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Atmospheric and geological CO_2 damage costs in energy scenarios

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ABSTRACT

Geological carbon dioxide capture and storage (CCS) is currently seriously considered for addressing, in the near term, the problem of climate change. CCS technology is available today and is expected to become an increasingly affordable CO_2 abatement alternative. Whereas the rapidly growing scientific literature on CCS as well as experimental and commercial practice demonstrate the technological and economic feasibility of implementing this clean fossil fuel option on a large scale, relatively little attention has been paid so far to the risks and environmental externalities of geological storage of CO_2. This paper assesses the effects of including CCS damage costs in a long-term energy scenario analysis for Europe. An external cost sensitivity analysis is performed with a bottom-up energy technology model that accounts not only for CCS technologies but also for their external costs. Our main conclusion is that in a business-as-usual scenario (i.e. without climate change intervention or externality internalisation), CCS technologies are likely to be deployed at least to some extent, mainly in the power generation sector, given the economic benefits of opportunities such as enhanced coal bed methane, oil and gas recovery. Under a strict climate (CO_2 emissions) constraint, CCS technologies are deployed massively. With the simultaneous introduction of both CO_2 and CCS taxation in the power sector, designed to internalise the external atmospheric and geological effects of CO_2 emissions and storage, respectively, we find that CCS will only be developed if the climate change damage costs are at least of the order of 100 €/t CO_2 or the CO_2 storage damage costs not more than a few €/t CO_2. When the internalised climate change damage costs are as high as 67 €/t CO_2, the expensive application of CCS to biomass-fuelled power plants (with negative net CO_2 emissions) proves the most effective CCS alternative to reduce CO_2 emissions, rather than CCS applied to fossil-based power plants.

1. Introduction

Today, overwhelming evidence exists that mankind is modifying the Earth's environment and is provoking an increase of the average global atmospheric temperature and the associated detrimental effects of regional and local climate change (IPCC, 2001). In order to minimise the risks induced by climate change (UNFCCC, 1992), carbon dioxide concentrations should be stabilised, preferably during the 21st century and probably at a level not exceeding much more than twice the pre-industrial level (IPCC, 1996). To do so, reducing CO_2 and other anthropogenic greenhouse gas emissions substantially below the levels that would be implied by a "business-as-usual" scenario is imperative. Given current and likely near-

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term future energy consumption increases and corresponding emission evolution patterns, this challenge is large. But the challenge can be met. Whatever specific means may contribute to alleviating the climate change problem, a (partial) decarbonisation of energy use is a necessity. No panacea exists for decreasing the carbon intensity of energy consumption. Hence, the energy system should probably, for the moment at least, stay as diversified as possible with all non-carbon emitting options remaining part of the overall mix. Among these are energy resources such as renewables, nuclear energy and decarbonised fossil fuels. This article examines the decarbonisation of fossil fuels through carbon dioxide capture and storage technology, as well as its interplay with alternatives to address the climate change problem, like renewables and nuclear energy.

The decarbonisation of fossil fuels through geological carbon dioxide capture and storage has the potential to contribute significantly to reducing anthropogenic greenhouse gas emissions (see, for example, Parson and Keith, 1998; UNDP, 2000; IPCC, 2001; IEA, 2004; Anderson and Newell, 2004). Indeed, technologies for both pre- and post-combustion carbon dioxide capture in power stations, as well as pre-combustion capture fuel cell applications, are available and have been demonstrated, notably through their use for a number of other industrial purposes (Hendriks, 1994; Williams, 1998). It has been shown that the implementation of geological CO_2 capture and storage is technically feasible today, and, even while it is difficult to precisely predict the evolution of public opinion under large-scale application, so far it seems that a majority of the public views this technology as an acceptable climate change mitigation option (Herzog et al., 2000). Technologies for carbon dioxide compression and transportation to storage sites, via pipelines or with tankers, are well known in principle. The Earth's geological storage capacity, in (partly) depleted natural gas and oil fields, aquifers and coal seams, is likely to be large (see, e.g. Socolow, 1997). Given that carbon dioxide capture and storage might already in the short-term play an important role in mitigating climate change (Yamashita and Barreto, 2003), energy analysts have started presently to include carbon dioxide capture and storage alternatives in integrated assessment models of climate change (Riahi et al., 2004; McFarland et al., 2002). Still, insufficient attention has so far been paid to the external environmental effects of carbon dioxide capture and storage, especially in energy scenario research. The IPCC (Working Group III), in its Special Report on Carbon Dioxide Capture and Storage, has assembled a comprehensive overview of carbon dioxide storage options, including their detrimental environmental impacts (IPCC, 2005). This IPCC report points out that there is still much to be researched with regard to carbon dioxide storage externalities. Our paper attempts to fill this gap in the current literature.

In Section 2 of this article we list some of the possible risks and environmental externalities of geological carbon dioxide capture and storage (CCS). In Section 3 we quantify the external costs of various environmental impacts of the power sector, and present assumptions on the sensitivity range for CO_2 damage costs resulting from both climate change and CCS. In Section 4 we briefly recall some of the main characteristics of the MARKAL model we use for our analysis, and describe our findings in terms of the effect of including CCS – as well as its possible external costs – in long-term energy and climate change scenarios. Section 5 provides our major conclusions and gives a few recommendations for policy action and further scientific research.

2. Environmental externalities of geological carbon dioxide storage

As natural gas and oil fields have a proven containment integrity record for millions of years, there is good reason to believe that CO_2 can also be stored without noteworthy leakage, at least in these (depleted) fields, for long periods of time, rendering CCS fit for controlling climate change. Whereas the prospective climate benefits of CCS may thus be significant, important questions related more broadly to environmental hazards and safety risks remain for all storage options, even for depleted gas and oil fields (for a taxonomy of the risks involved with geological carbon dioxide storage, see, e.g. Wilson et al., 2003). Our knowledge about the potential negative environmental effects of CCS is still incomplete. Uncertainties associated with the external impacts of CCS abound, and their nature and extent are still insufficiently understood. Without attempting to be exhaustive or trying to assign probabilities, we indicate here some of the potential geological CO_2 storage externalities.

