Environ Model Assess
DOI 10.1007/s10666-007-9125-3

CO_2 Capture and Storage with Leakage in an Energy-Climate Model

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Received: 17 September 2006 / Accepted: 29 August 2007

Abstract Geological CO_2 capture and storage (CCS) is among the main near-term contenders for addressing the problem of global climate change. Even in a baseline scenario, with no comprehensive international climate policy, a moderate level of CCS technology is expected to be deployed, given the economic benefits associated with enhanced oil and gas recovery. With stringent climate change control, CCS technologies will probably be installed on an industrial scale. Geologically stored CO_2, however, may leak back to the atmosphere, which could render CCS ineffective as climate change reduction option. This article presents a long-term energy scenario study for Europe, in which we assess the significance for climate policy making of leakage of CO_2 artificially stored in underground geological formations. A detailed sensitivity analysis is performed for the CO_2 leakage rate with the bottom-up energy systems model MARKAL, enriched for this purpose with a large set of CO_2 capture technologies (in the power sector, industry, and for the production of hydrogen) and storage options (among which enhanced oil and gas recovery, enhanced coal bed methane recovery, depleted fossil fuel fields, and aquifers). Through a series of model runs, we confirm that a leakage rate of 0.1%/year seems acceptable for CCS to constitute a meaningful climate change mitigation option, whereas one of 1%/year is not. CCS is essentially no option to achieve CO_2 emission reductions when the leakage rate is as high as 1%/year, so more reductions need to be achieved through the use of renewables or nuclear power, or in sectors like industry and transport. We calculate that under strict climate control policy, the cumulative captured and geologically stored CO_2 by 2100 in the electricity sector, when the leakage rate is 0.1%/year, amounts to about 45,000 $MtCO_2$. Only a little over 10,000 $MtCO_2$ cumulative power-generation-related emissions are captured and stored underground by the end of the century when the leakage rate is 1%/year. Overall marginal CO_2 abatement costs increase from a few €/tCO_2 today to well over 150 €/tCO_2 in 2100, under an atmospheric CO_2 concentration constraint of 550 ppmv. Carbon costs in 2100 turn out to be about 40 €/tCO_2 higher when the annual leakage rate is 1%/year in comparison to when there is no CO_2 leakage. Irrespective of whether CCS deployment is affected by gradual CO_2 seepage, the annual welfare loss in Europe induced by the implementation of policies preventing “dangerous anthropogenic interference with the climate system” (under our assumption, implying a climate stabilisation target of 550 ppmv CO_2 concentration) remains below 0.5% of GDP during the entire century.

Keywords Carbon dioxide · Climate change · CCS · Geological leakage · Bottom-up model

1 Introduction

Reductions of anthropogenic greenhouse gas emissions significantly below levels implied by a baseline scenario for future global energy use are imperative, given the ensuing

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increase in the average atmospheric temperature of at least a few degrees Celsius. To minimise the risks induced by climate change, especially the atmospheric concentration of CO_2 should be stabilised, probably at not exceeding twice the pre-industrial level [15, 16, 35]. No silver bullet exists for decreasing the carbon intensity of our energy system, but non-carbon resources like renewables and nuclear energy are both likely candidates (e.g. [2]). Available today is also CO_2 capture and storage (CCS), which is expected to become an increasingly affordable CO_2 emissions abatement technology that for the time being would allow the continued use of fossil fuels but in an essentially carbon-free manner. While experimental and commercial practice demonstrates the technological and economic feasibility of CCS implementation, the environmental risks of large-scale geological CO_2 storage are still poorly known. This article examines the climatic and economic implications of one such risk, the gradual leakage of CO_2 from geological formations to the atmosphere, and investigates how the use of CCS affected by leakage influences the deployment of low-carbon alternatives.

The decarbonisation of fossil-based energy through CCS application has the potential to contribute significantly to reducing CO_2 emissions (see, for example, [1, 14, 16, 27, 34]). Pre-, post- and oxyfuel-combustion CO_2 capture technologies exist for power stations, and pre-combustion ones for fuel cell applications, whereas CO_2 capture techniques operate since long in a number of industrial processes (e.g. [9, 11, 38]). Technologies for CO_2 compression and transportation via pipelines or with tankers are well known and in use already [17]. The Earth's storage capacity, in depleted oil and gas fields, coal seams, and aquifers, is likely to be large [17]. Given that CCS may soon play an important role in reducing CO_2 emissions, it is presently included in climate-change integrated assessment models [7, 18, 22, 28, 32, 40]. Yet our knowledge about the potential external impacts of geologically stored CO_2 is still incomplete. The Intergovernmental Panel on Climate Change (IPCC) has assembled a comprehensive overview of options for geological CO_2 storage and its possible environmental implications [17]. The IPCC points out that much is still to be researched with regard to CCS externalities, in particular concerning the significance of risks for physical CO_2 leakage. This paper attempts to contribute to filling the gap in the existing literature by presenting a study on the role of leakage of CO_2 stored underground in energy scenario analysis.

In Section 2, we summarise the possible external effects of geological CO_2 storage associated with the deployment of CCS technology. Section 3 focuses on the current scientific understanding of leakage of CO_2 artificially stored underground. In Section 4, we describe some of the main characteristics of MARKAL, as well as how we used this model for our analysis of CCS technology implementation with varying assumptions regarding the CO_2 leakage rate. We present our main findings in Section 5 and reserve Section 6 for our conclusions and recommendations for policy making and further scientific research.

