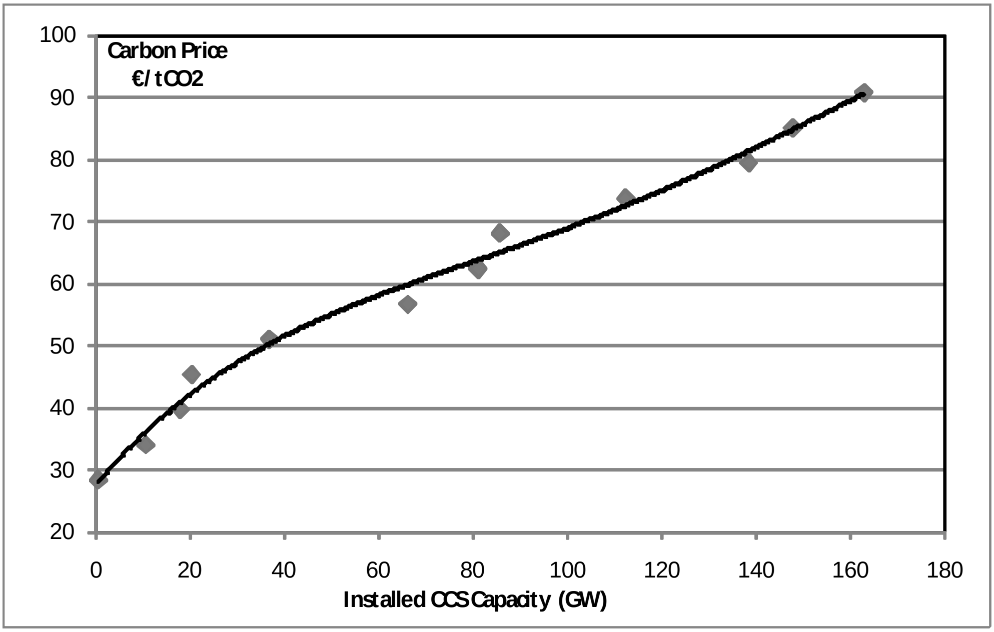
A number of assumptions are critical for the analysis: the assumed greenhouse and climate policy in 2020 and beyond (including the scope of JI/CDM), the carbon price, fuel prices, and the costs of CCS, including the costs of storage, vis-à-vis other technologies (e.g. renewables and nuclear). In particular it is assumed that both the EU climate change target of 20% reduction in GHG emissions from 1990 levels by 2020 and the 20% renewable energy target by the same year are met in all scenarios. Moreover, a gradual further decrease in CO_2 emissions reaching approximately 30% of 1990 levels by 2030 has been considered, along with a continuation of the promotion of renewables that consequently increase their share reaching approximately 25% of final energy demand by 2030. In all cases no change in energy taxation across the EU compared with current national policies is assumed.

A series of sensitivity analysis cases have been studied in order to investigate the implications of various factors in the deployment of CCS. The dependence of the CCS capacity installed in 2030 as function of the ETS carbon price alone is depicted in *Figure*, which plots a series of sensitivity analysis cases quantified with PRIMES. Even in the absence of specific policies to promote the deployment of CCS the technology starts to emerge at carbon prices slightly above 28 €/tCO_2 in 2030.

Table 12. Air pollution impacts of policy options in 2030 for the EU27

	Option 1	**Option 2d**	**Option 3**
	ETS	**New + old coal + gas**	**ETS + subsidy**
CO_2 emissions –energy ($MtCO_2$)	3471	3333	3471
SO_2 (Kt)	2990	2890	2934
NOx (Kt)	5381	5312	5372
PM2.5 (Kt)	1102	1089	1082
Health impacts (mln life years lost due small particles)	2.66	2.62	2.65
Forest Ecosystems with nitrogen above critical loads (1000 km^2)	844.1	841.5	843.9
Forest Ecosystems with acidification above critical loads (1000 km^2)	82.4	76.6	81.52

Figure 1. Capacity of CCS installed in 2030 (GW) in relation to the ETS Carbon price in 2030



CCS deployment, in terms of both capacity expansion and its geographic distribution, is also sensitive to assumptions concerning costs and availability of storage, especially in the Eastern and Central European countries where the basic data (ECOFYS 2004) indicate that a significant low-cost potential of storage could develop. A sensitivity analysis case was considered for which it was assumed that these countries will face equal costs than other EU Member-States in developing storage facilities. Mandatory enforcement of CCS for new coal and gas power plants was also assumed as in the case of Option 2b. For simplicity it was also assumed that the carbon price and the marginal value of the renewable energy would remain unchanged compared to Option 2b. The model results showed that the storage costs increase lead to higher emissions than in standard Option 2b, which implies that a higher carbon price would be necessary to achieve the emission reduction target. Therefore, storage costs increases imply higher carbon abatement costs due to higher costs of CCS deployment. The deployment of CCS is found lower overall and in particular in the Eastern and Central European countries (e.g. almost half in Poland) owing to higher storage costs, whereas CCS deployment in the rest of the Member-States remains roughly unchanged.