Deep geological carbon dioxide storage, independently of whether in (depleted) gas and oil fields, coal seams or aquifers, can acidify water present at large depths underground (see Riemer et al., 1999, various contributions). If the geological containment layers into which CO_2 is injected are breached, pollution of nearby aquifers containing fresh groundwater may result. This could affect the quality of drinking water, if the latter is obtained from sources fed by the polluted groundwater. A related problem is that the displacement of natural reservoir fluids or gases, as a result of CO_2 injection underground, and the subsequent modification of the hydrodynamic properties of the geological layers concerned, can have a negative impact on the water extraction potential of certain sources. In the case of CO_2 injection in aquifers, the brine they contain could migrate to freshwater aquifers that serve as source for drinking water.

As a result of carbon dioxide storage underground, changes can occur in the structure and thermodynamic properties of geological formations. These geological modifications, as well as the CO_2 injection process, can involve seismic activity or soil cave-ins, with uncertain aboveground impact, depending on site, option and storage medium chosen. Altered chemical properties of underground formations as a consequence of carbon dioxide storage, or the build-up of localised high pressures, can affect the stability of the geological layers above. Resulting from a large range of possible chemical reactions of CO_2 with geological substances and materials, cocktails of gases can be formed, the bearings of which to the underground and aboveground environment, as well as to habitat conditions of plants and animals, are largely unknown today.

Although natural gas has been stored underground over geological time scales, there are scenarios imaginable in which carbon dioxide gradually migrates and slowly leaks from its storage medium (Ha-Duong and Keith, 2003). This threat ranks high among the potential risks of geological CO_2 storage, since it could seriously hamper its suitability as climate change mitigation alternative. Especially for options other than depleted gas and oil fields, such as aquifers and coal beds, long-term storage effectiveness aspects are uncertain. A large number of sites exist where one might have expected to find natural gas but where no such resources proved available. At many places large quantities of natural gas may once have been stored underground, e.g. associated with present-day oil and coal deposits, but that in the distant past escaped to the atmosphere. Hence, especially when the storage formations employed today are geological layers other than depleted oil and gas fields, it may not be guaranteed that the employed underground storage layers retain integrity forever. If this indeed proves the case, migration times may vary according to the storage option considered and depend on the characteristics of the formation of the site specified (NITG, 2005). The leakage time frame that characterises each option, and the compatibility of that time frame with features of the natural carbon cycle, is determinant for the option's suitability to mitigate (preclude or postpone) climate change.

Probabilities for catastrophic well blowouts may be exceedingly small and the associated risks negligible in comparison to those involved with slow carbon seeps, but the eventuality that artificially stored carbon dioxide escapes rapidly, in large amounts at once, may not be left unmentioned. Sudden carbon dioxide releases interfere with climate change mitigation efforts and could involve severe accidents with human casualties. Although the hazards involved are likely to be local and temporary, they could be pervasive. In Cameroon in 1986, carbon dioxide produced naturally from volcanic activity welled up from deep in Lake Nyos, and was responsible for killing, by asphyxiation, 1700 people and their livestock (Holloway, 2000). This concerned a very unique and unfortunate case, different in many ways from CO_2 artificially stored underground, but it shows that one has to be wary of accidental releases of CO_2. Such releases should also be considered in high-pressure CO_2 transportation, which would become part of the overall CCS solution. CO_2 pipelines exist already and their safety record is high, but risks for personal accidents as a result of pipeline defaults are not zero.

3. Damage costs of atmospheric and geological CO_2

To evaluate the damage costs resulting from the emissions of a pollutant, one can carry out an ''impact pathway analysis'', tracing the passage of the pollutant from the place where it is deposited or emitted to the affected population. The principal steps of such an analysis involve (1) a specification of the amounts of pollutant disposed or emitted, (2) a calculation of the dispersion of the pollutant, (3) a calculation of the impact of the pollutant and (4) the monetary valuation of the costs of these impacts. For any power production option, the impacts and costs must be summed over all pollutants, impact types and receptors of concern to obtain the total damage costs associated with that technology. For fossil-fuelled electricity generation, the main pollutants involved are SO_2, NO_x, PM_{10} and CO_2 (others, such as VOC and CO, are relatively low, and will not be considered in this study). For fossil-based power plants including CCS technology, the total damage costs inflicted include, in addition to those related to SO_2, NO_x and PM_{10} emissions, CO_2 storage damage costs, downstream from the power generation process, as a result of the environmental externalities related to geological carbon dioxide storage. And even in this case, climate change damage costs are not entirely absent, as there are thermodynamic, technical, economic and environmental (life-cycle emissions-related) limitations to the capture level that can be reached, as a result of which capture technology is unlikely to ever become 100% efficient (but rather, e.g. 90%): a share of the CO_2 remains thus un-captured and is emitted into the atmosphere.

For most pollutants and energy resources, impact pathway analyses of environmental damages have been performed in the ExternE (External costs of Energy) Project series of the European Commission (see, e.g. ExternE, 1998). The ExternE studies have so far not included calculations on externalities resulting from geological carbon dioxide storage. The scientific knowledge required for calculations and quantifications of the externalities of underground storage of CO_2, e.g. related to the migration of carbon-induced products through geological formations, is still largely absent. Without data on geological and chemical diffusion processes, these calculations cannot be performed. If these data were available today, the effort to perform such detailed calculations would be large (and would fall beyond the more limited scope of this paper).

Still, it is useful for policy making to perform energy scenario analyses that include not only CCS technologies, but also estimates for the external costs that could be associated with them. Lacking either theoretical or experimental data regarding CCS external impacts, we chose to make hypothetical assumptions concerning the corresponding damage costs in an earlier paper (Smekens and van der Zwaan, 2004). Contrary to that study, in this article we avoid making 'guesstimates', but rather make assumptions about the ranges in which these damage costs could possibly lie. We use these ranges of external costs of carbon dioxide capture and storage technologies to investigate how sensitive energy scenario analysis is to assumptions on CCS damage costs. We thereby hope to get a better sense of the consequences of external costs internalisation for energy-climate modelling, as well as of the corresponding policy implications.