2 Impacts and Leakage of Geologically Stored CO_2

The prospective climate benefits of CCS deployment may be significant, but important questions remain related to a range of possible environmental hazards and safety risks associated with the geological storage of CO_2, as pointed out by the taxonomies of e.g. Wilson et al. [39] and IPCC [17]. We do not attempt to be exhaustive, assign probabilities, or determine uncertainties, but briefly mention in this paper that leakage is only one among several potential external impacts of CO_2 storage to put our focus into perspective. For example, storing CO_2 underground can acidify water in the geological layer under consideration (see e.g. [29], various contributions). If the geological layers, below which CO_2 is injected, are breached, the groundwater contained in nearby aquifers may acidify, affecting the quality of drinking water if it is obtained from these sources. Underground injection of CO_2 can also mobilise brine, minerals, and metals that subsequently may migrate and similarly pollute fresh-water pockets, or could induce the displacement of natural reservoir fluids or gases, or a modification of the hydrodynamic properties of surrounding geological layers, which can have negative impacts on the extraction potential of water supplies. Likewise, changes can occur in the chemical properties of geological formations, or localised high pressures can build up, potentially affecting the stability of geological structures above. Such modifications, and the CO_2 injection process itself, can lead to seismic activity or soil cave-ins. Geo-chemical reactions provoked by CO_2 or mobilised substances may disturb the sub-surface or aboveground environment, including the life and habitats of plants and animals.

The presence of oil, natural gas, and CO_2 trapped in geological formations implies that in sedimentary basins, impermeable cap-rock is available with sufficient quality to confine fluids and gases for long periods of time. Such evidence from natural systems demonstrates that reservoir seals exist that are able to contain fossil fuels and CO_2 underground over time scales of at least millions of years. Still, it is imaginable that CO_2 artificially stored underground gradually dissipates and slowly leaks from its geological storage medium. Notably for options such as aquifers and coal beds, long-term storage effectiveness aspects are uncertain. For example, a large number of sites exist where one would have expected to find oil or natural gas but where no such resources proved available as a result of insufficient quality of geological cap-rock material. At many places on Earth, large quantities of oil and natural gas may once have been stored underground that eventually escaped to the outside environment or atmosphere in the absence of appropriate containment layers. Hence, especially when the formations employed today for CO_2 storage are underground reservoirs other than depleted oil and gas fields, it may not be guaranteed that they retain integrity forever. As the hazard associated with gradual CO_2 leakage ranks high among the potential risks of geological CO_2 storage – mostly since it could reduce or eliminate the suitability of CCS as climate change mitigation option – it is the main subject of this article.

Slow seepage phenomena, involving per short units of time only relatively small amounts of CO_2 released, are fundamentally different from sudden large releases of this gas. While probabilities for catastrophic well blow-outs may be exceedingly slight and the associated risks small in comparison to those involved with carbon seeps, the eventuality that artificially stored CO_2 escapes rapidly in great amounts at once cannot be completely neglected. Of course, sudden CO_2 releases interfere with climate change mitigation efforts, but the main concern in this context is the risk of severe accidents with human casualties. Although the hazards involved are likely to be local and temporary, they could nevertheless be pervasive. In Cameroon in 1986, CO_2 produced naturally from volcanic activity welled up from deep in Lake Nyos, and was responsible for killing, by asphyxiation, 1,700 people and their livestock [12]. This concerned a unique and unfortunate case, different in many ways from CO_2 artificially stored underground, but it shows that one in principle has to be wary of the possible consequences of accidental releases of geologically stored 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. Issues of sudden CO_2 leakage are not analysed here, as this goes beyond the scope of our paper.

To evaluate the costs associated with the human health impacts of emissions of energy production pollutants, “impact pathway analyses” can be made, tracing the passage of each pollutant from the place where it is emitted to the affected population. While for many pollutants such environmental damage analyses have been performed in the ExternE (External costs of Energy) project series of the European Commission, these studies do not cover quantifications of externalities resulting from geological CO_2 storage [5]. In the absence of more complete experimental data required for proper CO_2 storage damage cost calculations, in a prior study we made assumptions about their possible ranges to perform externality-inclusive energy scenario analysis [32]. This paper builds on that work by investigating the behaviour of energy technology deployment scenarios under different assumptions regarding the rate of leakage of CO_2 stored underground.

3 Rates of CO_2 Leakage

Many examples exist showing that fossil fuels and CO_2 can remain trapped in underground reservoirs for long periods of times. Today’s fields of sequestered fossil fuels like oil and natural gas have retained their storage integrity during millions of years. The CO_2 used in Texas for enhanced oil recovery originates from CO_2 pockets stored naturally for at least millennia. The CO_2 volume trapped underground in the Pisgah Anticline (Mississippi) was probably created more than 65 million years ago. As oil and natural gas 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 depleted oil and natural gas fields, for time frames compatible with the natural carbon cycle. This would render CCS fit as climate change mitigation option. There seems thus little doubt that the long-term secure storage of CO_2 is feasible in many geological formations, notably if they concern empty fossil fuel fields. Still, no full certainty exists, as examples abound of natural CO_2 leakage from the underground. Fossil fuels are rare from a long-term resource consumption perspective. They are only found at sites with specific geologic features, like the presence of a cap-rock that prevents the confined fuel from dissipating. Most likely, during the Earth’s history, in many more places fossil fuels once accumulated, but seeped away as a result of unfavourable containment conditions. Many fossil fuel reservoirs that existed long ago, or past oil and natural gas fields *in statu nascendi*, have probably disappeared [3]. These kind of observations confirm that leakage back into the atmosphere of artificially stored CO_2 is a phenomenon that deserves attention and ought to be studied in the context of geologically storing CO_2 for climate change control purposes (e.g. [19]).