Sensitivity analysis regarding the impact of changes in nuclear policy has also been conducted. More specifically the high nuclear scenario assumes that there will be a cancelling of the phase-out in Germany and Belgium but no new nuclear plants would be allowed. Furthermore, lifetime extension of old nuclear plants is implemented in some Member-States, but nuclear policy in Member-States that did not opt for nuclear power in the Baseline scenario is not altered. The resulting nuclear capacity remains roughly at the present level throughout the projection period, but still 29 GW more compared to the Baseline in 2030 which corresponds to an increase of 239 TWh of nuclear power in 2030 compared to the Baseline. Mandatory CCS for new coal and gas power plants was also assumed, while the carbon price and the marginal value of renewables were kept unchanged compared to Option 2b. The model results show that, as expected, the emissions are lower compared to the standard Option 2b, owing to the upkeep of nuclear power. However, CCS deployment, albeit reduced (down to 61 GW from 68 GW for case 2b), still remains among the major means of emission reduction, partly because the Member-States where the changes in nuclear policies were implemented are not the ones with high potential for CCS deployment.

4. Conclusions

Analysis showed that without CCS the costs of meeting a reduction in the region of 30% GHG in 2030 in the EU could be up to 40% higher than with CCS (60 bn €/year in 2030). Thus not enabling CCS would have substantial negative impacts on Europe's capacity to meet the 2 degrees Celsius target as well as on competitiveness and employment, and would have a slight negative impact on security of supply.

On the understanding that the ETS is implemented to deliver the EU's climate objectives, Option 1 (enabling CCS under the ETS market) internalises positive climate externalities of CCS deployment. With the carbon price resulting from the efforts required to meet the 20% reduction in greenhouse gas emissions by 2020 being around 40 €/ton CO_2 by 2020, CCS becomes a significant part of the energy mix, but not before 2030. Since Option 1 leads to a significant reduction in fossil fuel use, all environmental impacts, other than climate change, associated with fossil fuel use also decline compared to business-as-usual. The net additional cost of Option 2 (making CCS mandatory) compared with Option 1 (around 6 bn €/year in 2030) are partly justified by expected additional non-climate benefits. The additional impact on learning compared to Option 1 may lead to around 10% reduction in the additional resource costs of CCS. It is hard to quantify what difference this would make to technology export potential of EU manufacturers and thus hard to distinguish between Option 2 and Option 1 on macroeconomic grounds. The option whereby CCS is made mandatory for coal and gas has a positive effect on security of supply, but the other options, such as not enforcing mandatory CCS on gas power plants, have a negative impact by increasing the gas use, hence gas imports. Net[10] employment effects are negative: roughly, an increase in employment in the coal and equipment goods industries being offset by negative effects resulting from the increased energy costs.

The impact of mandatory CCS would affect a small number of Member States. For the extreme mandatory scenario (Option 2d above), three-quarters of the CO_2 capture would take place in four Member States (in descending order, Germany, Poland, UK and Belgium) with 35% of the effort in Germany alone.

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[10] Taking into account all direct and indirect effects and also in the context of general economic equilibrium.

The impact analysis of Option 3 (subsidy for post-demonstration CCS) showed that by 2030 a 10% investment subsidy leads to 50% higher deployment (and hence total investment) than would be the case under Option 1, at small resource cost (i.e. a subsidy of 5.5 bn € stimulates 27 bn € additional investment). However, the effects on learning of additional deployment are small and the benefits in terms of cost of meeting the emission reduction targets, as well as in terms of export potential, would be low. The changes implied by Option 3 compared to Option 1, as evaluated in terms of air quality, employment and security of supply, are also rather insignificant.

On this basis, there is little evidence justifying going beyond the carbon market (ETS). Considering mandatory CCS as an additional policy option, the additional learning resulting from the increased deployment does not seem to compensate for the cost of the policy, whereas the impact on other externalities is also not significant. Considering an investment subsidy (beyond R&D subsidy for the demonstration phase) as another policy option, although substantial extra investment would be leveraged, the benefits from positive externalities do not seem to justify the subsidy costs. However if the ETS is kept as the single policy option, it shall be emphasised that there must be sufficient certainty about a stringent cap on total emission allowances imposed on ETS, and its enforcement, on a long term basis, in order to enable CCS technology deployment and investment.

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