In principle, we rely on the numbers generated by Rabl and Spadaro (1999), based on ExternE (1998), for the externalities and corresponding damage costs resulting from the use of fossil fuels for power production. These studies show that the damage costs associated with the use of renewables and nuclear energy are 1–2 orders of magnitude smaller than those of fossil-fuelled electricity generation. They are therefore neglected in our analysis. Whereas nuclear power is already available at a sizeable commercial scale (some 17% of global electricity production being generated by nuclear power plants), scale-related issues in this context remain for renewables. The baseline ExternE assumption is that damages are linearly correlated to the installed capacity of the power production option considered. A controversial matter and ongoing subject of investigation are the limitations of this

Table 1 – Applied damage costs for (fossil-fuelled) power plant emissions in the EU

Emission type	Damage costs (€/t)
SO_2	11000
NO_x	16000
PM_{10}	15000
CO_2 (climate change)	1.4–14–67
CO_2 (geological storage)	0.3–30–300

Sources: ExternE (1998), Tol (2005) and authors' assumptions for geological CO_2 storage.

linearity assumption. Energy and environmental specialists correctly point out that, when, e.g. renewables are going to be utilised on a large scale, previously hidden effects may become evident and known impacts prove non-linear.[1] While on the one hand, clearly recognising the validity of this observation, on the other hand, we encounter the difficulty to practically incorporate it in our modelling framework, given the large number of unknowns involved. Because the difference in external costs between fossil and non-fossil power production at present probably constitutes 1–2 orders of magnitude, however, we think we can for the moment at least safely neglect these hidden and non-linear effects. Only further externality investigation and renewables implementation can demonstrate the extent to which this assumption is true.

The Rabl and Spadaro (1999) figures for SO_2, NO_x and PM_{10} damage costs are quoted in Table 1, expressed in € per tonne of pollutant emitted.[2] They calculate the climate change damage costs as a result of CO_2 emissions to be approximately 30 €/t CO_2, and estimate that the uncertainty in this figure is (readily) a factor of 3. This explains why we initially, in an earlier version of this analysis, employed a sensitivity range of 10–100 €/t CO_2 (with 30 €/t CO_2 as central value). The ExternE (1998) study behind the Rabl and Spadaro (1999) publication generated outcomes that were outliers in the late 1990s. Today, some authors consider the ExternE (1998) results outdated. For example, Tol (2005) provides an up-to-date review of much of the CO_2 emissions damage cost literature, and finds climate damage cost numbers that are smaller than the ExternE (1998) ones.[3] In the current version of our paper we have therefore corrected for these newer data, by using for the damage costs the values of the mode, mean and 95% level of the composite probability density function of the marginal costs of carbon dioxide with quality weights including peer-reviewed studies only. These figures (see Table 1) are 5.0, 50 and 245 €/tC, that is, 1.4, 14 and 67 €/t CO_2, respectively.

Since much less is known about the environmental impacts of CO_2 storage underground, we assume a much larger sensitivity range for their damage costs (resulting from, e.g. CO_2 dissipation, sudden releases of CO_2, acidification of underground water, and the chemo-physical modification of geological formations): 0.3–300 €/t CO_2 (with 30 €/t CO_2 as central value), as indicated in Table 1. This range is also purposefully high because to our knowledge no attempts to quantify damage costs for geological carbon dioxide storage have so far been made. CCS technology has in any case not yet been included in the ExternE study. In this context, we thought it best to assume an uncertainty range as wide as reasonably possible. We have hypothesised a storage damage cost uncertainty range larger than that for climate damage costs. The reason is that many studies have been performed quoting climate damage costs, and thus more is known about these costs in comparison to those associated with CCS application. Our personal estimate is that storage damage costs will prove smaller than those resulting from climate change. If they are not, this may constitute a reason not to further proceed with CCS implementation. By choosing a storage damage cost uncertainty range that is larger than that for climate damages, we have chosen a bandwidth broad enough to cover all possible 'true' damage costs.

In our scenario analysis, for the non-carbon damage costs we assume fixed values, since these numbers are known with smaller uncertainties, and because our analysis focuses on the problem of climate change (rather than air pollution), and thus the external impacts (both provoked by atmospheric emissions and by geological storage) of CO_2. With the ranges in CO_2 damage cost values we perform a sensitivity analysis, and analyse the effect of a corresponding damage cost variation on our scenario results. Note that damage costs are, of course, intrinsically time-dependent (e.g. as a result of the disputable claim that CO_2 storage costs were virtually zero a century ago). In this paper, however, we make the stylistic assumption that the changes that occur over time for both climate- and storage-related damage costs fall within the uncertainty range of these costs as given in Table 1, so that we may postulate their time-independence.

In an earlier preparatory study (Smekens and van der Zwaan, 2004), we internalised external costs through an inclusion of damage costs expressed in cents/kWh of electricity produced. For a number of reasons, however, this is retrospectively not the best approach. First, the ExternE Project (1998) calculates and reports damage costs associated with the discharge of specific pollutants, rather than the damage costs per unit of electricity generated (although the latter can in principle be calculated on the basis of the former). By using damage costs associated with the discharge of specific pollutants one sticks closer to the original ExternE literature data. Second, markets with external costs from environmental pollution can be made economically efficient by setting appropriate discharge levels for the corresponding pollutants, or, alternatively, by imposing effluent charges (in $ or €/t of pollutant produced; see Maler, 1974). One of the right ways to implement this principle in our model is to "correct" emissions with effluent charges (e.g. by taxation/t of pollution generated). In this paper, we have done so and improved our analysis with respect to our 2004 study, by using damage costs (expressed in €/t) applied directly to the emissions of each pollutant.

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[1] See, for example, Bruggink and van der Zwaan (2002). Examples are the land-use and food-production consequences of large-scale biomass production for the satisfaction of mankind's energy requirements, and the environmental impacts of the pervasive use of wind power (including weather-related ones).

[2] In this paper, tonnes refer to metric tonnes and are indicated by t.

[3] Tol's analysis gathered 103 estimates of the marginal damage costs of carbon dioxide emissions, from 28 published studies, and combined them to form a probability density function.

4. Long-term energy scenarios

If the energy system will be subjected to stringent climate constraints, fossil-fuel-based power generation will in principle be put into disadvantage. When ambitious climate change goals are to be met, the role of fossil fuels in our energy mix should normally be significantly reduced. However, with much of CO_2 emissions being susceptible for carbon dioxide capture and storage technology application, notably in the power sector (the main focus of this study), this picture could dramatically change: fossil fuels can technically continue to play the important role they do today. The costs of CCS application, and the resulting competitive economic position of CCS-integrated fossil-fuelled power plants with respect to, e.g. renewables and nuclear energy, will be important in determining to what extent fossil fuels will actually be able to continue to play their predominant role in current electricity infrastructures under climate change intervention. If external costs of electricity production are internalised in the future, then the size of the damage costs of all power production alternatives will also contribute to determining their affordability and relative competitive position. For fossil-fuelled power plants with CCS technology application, damage costs include those related to the environmental impacts of geological carbon dioxide storage. We use the MARKAL model to analyse what the future role of fossil fuels may be in long-term power supply scenarios when CCS technology and their damage costs are accounted for.