It may prove difficult to find storage sites characterised by 100% storage efficiency. What are leakage rates that may still be considered acceptable from a climate control point of view? Under imperfect storage conditions, CO_2 migration times are likely to vary according to the storage option considered, and depend on the characteristics of the formation of the site specified [24]. The leakage time frame that characterises each option, and the compatibility of that time frame with climate change policy and targets as well as features of the carbon cycle, is determinant for the option’s suitability to mitigate, postpone, or preclude climate change. A back-of-the-envelope calculation readily demonstrates that a 0.1%/year CO_2 leakage rate is likely to be more or less acceptable, while a 1%/year rate is probably not. For a storage option with a 1%/year leakage rate, a given quantity of geologically stored CO_2 will have reduced to 37% of that amount after 100 years, whereas 90% of that quantity is still stored underground after a century for a storage medium characterised by a 0.1%/year leakage rate. Given that climate change is a problem stretching over the forthcoming couple of centuries, one may conclude that in the 1%/year leakage case, CCS becomes an ineffective emissions abatement option. If a 0.1%/year leakage rate applies, however, much of the geologically stored CO_2 remains sequestered even after the time frame of several centuries, so that CCS retains at least part of its value as climate change management technology. This simple observation is confirmed by more refined analyses, as in Ha-Duong and Keith [8].

The IPCC [17] concluded that observations from engineered and natural analogues as well as models suggest that the fraction retained in appropriately selected and managed geological reservoirs is very likely to exceed 99% over 100 years and is likely to exceed 99% over 1,000 years. If, however, limitations exist with respect to our storage site selection capabilities, or management proves insufficient during site operation, leakage rates of 1 or 0.1%/year cannot be excluded. The relevance of these rates for energy scenario analysis should thus be investigated. Leakage at rates within this range may also be subject to changes over time. What can be said about the long-term evolution of the global mean leakage rate? On the one hand, one can assume that injection occurs randomly distributed across a large collection of heterogeneous reservoirs, about which we know virtually nothing before actually operating them as storage sites. In other words, we start employing storage reservoirs without precise prior knowledge about the potential range of their associated leakage rate (as in Pacala [26]). In this case, the average leakage rate decreases in the long run because the fraction of CO_2 remaining in less leaky reservoirs increases.

On the other hand, at some point, it may be possible to develop prior understanding of what the approximate leakage rate ranges are of specific geological storage sites, e.g. through detailed modelling exercises of the behaviour of geological formations (as in Hepple and Benson [10]). If the quantities of CO_2 we plan to store underground become large, and thus the limited capacity of each single reservoir necessitates the use of a growing number of storage reservoirs, the probability of selecting less favourable sites, i.e. with higher leakage rate, will gradually increase. In this case, the overall mean leakage rate is likely to gradually augment over time. Given the wide range of leakage rate values we study in this paper, most values of which are considered pessimistic by the IPCC [17], we abstract from leakage time-variability. Instead, we investigate four time-independent leakage scenarios, in which the leakage amounts to 1, 0.5, 0.1, and 0.05%/year, respectively. Climate change effects are not entirely absent when applying CCS technology to fossil-based energy generation, as there are thermodynamic, technical, economic and life-cycle-emissions-related limitations to the capture level that can be reached. As a result, CO_2 capture technology is unlikely to ever become 100% efficient, but rather e.g. 90%. In this paper, we only study the risk associated with the captured and stored CO_2 and its subsequent leakage from underground storage.

4 MARKAL with CCS and CO_2 Leakage

If the energy system is subjected to stringent climate constraints, fossil-fuel-based power generation – the main focus of this study – will in principle be put into disadvantage. Given that current combustion processes of coal, oil, and natural gas intrinsically involve emissions of the most important greenhouse gas, CO_2, the predominant role of fossil fuels in the present energy mix should normally be significantly reduced when ambitious climate change goals are to be met. With much of the CO_2 emissions being susceptible to CCS technology application, however, notably in the power sector, this picture could change dramatically: fossil fuels can technically continue to play the role they do today. The costs of CCS application and the resulting competitive 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 their principal role in current electricity infrastructures under stringent climate change policy. MARKAL is one of the available models that allows for studying the integrated economics of the energy system and assessing the relative competitive position and affordability of, in particular, power production alternatives, including fossil-fuelled electricity plants with CCS technology application. We therefore use MARKAL to analyse what the future role of fossil fuels may be in long-term power supply scenarios when CCS technology is one of the CO_2 emission reduction options. For the purpose of this paper, we use an adapted version of MARKAL, in which geological leakage of CO_2 is accounted for.

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. [21, 31, 32]). 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, that optimises and matches the supply and demand sides of energy use for the modelling time frame under consideration, 1990–2100 for this study. The net present value of total costs, or NPV, is the objective function and consists of the sum over all regions of the discounted stream of annual costs incurred in each year until the time horizon of 2100 [4]:

$$\mathrm{NPV} = \sum_{r=1}^{R} \sum_{t=1}^{\mathrm{NPER}} (1+d)^{1-t} \bullet \mathrm{ANNCOST}(r,t) \bullet \begin{pmatrix} 1 + (1+d)^{-1} + (1+d)^{-2} \\ + \cdots + (1+d)^{1-\mathrm{NYRS}} \end{pmatrix},$$

in which the indices r and t refer to the region and time period, respectively, R is the total number of regions, and NPER the number of periods simulated until the planning horizon. The parameter d is the general discount rate, ANNCOST(r,t) the annual (or rather 'periodal') total energy system cost (per region and period), whereas the last factor in the expression represents the intra-period discount factor and NYRS the number of years in each period. ANNCOST(r,t) is the sum over all technologies, years per period, and commodities of a large range of different types of costs.[1] ANNCOST(r,t) also accounts for e.g. taxes levied on emissions of environmental pollutants, such as (in our case) CO_2, as well as consumer welfare losses induced by increasing commodity prices and price-elastic demand behaviour.[2] The modelling horizon is divided in steps (periods) 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 demand. The geographical coverage studied is Western Europe (WEU), including the 15 European Union (EU) countries (in 2003), expanded with Norway, Switzerland, and Iceland. This area is treated as a single region, without country disaggregation.

Although MARKAL may cover various greenhouse gases, this study has been restricted to CO_2 only, as CO_2 accounts presently for about 80% of all greenhouse gas emissions in Western Europe. Considered are CO_2 emissions from fossil fuel combustion for power production and transport, as well as from industrial processes. CO_2 emission reduction in the fossil-fuelled sectors is notably accounted for through a large set of CCS options, while the model also includes a highly stylised module that rudimentarily reflects carbon circulating in the biosphere via CO_2 sequestration by land use, agriculture, and forestry. The model distinguishes six geological CO_2 storage options: enhanced oil (and gas) recovery (EOR), enhanced coal bed methane (ECBM) recovery (two different options at different depths), aquifers, 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).[3] 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 production 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

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[1] Among these are notably the lump sum unit investment costs, the fixed and variable operation and maintenance costs, the delivery costs per unit of commodity transferred to the relevant energy technology (and the amount of commodity required to generate one unit of energy per technology), mining costs, transportation and transaction costs, and the (exogenous) import and export prices of each commodity.

[2] Consumer welfare loss is the reduction in surface between the demand curve and the equilibrium price level. Likewise, producer welfare loss is the reduction in surface between the supply curve and this equilibrium price.

[3] These options are assumed to have potentials (in Europe) of 17, 30, 250 and 5 $GtCO_2$, respectively, but it is recognised that these figures may significantly change with increasing natural scientific and economic knowledge of geological CO_2 storage.

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 cost trends in clean coal technology deployment [30].

In traditional MARKAL models, changes in prices do not affect demand. In recent years, through a couple of different approaches, the MARKAL algorithms have been extended to include price-dependent demand levels. We here use MARKAL-Elastic-Demand (MARKAL-ED), a partial equilibrium model in which the common exogenously defined demand relations have been replaced by price-driven demand functions [20]. These functions enrich the bottom-up modelling of MARKAL with an important macro-economic feature by reflecting that energy demand decreases as a result of increasing energy prices. A main advantage of MARKAL-ED is that it is still based on linear equations, so that energy scenarios can be simulated with a relatively short computer calculation time. 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, or BAU) scenario, energy use continues to rise over the twenty-first century. No serious climate change policy intervention is assumed, so that in principle CO_2 emissions should also continue to rise over this time frame. As we will see, however, we assume that there will be an ‘autonomous’ reduction in emissions during the second half of the century, as a result of some modest climate change measures, more integrated European energy security policy, the ensuing deployment of e.g. renewables and nuclear power, and the increasing competitiveness of these technologies. Second, in a stringent policy scenario, a climate change control instrument is introduced in the form of the imposition of an atmospheric CO_2 concentration ceiling. We adopt a climate stabilisation at 550 ppmv CO_2 and assume that this target is achieved by limiting the cumulative amount of CO_2 emissions to a maximum allowed level of 362 $GtCO_2$ for Western Europe over the period 1990–2110. This assumption allows for the implementation of a concentration viz. cumulative emissions constraint for Western Europe in MARKAL in a similar way as done for the analyses presented in the Special Report on Emissions Scenarios (SRES) and other IPCC reports [15, 16, 23]. Third, in four additional scenarios, the simulation of climate change control is complemented with that of gradual leakage of CO_2 from underground geological storage formations. These scenarios reflect CO_2 leakage rates of 1, 0.5, 0.1, and 0.05%/year, respectively, that are assumed to be constant over time and are programmed through a variable introduced for this purpose, representing the cumulative amount of geologically stored CO_2.