4.1. *The MARKAL model*

We recall some of the main features of the MARKAL version employed for our analysis, but refer to previous publications for a more complete model description (see, e.g. Smekens, 2004; Smekens and van der Zwaan, 2004). MARKAL is a commonly used linear-programming bottom-up model for energy systems analysis. The model algorithm has been expanded over the years, resulting today in a number of possible extensions that can be employed in conjunction with the basic version, of which the main characteristics remain. It is an ideal-market cost-minimisation decision model with rational behaviour, perfect information and perfect foresight, which optimises and matches the supply and demand sides of energy for the modelling time frame under consideration (1990–2100 for this study). The modelling horizon is divided in steps of 10 years each; the programme solves these steps simultaneously. The database linked to MARKAL contains about 70 demand categories at the end-use-side, and more than 900 energy technologies at the supply-side. The version often used for policy studies, like for this analysis, includes endogenous technological learning and price elasticities for end-use demands. The geographical coverage studied is Western Europe (WEU), including the 15 EU countries (in 2003), expanded with Norway, Switzerland and Iceland. This area is treated as a single region, without country dis-aggregation.

Although MARKAL may cover other greenhouse gases than CO_2, this study has been restricted to CO_2 only, as carbon dioxide accounts presently for about 80% of all greenhouse gas emissions in Western Europe. Considered are CO_2 emissions from fuel combustion for power production and transport, as well as from industrial processes. CO_2 emission removal is accounted for through various geological carbon dioxide storage options, while the model also includes a highly stylised module that rudimentarily reflects carbon circulating in the biosphere via CO_2 uptake by land use, agriculture and forestry. The model distinguishes six geological CO_2 storage options: aquifers, enhanced oil recovery (EOR), enhanced coal bed methane (ECBM) recovery (two different options, at different depths) and depleted oil and gas fields (two options: on-shore and off-shore). They are all characterised by specific data on storage potential, injection and storage costs, and the rate of energy recovery (for EOR and ECBM). Costs related to transportation, from the site where CO_2 is captured and compressed to the injection point, are also included. For the capture of CO_2 from large point-sources, in total 21 technologies are modelled: 10 in the electricity sector (coal, oil, natural gas and biomass-based), 6 in industry (mainly in ammonia, iron and steel production) and 5 in the fuel conversion sector (in the production of, e.g. hydrogen from fossil fuels). No CCS options à la Sleipner are included, in which CO_2 is captured from natural gas field exploitation and subsequently re-entered in geological formations (in, e.g. aquifers, as in the Sleipner case, under the seabed).

Cost reductions of technological options are assumed to evolve through learning curves. This implies that the unit investment cost of a particular technology, or a particular technology component (such as a gas turbine or gasifier), decreases with increasing cumulative installed capacity. Learning curves are based on observed phenomena in the past, and applied in our MARKAL version to future technological cost developments. With our use of learning curves, a fixed ratio (the progress ratio) exists between investment cost reductions and every doubling of cumulative installed capacity. For relatively mature technologies, progress ratios typically are assumed to lie between values of 0.90 and 0.95, meaning a cost reduction of 10 and 5%, respectively, per doubling of installed capacity. Promising new technologies may have progress ratios as low as 0.70. In our model, most learning technologies or components are found in the electricity production sector, while some appear in other sectors such as transport, and upstream oil and gas industries. For both the capture and storage parts of CCS technology – the main focus of this paper – we assume a progress ratio of 0.90, as justified by recent analysis of historic trends in clean coal technology deployment (Rubin et al., 2004).

In traditional MARKAL models, changes in prices do not affect demand, that is, demand is exogeneously defined. In recent years, the MARKAL algorithms have been extended to include price-dependent demand levels. Two approaches have been developed: MARKAL-MACRO (see Hamilton et al., 1992) and MARKAL-Elastic-Demand (MARKAL-ED, see Loulou and Lavigne, 1996). We use the latter, mostly because of the differences that exist between the two in computer calculation time. Both MARKAL-MACRO and MARKAL-ED are attempts to bridge the worlds of bottom-up versus top-down modelling. MARKAL-ED is a partial equilibrium model in which the common exogenously defined demand relations have been replaced by price-driven demand functions. Energy demand decreases as a result of increasing energy service prices. A main

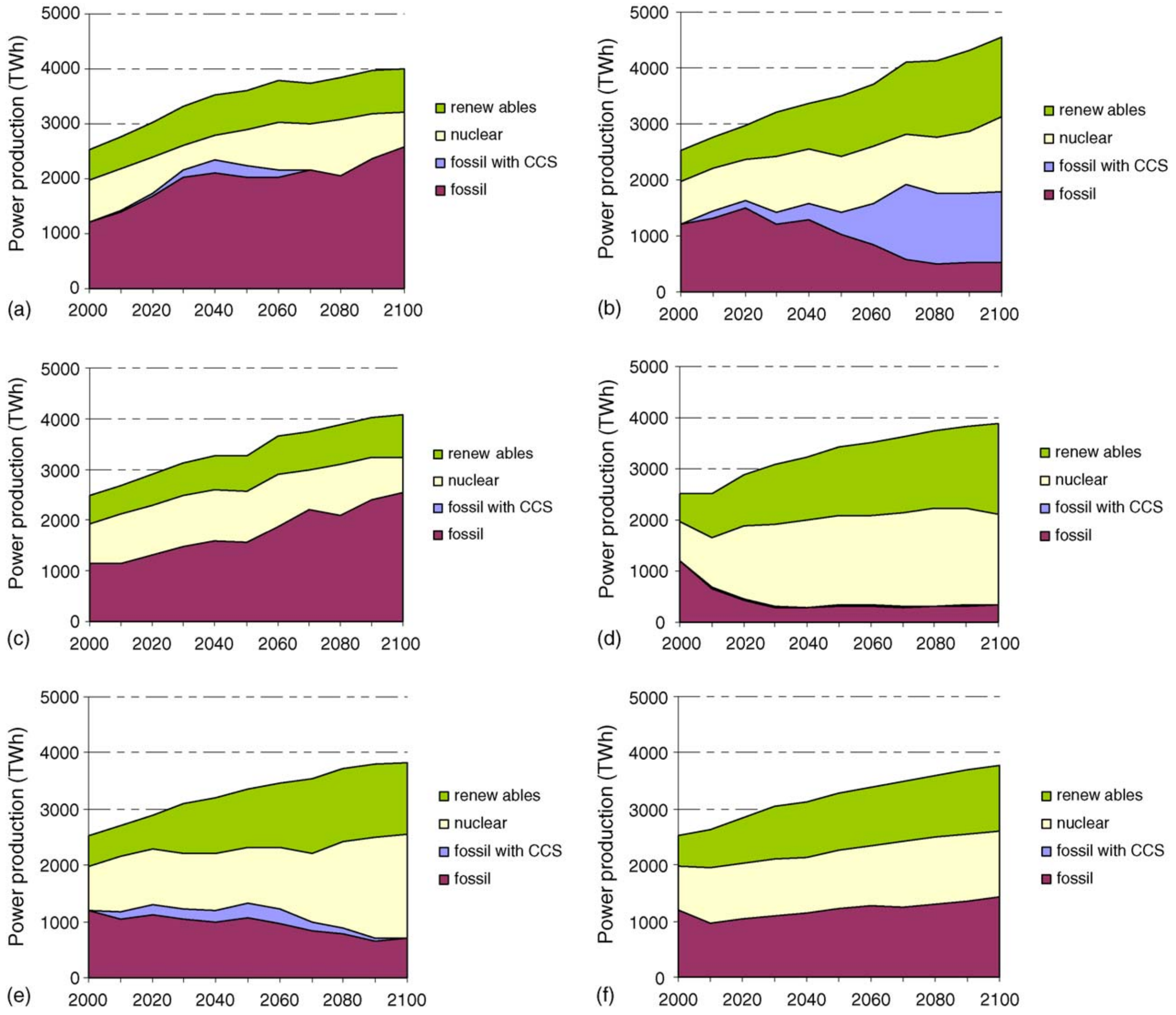

Fig. 1 – Annual electricity generation (in T Wh) from renewables, nuclear, fossil fuels with CCS and fossil fuels without CCS. Scenario (a) is the base case without climate constraint; in scenario (b) a climate constraint of 550 ppmv CO_2 concentration is imposed; scenario (c) is the base case with 1.4 €/t CO_2 climate change damage cost; scenario (d) the base case with 67 €/t CO_2 climate change damage cost; scenario (e) the base case with 0.3 €/t CO_2 CCS damage cost; and scenario (f) the base case with 300 €/t CO_2 CCS damage cost.

advantage of this model is that it is still based on linear equations, allowing relatively rapid computer simulations. With non-linear demand equations, it would currently not be possible to run MARKAL-like models for the WEU and the large number of technologies assumed. In practice, non-linear (top-down) models can today only be solved with a limited number of available technologies and regions, thereby rendering them less realistic than bottom-up models from a technology point of view.

We use MARKAL to calculate a number of different policy scenarios. First, in the base case (business-as-usual, BAU) scenario, no climate change intervention is assumed, so that both energy use and CO_2 emissions continue to rise over the 21st century. Second, in a stringent policy scenario a climate change control instrument is introduced, in the form of the imposition of an atmospheric carbon concentration ceiling. Climate stabilisation, at a level of 550 ppmv CO_2 concentration, is achieved by the implementation of an emission constraint corresponding to the cumulative emissions allowed for Western Europe in the (1990–2100) 550 ppmv SRES scenario (Nakicenovic et al., 2000). Third, in four additional scenarios climate change control is accomplished through taxation that internalises the external costs of carbon dioxide. These scenarios superimpose atmospheric and geological CO_2 damage costs onto the base case scenario.

4.2. *Results*

Fig. 1(a), depicting the annual European electricity generation from four different sources, shows that in the base-case scenario around the middle of the century, during several decades, some CCS is applied, while non-CO_2-abated fossil fuel use is expanded more than 2-fold.[4] When a strict climate

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[4] It is assumed that, during the 21st century, transportation will not become an electricity-based sector.

constraint is applied, non-carbon energy resources need to be massively deployed, as depicted in Fig. 1(b) for a 550 ppmv atmospheric carbon dioxide concentration limit. In addition to an expansion of renewables and nuclear energy, CCS is deployed on a large scale in order to achieve the required CO_2 emission reductions.

Suppose that, instead of imposing a strictly binding constraint on cumulative CO_2 emissions (in the form of, e.g. a 550 ppmv atmospheric CO_2 concentration), one addresses environmental problems through an internalisation of external costs. The resulting scenarios are shown in Fig. 1(c–f), in which damage costs as a result of SO_2, NO_x, PM_{10} and CO_2 production (the latter both through its impact when emitted into the atmosphere and via its externalities when geologically stored underground) are imposed on the base case scenario. The four graphs represent a sensitivity analysis for varying values of the two kinds of CO_2 damage costs (while the SO_2, NO_x and PM_{10} damage costs are held constant): in (c) a 1.4 €/t CO_2 climate change damage cost is assumed; in (d) a 67 €/t CO_2 climate change damage cost is accounted for; scenario (e) involves a CCS damage cost of 0.3 €/t CO_2; and scenario (f) is the base case with a 300 €/t CO_2 CCS damage cost included.

From Fig. 1(c–f) a couple of observations can be made, the first one being that the inclusion of external costs significantly changes energy scenarios based on cost minimisation. Accounting for climate damage costs precludes the massive expansion of the use of fossil fuels during the 21st century, except when these costs are very low (as in scenario c). If the climate damage costs are high (as in scenario d), its use must be substantially reduced. In scenarios (e and f) the use of fossil fuels slightly decreases, respectively, increases. In all four scenarios, except scenario (c), the generation of electricity through the use of renewable resources and nuclear energy is greatly increased. As opposed to the climate-constrained scenario (b), however, the internalisation of damage costs does not automatically result in the large-scale application of CCS technologies to fossil-based electricity generation. A difference between scenario (b) and the four externality scenarios is that the CO_2 concentration limit allows flexibility as to when and how emission reductions can optimally take place, while the inclusion of external costs in the latter four scenarios (from a modelling point of view, similar to the imposition of a tax) implies a tight constraint as of the first simulation period (that takes away a degree of freedom). One of the consequences is that the 67 €/t CO_2 climate change constraint in scenario (d) is more binding than the 550 ppmv constraint in scenario (b). Whereas in scenario (b) the application of CCS technology to fossil fuel use is optimal to gradually reduce CO_2 emissions, in scenario (d) more radical emission reduction is imposed. Since the application of CCS to biomass can involve net negative emissions, this option proves in scenario (d) the most effective (but not the cheapest) way to respond to the tight carbon emission constraint as a result of climate change internalisation, rather than the application of CCS to fossil fuel use. The application of CCS to biomass is accounted for under renewables in the scenario plots (while it is explicitly visualised in Fig. 3).