5 Results and Long-Term Energy Scenarios

Figure 1a, depicting the annual European electricity generation from four different sources – renewables, nuclear energy, fossil fuels with CCS, and fossil fuels without CCS – shows that in the base-case scenario, fossil-based power production continues to play an important role throughout the entire twenty-first century. A few differences can be observed between this base-case scenario and the one reported in Smekens and van der Zwaan [32]. Through more optimistic cost evolution assumptions, a larger share is reserved for nuclear energy and especially renewable resources (notably wind power), reflecting both current tendencies and the impact that EU climate change and energy supply security policies are expected to have. These non-carbon options curb the use of fossil fuels downward from around the middle of the century, thereby halting their continued expansion until 2050. During a couple of decades, a small amount of CCS penetrates, but significantly less than under our previous assumptions, as a result of less optimistic (more realistic) ECBM cost assumptions.[4] When a strict climate constraint is applied, non-carbon energy resources need to be massively deployed, as depicted in Fig. 1b for a 550 ppmv atmospheric CO_2 concentration limit. In addition to a further expansion of renewables and nuclear energy with respect to Fig. 1a, CCS is deployed on a large scale to achieve the required reduction in CO_2 emissions. Given the more optimistic prospects for especially renewables, however, CCS develops less and later in comparison to the 550 ppmv scenario of Smekens and van der Zwaan [32].

If one assumes that in addition to a strictly binding constraint on cumulative CO_2 emissions – in our case (as in Fig. 1b) in the form of a 550 ppmv atmospheric CO_2 concentration target – geologically stored CO_2 gradually

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[4] Under a climate constraint, biofuels appear to play an increasing role and prove to become responsible for the lion’s share of emission reductions in the transport sector (while hydrogen and electricity hardly do). Note that all plots of Fig. 1 represent power production for stationary use only, as MARKAL calculates that under our assumptions an electricity-based transport sector does not become cost-effective during the twenty-first century.

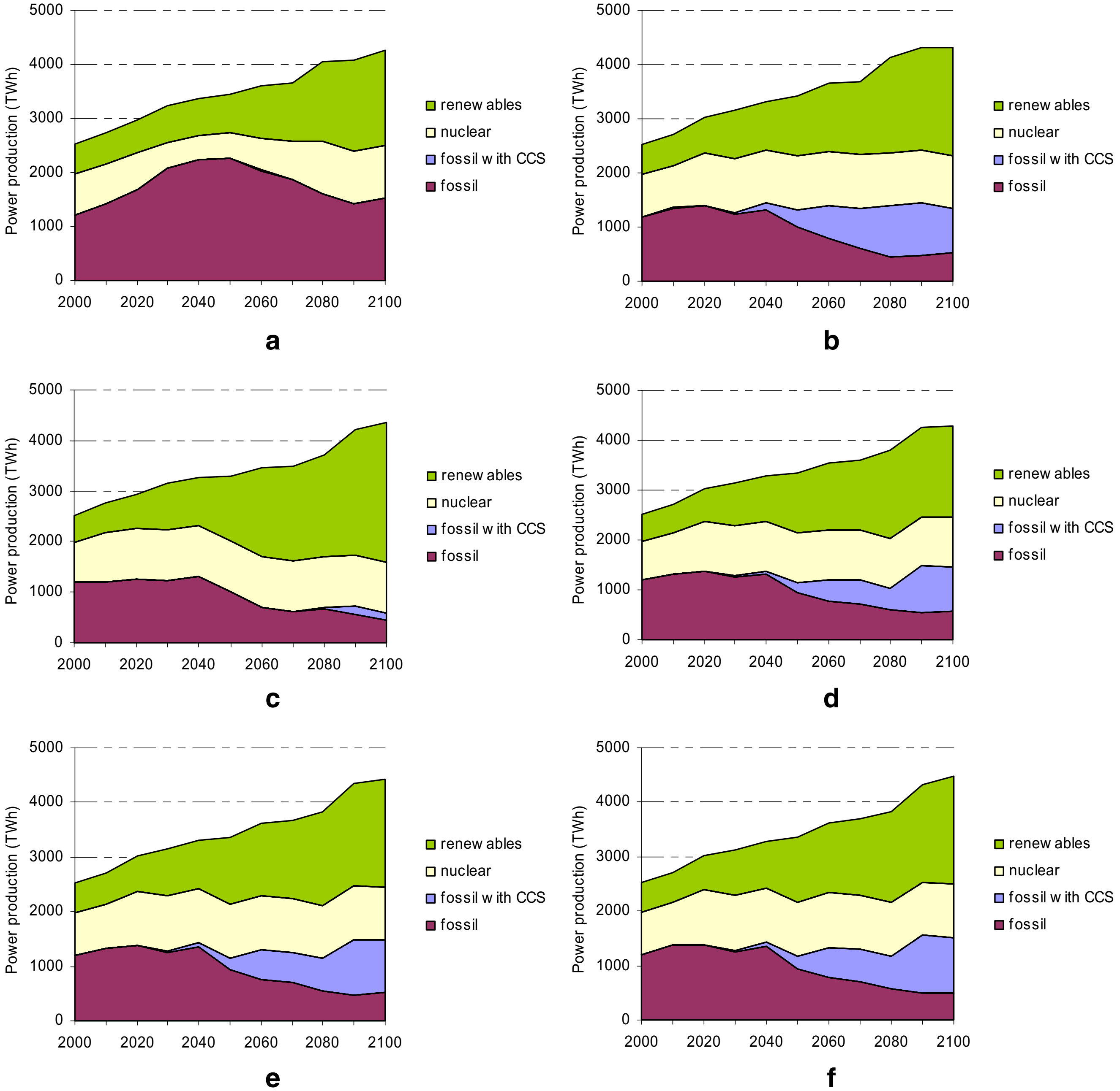

Fig. 1 Annual electricity generation (in TWh) from renewables, nuclear, fossil fuels with CCS, and fossil fuels without CCS. Scenario (**a**) is the base case without climate change constraint; in scenario (**b**) a climate constraint of 550 ppmv CO_2 concentration is imposed; in scenarios (**c**), (**d**), (**e**), and (**f**) the same climate constraint of 550 ppmv is assumed, plus a geological CO_2 leakage rate of, respectively, 1, 0.5, 0.1, and 0.05%/yr

seeps from the underground, the prospects for the contribution of fossil fuel power generation equipped with CCS technology may radically modify. The resulting scenarios are shown in Fig. 1c–f, in which CO_2 leakage rates are assumed that are constant over time of, respectively, 1, 0.5, 0.1, and 0.05%/year. The four graphs thus represent a sensitivity analysis for varying values of the CO_2 leakage rate, with all other parameters held constant. On the basis of Fig. 1c–f, various different observations can be made, the first one being a confirmation of our suspicion that the inclusion of CO_2 leakage in energy systems models based on cost minimisation may indeed significantly change the scenarios derived with these models. For example, if the leakage rate is as high as 1%/year, as in scenario (c), the deployment of CCS technology is almost entirely phased out, with only little room for its use by the end of the century. With a leakage rate of 0.5%/year, as in scenario (d), much of the CCS deployment observed in scenario (b) is restored, while the plots of scenarios (e) and (f) show that leakage rates at the 0.1%/year level or lower hardly affect the prospected opportunities for CCS application. In other words, scenarios (b), (e), and (f) differ only modestly and have approximately the same cumulated CCS levels – only the shape of their evolutions show slight variations (partly for programmatic reasons).

In any case, whether there is CO_2 leakage or not, the climate constraint in all scenarios (b)–(f) is stringent enough so as to preclude the great expansion of fossil fuels consumption of scenario (a), during the first half of the twenty-first century, and a continued importance of their use until 2100. Rather, the demand for fossil fuels without CCS must in each of these five cases be substantially reduced during the twenty-first century, typically down to about a third of their current usage. Meanwhile, the behaviour of fossil fuels without CCS – between scenarios (b)–(f) – remains nearly unchanged, that is, it remains unaffected by the level of the leakage rate. Whereas in principle, within the imposed CO_2 concentration limit, flexibility is allowed as to when and how emission reductions can optimally take place, it proves that in this respect the no-CCS fossil fuel usage profile is remarkably constant. This points towards the strictness of the binding climate constraint and to the fact that within the context of expected European energy requirements under the ambitious climate control target, the main degree of freedom lies in the choice between the major non-carbon energy options, that is, renewables, nuclear energy, and decarbonised fossil fuels through CCS technology application. In the five climate-constrained scenarios, the generation of electricity through the use of renewable resources and nuclear energy are both greatly increased with respect to the base case scenario. The prospects for nuclear power vary little across these five scenarios. The extent to which renewables are deployed, however, is strongly determined by how much CCS is implemented. If the availability of CCS technology is modelled in conjunction with CO_2 leakage, no automatic large-scale application follows of CCS technologies to fossil-based electricity generation, as demonstrated by scenarios (c)–(f). In those cases where CCS expands significantly, the increase in the use of renewables is reduced, and vice versa. For example, while in scenario (b) the large-scale application of CCS technology to fossil fuel use is optimal to gradually reduce CO_2 emissions, in scenario (c) sizeable leakage makes that other emission reduction options need to be employed: in this case renewables, as they are more cost-effective. Note that around 2100 CCS as applied to fossil-based power plants loses a bit in interest in each of the five scenarios. The explanation is that by that time renewables and nuclear energy have become cheap enough to constitute more interesting CO_2 abatement options from an overall cost point of view than they already had become in the decades before.

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 all energy technologies, in this case notably with respect to fossil-based electricity production costs, CCS application costs, and the costs of renewables and nuclear energy. The assumed present-day costs of these energy technologies greatly matter for the results obtained with our modelling runs. Likewise, also our simulation of the future evolution of these costs, in our case through the adoption of learning phenomena, lies at the basis of our findings. We assume that renewables possess a higher learning rate (of 20–30%) than their fossil- and CCS-based counterparts (not more than 10%), whereas nuclear energy hardly learns at all, which is probably realistic. We cannot possibly report our cost (or technical) assumptions for all modelled energy technologies, other than recalling that these are close to competitive in some cases (as for certain wind power options) and far from cost-effective in others, at least today (as for e.g. photo-voltaics). Since CCS technology constitutes the main subject of this article, we only specify some of the relevant characteristics of this carbon mitigation alternative (see Table 1).