The scenarios of Fig. 1(c and d), calculated with a central value of the CCS external costs of 30 €/t CO_2, show the effect of lowering the climate change external costs to 1.4 €/t CO_2 and increasing it to 67 €/t CO_2, respectively. Evidently, the high climate costs in the latter case imply a near phase-out of fossil-based energy consumption, while the very modest climate costs in the former imply that its use may be significantly expanded over the century with respect to current production levels. Apparently, in both cases CCS damage costs are sufficiently high so as to preclude an implementation of CCS technologies as applied to fossil-fuelled power plants. In scenario (d), power plants using fossil fuels are negatively affected as a result of accounting for climate damage costs, irrespective of whether CCS technology (which is never 100% efficient in capturing all CO_2 emissions) is applied or not. Of course, in our MARKAL cost-minimisation setting, results like these, as well as the other findings reported in this article, are highly dependent on the assumptions made regarding the (uncertain) present and future costs of both technologies and externalities, in this case notably with respect to the fossil-based electricity production costs, the CCS application costs, and the damage costs of climate change and carbon dioxide storage. But it is important to bear in mind, regarding all our modelling results, that the assumed (internal and external) costs of all other non-fossil technologies greatly matter too.

Fig. 1(e and f) depict scenarios that assume as central value of the climate change external costs a level of 14 €/t CO_2. They show the effect of lowering the CCS external costs to 0.3 €/t CO_2 and increasing it to 300 €/t CO_2. Absolute fossil energy does not alter very much, in both cases, given the central value of the climate change costs incurred. CCS technologies, as applied to both fossil-based and biomass-based power plants, are given even less chance to develop in scenario (f), in comparison to scenario (d). The reason is that CCS damage costs are 300 €/t CO_2 in scenario (f), and thus higher than the CCS damages in scenario (d), while the climate change costs in the former are lower than in the latter. If, however, CCS external cost are lowered to 0.3 €/t CO_2 (as in scenario e), then it becomes sufficiently interesting to deploy CCS (as applied to mostly fossil-fuelled power plants, and with coal seams as storage medium) during the 21st century. Around 2100, it proves that CCS as applied to fossil-based power plants loses its interest, as by that time renewables and nuclear energy have become cheap enough to constitute more interesting carbon abatement options from an overall cost point of view. It also proves to then become most cost-efficient to apply CCS to biomass power plants. Naturally, our assumptions regarding the learning rates of different energy technologies lie at the basis of these results: it is expected that, e.g. renewables possess a higher learning potential (of 20–30%) than their fossil- and CCS-based counterparts (not more than 10%).

Fig. 2 depicts the CO_2 emissions of the electricity sector as well as the total amount of CO_2 emissions, in the six scenarios (a–f) of Fig. 1. From the left graph, one sees that whereas emissions from electricity generation gradually increase over time in the base case and scenario (c), in the other climate-constrained scenarios (either with a carbon concentration constraint or through the internalisation of damage costs) they are significantly lower in 2100 than they are today. Of course, with higher climate change costs the incentive to reduce emissions is higher than with lower costs, and with high damage costs as a result of CCS it becomes less attractive to realise emission reductions than when these costs are low.

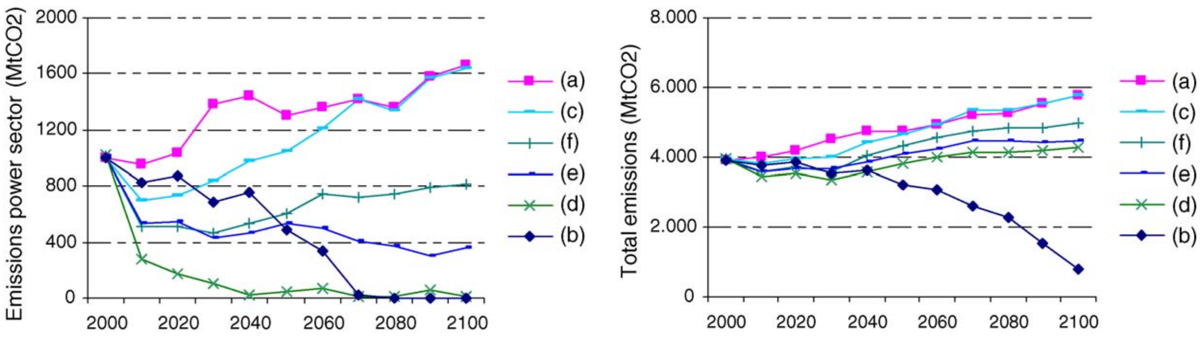

Fig. 2 – Annual emissions of CO_2 from the electricity sector (left) and total annual emissions of CO_2 (right) (in Mt CO_2), until 2100, in the six scenarios (a–f).

The changes that occur in the power sector are the origin of the lower level of total emissions of CO_2 in three of the four externality-scenarios, in comparison to the BAU scenario (see right graph). As sectors other than the power sector are not subjected to the inclusion of externality costs, the reduction of total CO_2 emissions in 2100 does not exceed the 25% level, irrespective of the level of internalised damage costs. In the 550 ppmv CO_2 concentration constraint case, on the other hand, all sectors are affected – not just the electricity sector but also transport and industry – so that the emission reductions achieved in this scenario are much more substantial during the 2nd half of the century.

No carbon dioxide capture is realised when the damage costs from climate change are assumed to be low or when the externalities involved with CCS are expected to be high (scenarios (c and f), respectively, in Fig. 1, confirmed this for the power sector; this conclusion, it appears, may be extrapolated to industry and hydrogen production). Fig. 3 shows in what sectors CO_2 is captured in the other four scenarios, and what options are used to store this CO_2 away from the atmosphere. In the base case, CO_2 is captured in the H_2 production, industry and power generation sectors. In the power sector, only fossil fuels are subjected to CCS, as combining biomass with CCS is too expensive. All CO_2 captured is used for methane gas recovery through ECBM, given (I) that in Europe it may become among the cheapest ways to store CO_2 underground. As said, in our model runs it is assumed (II) that the economic value of natural gas is high and that ECBM methane is particularly competitive with foreign gas, e.g. as imported from Russia. These two assumptions lead to the predominance of ECBM CO_2 storage in our model. We recognise, however, that in practice North Sea EOR might turn out the option through which CO_2 storage will first take off (Stephens and van der Zwaan, 2005). The reasons for this are at least 3-fold: (1) the oil recovered through EOR processes may prove more competitive than the gas recovered through ECBM, (2) EOR in the North Sea may postpone the expensive decommissioning of offshore oil platforms and (3) the porosity of European geological coal seams may prove insufficient for large-scale CO_2 storage.[5] Given that it is too early to predict with certainty which of the two options, ECBM or EOR, will first take the lead in Europe (that is, if CCS will be deployed on a large scale), for this study we stick to our pick of ECBM.

Another issue that may be questioned in this ECBM context is whether global coal resources suffice to allow for enough CO_2 storage. Related hereto is the argument that CO_2 storage in deep coal may render the seams unfit (polluted) for future exploitation, at least not without the release of coal-embedded CO_2. When ECBM coal formations are exploited at a distant point in time, CO_2 release may constitute an environmental catch for future generations, and the corresponding costs incurred should in principle be included in cost-minimisation CCS analysis. Global coal resources, however, amount to at least 6000 Gt. Even if the current global annual coal consumption of about 3.5 Gt is multiplied, this still corresponds to many centuries of coal availability. We think it is therefore likely that, for a long time to come, there will be large numbers of deposits for which coal exploitation remains uneconomical, predominantly because their depths require excessively expensive production technologies.[6] In Europe, coal deposits abound whose exploitation cannot compete, until far in the future, with high-caloric imported coal (from, e.g. Australia or the US), or that for environmental reasons (e.g. sulphur or ash content) are not worth mining. Hence, we think it is safe to make the assumption that – at least during the 21st century, to which our modelling framework applies – global and European coal resource availability is so large that concerns regarding a possible limitation of ECBM potential or undue pollution of existing coal reserves (including the costs this may represent for future generations) are unjustified, in any case in our modelling setting.

When a 550 ppmv climate constraint is imposed, all sectors are subjected to carbon dioxide capture, but the fossil-fuelled electricity sector remains by far the largest opportunity for CO_2 capture application. Since the quantities of CO_2 captured are so large in this scenario (b), ECBM does not suffice to store all of it underground. Gradually also EOR, aquifers and depleted oil and gas fields are phased in (sequentially in this order, on the basis of their assumed costs and potentials, as well as

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[5] At the RECOPOL site in Poland, tests are currently performed notably with respect to porosity aspects.

[6] Typically, coal beds worldwide that are expected to remain ‘economically unminable’ for a long time in the future, if not forever, amount to some 3000 Gt. For related figures and arguments, see also van der Zwaan (2005).

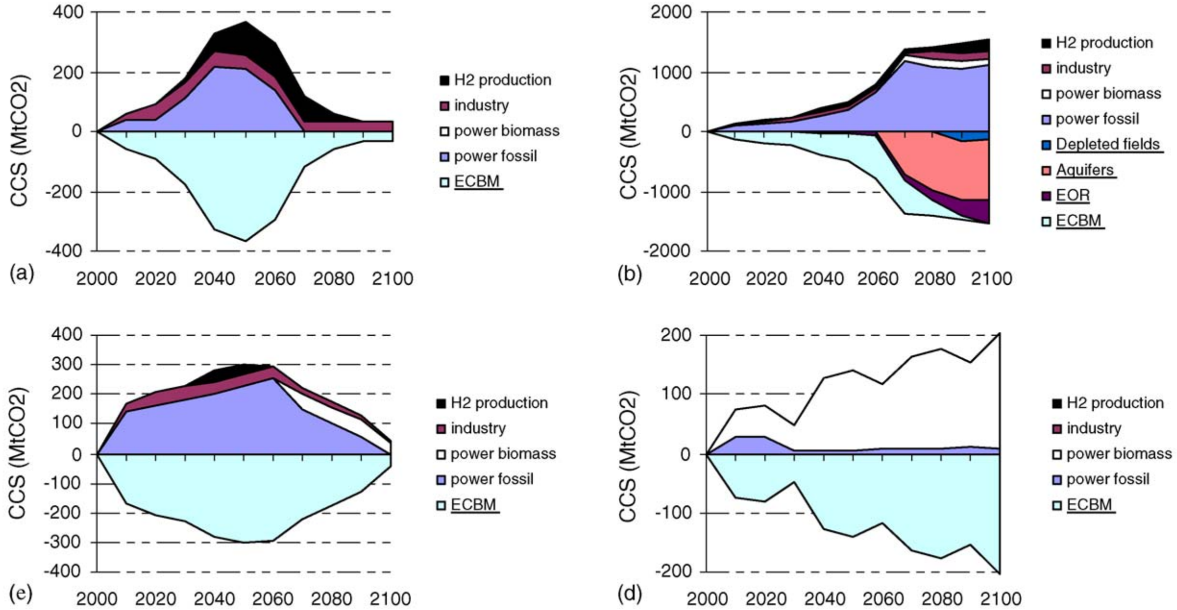

Fig. 3 – Annual amounts of CO_2 captured and stored (in Mt CO_2) per capture sector and per storage option, during the 21st century, in scenarios (a, b, e and d). The amount of CO_2 captured in different sectors is presented above the 0-line, while the alternatives used for carbon dioxide storage are depicted below the 0-line (the different storage options are underlined). Logically, these figures are symmetric in the x-axis (0-line).

co-benefits in terms of the additional gas or oil produced). Since the emission reductions that need to be achieved in externality scenario (d) are so immediate, we see that CCS applied to biomass power production fulfils the lion's share of the carbon dioxide capture technology implemented, and plays a role already from the very beginning of our simulation period (in the 550 ppmv scenario this relatively expensive but effective option is applied only at a late stage, given the available degree of freedom in terms of how and when the emission reductions can be realised, while in externality scenario (e) this option only appears during the last decades before our simulation horizon).