Figure 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. The left graph of Fig. 2 demonstrates that in the base case CO_2 emissions from electricity generation rapidly increase over the first few decades and from about 2040 gradually decrease to reach in 2100 an amount somewhat below today's emissions level, given the increasing role reserved for renewables and renewed interest for nuclear energy (see also Fig. 1). In the climate-constrained scenarios (b)–(f), power sector CO_2 emissions steadily decrease during most of the century and reach a level close to zero in 2100. One observes that the differences between the leakage scenarios are relatively small. In general, the power sector emissions are slightly lower when no leakage is present (b) in comparison to

Table 1 Main economic and technical assumptions for three different CCS options

CCS technology	Investment costs (M€/GWe)	Learning rate (%)	Capture efficiency (%)
Post-combustion coal	817	10	90
Pre-combustion coal	430	10	95
Post-combustion gas	595	10	88

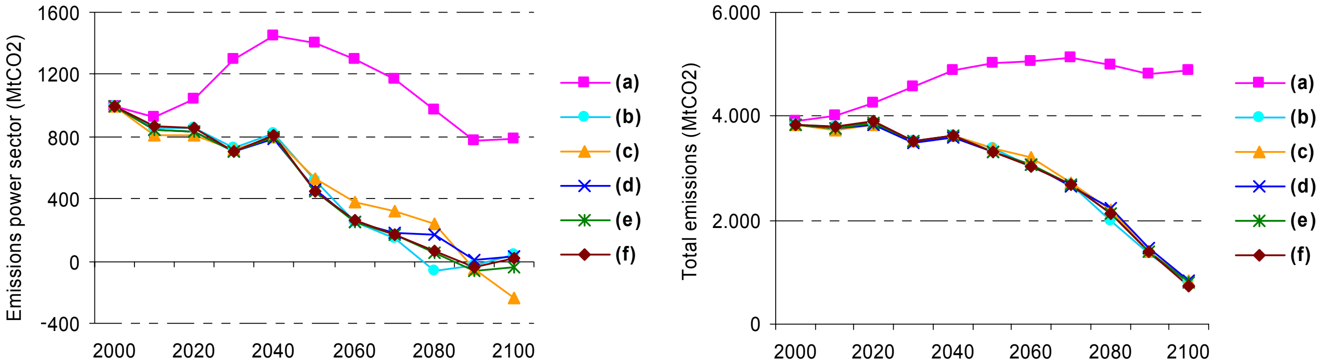

Fig. 2 Annual emissions of CO_2 from the electricity sector (*left*) and total annual emissions of CO_2 (*right*; in $MtCO_2$), until 2100, in the six scenarios (*a*)–(*f*)

when leakage is occuring (c)–(f), as it proves optimal to shift some emission reductions to sectors other than the power sector given the decrease in cost effectiveness of CCS affected by CO_2 leakage.[5] Overall, apart from intertemporal fluctuations, electricity consumption tends to be lower for higher leakage rates. Note that occasionally the plots may drop below the 0-line, the explanation for which is that CCS applied to biomass power plants, involving negative net emissions of CO_2, is one of the options chosen. Total CO_2 emissions increase during most of the century in the base case scenario (right graph of Fig. 2). The decreasing emissions of CO_2 in scenarios (b)–(f) in this figure can be explained by emission reductions in the power sector (left graph of Fig. 2) plus those in most other sectors, among which notably transport and industry. The extent to which the ensemble of these other sectors contribute to total CO_2 emission reductions can be derived through a comparison of the emission reduction patterns of scenarios (b)–(f) between the left and right graph of Fig. 2. Indeed, as the 550 ppmv CO_2 concentration constraint is stringent, most sectors need to be subjected to significant emission reductions, with overall achieved reductions that do not manifestly differ between the five climate-control scenarios (see Fig. 2, right graph).

Figure 3 shows in what sectors CO_2 is captured and what options are used to store this CO_2 away from the atmosphere in scenarios (a), (b), (c), and (e) – representing the baseline, and the 0, 1, and 0.1%/year CO_2 leakage rate cases, respectively. In the base case, only small quantities of CO_2 are captured, mostly in industry and somewhat in the fossil-based power generation sector, as there is no environmental policy stimulating costly CCS implementation. When a 550 ppmv climate constraint is imposed, as in scenario (b), CO_2 capture takes place on a large scale, reaching rates of well over 1,000 $MtCO_2$/year by the end of the century. More economic sectors are then subjected to CO_2 capture, including also hydrogen production and biomass-based power generation. The fossil-fuelled electricity sector becomes by far the largest opportunity for CO_2 capture application. As can be seen from scenarios (c) and (e), CO_2 capture is introduced much later and to a smaller extent if CO_2 storage leaks with a rate of 1%/year, while with a leakage rate of 0.1%/year the total annual amount of CO_2 captured differs little from that in the scenario without leakage. Whereas the sectors involved with CO_2 capture in the 0.1%/year leakage case are employed in essentially the same way as in the no leakage case, the 1%/year leakage scenario shows a relatively higher share of CO_2 capture in the biomass-based power sector. The explanation is that CO_2 capture associated with biomass power production is the most effective way to store CO_2 away from the atmosphere, as it can generate negative CO_2 emissions. It thus constitutes an option among the CCS alternatives that becomes more necessary when the leakage rate is as high as 1%/year. In scenarios in which CO_2 leakage is less or absent, relatively less need for large-scale biomass-based CCS exists: in both scenarios (b) and (e), CO_2 capture applied to fossil-based power plants proves the predominant CCS implementation opportunity. Since the emission reductions that need to be achieved in scenario (c) are relatively immediate, once they take off around 2070, we see that CCS applied to biomass power production fulfils a share of CCS technology implementation already from that year onwards. In the 550 ppmv no-leakage scenario, as well as scenario (e), this relatively expensive but effective option is applied later than the three other CO_2 capture options, given the available degree of freedom in terms of how and when the emission reductions can be realised. As demonstrated by the limited amount of CO_2 capture realized in the high leakage scenario (c), employing renewables and nuclear energy constitutes a more cost-effective way to achieve the necessary CO_2 emission reductions than through CCS options, notably as applied to fossil-based power generation.