As said, in the scenario with high climate change external costs (d), we observe that CCS in the biomass-based power sector is by far the largest source of CO_2 capture. The explanation is that biomass CCS is by far the most effective way to store CO_2 away from the atmosphere, since it can generate negative CO_2 emissions. Since in scenario (e) the climate damage costs are much less than in (d), and CCS damage costs are very low, significantly less need for large-scale biomass CCS exists. In scenario (e) carbon dioxide capture applied to fossil-based power plants proves the predominant CCS implementation opportunity. Given our results in terms of the overall amount of CCS realised, in scenario (d) it proves that employing renewables and nuclear energy constitutes a more cost-effective way to achieve CO_2 emission reductions than through CCS applied to fossil-based power generation (whereas fossil-based CCS is applied, on a fairly significant scale, in scenario (e)). In both scenarios (d) and (e) it is not necessary to use options of CO_2 storage other than ECBM, given the limited quantities of CO_2 involved, the affordability of this CO_2 storage option, and the economically competitive value of the methane produced.

5. Conclusions

We have seen that when no climate policy is introduced, fossil fuel use in Europe, in its current non-CO_2-abated form, is most likely to increase considerably. We hereby confirm an observation that many have made already, for not only the EU but for the world at large, that without climate change policies fossil fuels will continue to dominate energy production throughout the 21st century. Still, however, even in a world without climate intervention, where thus fossil fuels will provide the majority of mankind's energy needs, it is expected that CCS technologies will increasingly play a role in power generation, hydrogen production and industry. In Europe, the first main drivers are expected to be the application of ECBM and/or EOR, through which natural gas and oil are recovered by CO_2 injection in deep geological coal seams and oil fields, respectively. In other parts of the world, similar early opportunities for CCS can be realised, even without climate change intervention, given the economic benefits that such options may have.

When serious climate policy is introduced, the use of non-carbon energy resources will need to be expanded considerably. We find that renewables (including hydropower) and nuclear energy are among the carbon-free options whose deployment will be increased significantly, irrespective of the precise nature of the climate policy implemented, and that the expansion of fossil fuel usage will have to be halted drastically. If the climate policy introduced is an emissions ceiling in terms of an atmospheric carbon dioxide concentration limit (of 550 ppmv in our case), we see that CCS will be applied massively. While fossil-based power generation will be the main sector of application, also biomass electricity production, H_2 production and other industrial sectors will be subjected to CCS. In Europe, coal seams will then not suffice to store all the amounts of CO_2 captured, so that other storage options like (semi-) depleted oil and gas fields, and aquifers will be used as well. Ocean storage could in principle become an alternative too, but this option is not considered in this study as geological options are currently viewed as being earlier ready and more acceptable for practical implementation. If the climate policy introduced is CO_2 taxation, in order to internalise the external costs of CO_2 emissions, we find that CCS will only be developed if the climate change damage provoked is expected to be high (in the order of 100 €/t CO_2) or the damages that may result from geological carbon dioxide storage sufficiently low (typically only a few €/t CO_2).

Even if CCS proves one of the optimal options to achieve CO_2 emission reductions, the internalisation of damage costs does not automatically result in the large-scale application of CCS technologies to fossil-based power plants: CCS application to biomass electricity plants constitutes another of the options available. Accounting for 67 €/t CO_2 climate change damage costs (and CCS damage costs of 30 €/t CO_2) in the power sector results in such a binding and immediate climate constraint, that the most radical emission reduction option is called for. Since the (costly) application of CCS to biomass-fuelled power plants involves negative overall emissions, this option proves the most effective way to respond to such a tight carbon dioxide emission constraint. When CCS damage costs of only 0.3 €/t CO_2 are internalised along with 14 €/t CO_2 climate change damage costs, the climate constraint is sufficiently loose so as to let the application of CCS to fossil-based power plants be the optimal option to abate emissions through CCS during most of the 21st century, like in the case when climate policy is realised through the imposition of a 550 ppmv CO_2 concentration constraint. Of course, controlling climate change will come at a cost. We find that marginal electricity costs of about 1.0–2.0 €cents/kWh today will be increased to levels of 4.5–6.5 €cents/kWh during the 2nd half of the century.

We conclude that climate policy implemented through either the setting of an emissions ceiling (in the form of a long-term atmospheric CO_2 concentration target) or through the internalisation of damage costs (by the levying of environmental taxes on emissions) is in both cases capable of achieving emission levels in the power sector that are much lower in 2100 than they are today. We hereby provide justification for the EU strategy to promote damage cost internalisation with the purpose of limiting, e.g. climate change. Naturally, with higher expected climate change damage costs the incentive to reduce emissions becomes higher than with lower climate costs, and with high damage costs as a result of CCS, it becomes less attractive to realise emission reductions with this technology than when these costs are low. With our model we have confirmed the observation that with carbon abatement policies in which all sectors are penalised for CO_2 emissions, more radical emission reductions can be achieved than when policies only limit carbon dioxide emissions from certain sectors, such as the power sector. If in Europe only the power sector is subjected to CO_2 emission reductions, ECBM is in principle expected to be a sufficient option to store all CO_2 away from the atmosphere during the entire 21st century. When all sectors are subjected to CO_2 abatement, alternatives are needed such as EOR, depleted oil and gas fields and aquifers (likely in this sequence, on the basis of cost and potential arguments).

One of our main conclusions is that the application of CCS technologies may significantly prolong the consumption of fossil fuels and delay a decrease of their use under climate control policies. We thus confirm what other sources in the literature have recently reported too, regarding all fossil fuels and carbon-intensive coal in particular (see Anderson and Newell, 2004; McFarland et al., 2002; Riahi et al., 2004; Smekens, 2004; Smekens and van der Zwaan, 2004; Yamashita and Barreto, 2003). New in our analysis is that we have not only included CCS technologies in a bottom-up energy-environment model, but have also accounted for their possible externalities, because geological carbon dioxide storage may have substantial external impacts, in terms of both environmental damage and health risks. It proves that accounting for the environmental effects of carbon dioxide capture and storage may significantly influence the nature of future world energy supply scenarios. We thus recommend that extensive studies are performed to further analyse these effects, as well as to better quantify them, before CCS is deployed at a large scale. The site-dependence of CCS external impacts is likely to be high, given the large geological differences that exist between the many kinds of possible storage mediums. The proper way to proceed would perhaps be to determine more precisely the damage costs of geological CCS through a complete impact pathway analysis along the lines done for other energy resources and technologies in the EU externalities project (ExternE, 1998). Still, the specific assumptions on internal and external costs of all energy technologies, in a cost-minimisation framework as that of MARKAL, remain determinant for the nature of the modelling results and corresponding recommendations for policy makers.

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