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[5] Figure 2 (left graph) shows an exception during the last decade of the century, for programmatic (cut-off) reasons.

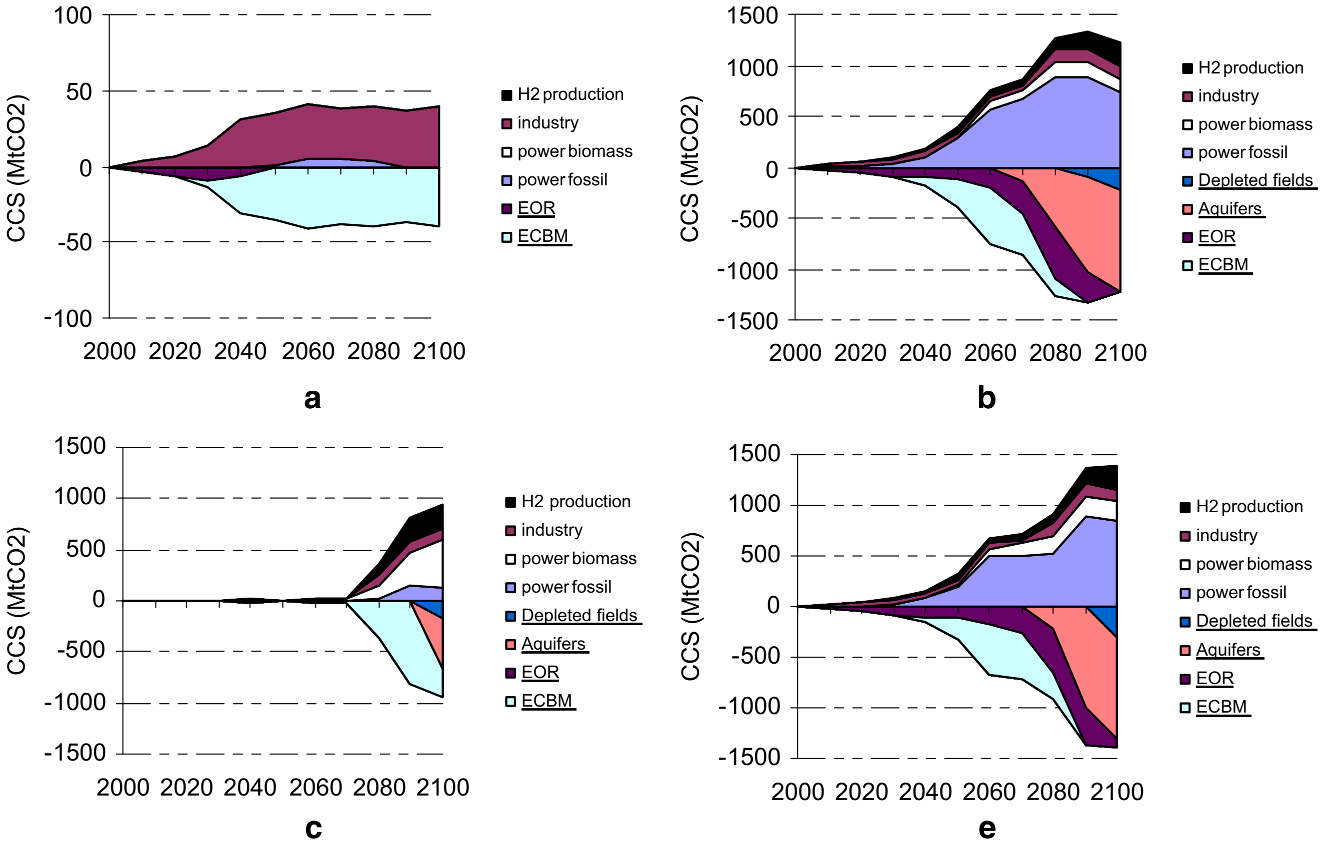

Fig. 3 Annual amounts of CO_2 captured and stored (in $MtCO_2$), per sector of capture and per storage option chosen, during the twenty-first century, in scenarios (**a**), (**b**), (**c**) and (**e**). The amount of CO_2 captured in different sectors is presented above the 0-line, while the alternatives for carbon storage are depicted below the 0-line (the different storage options used are *underlined*). Note the different scale of the *y*-axis for scenario (**a**) only

Given that all CO_2 captured needs to be stored underground, it is logical that the scenario-figures (a), (b), (c), and (e) are symmetric in the *x*-axis (0-line). In these four scenarios, the order (but not the quantities) with which different storage mediums are utilised proves the same. Initially, all CO_2 captured is used for EOR, as this option is assumed the most affordable, resulting from both relatively low storage costs and the economic benefits derived from the continuation of oil production in fields that near depletion. In Europe, North Sea EOR in particular might turn out an option through which CO_2 storage will first take off, as it possess the additional advantage of postponing the costly decommissioning of offshore oil platforms (see e.g. [33]). Typically a few decades later than EOR, methane gas recovery through ECBM develops and becomes an important option for storing CO_2 during especially the second half of the century. The reasons for EOR developing earlier than ECBM CO_2 storage in our modelling set-up are twofold: (1) EOR storage costs are assumed lower than those of ECBM, (2) the oil recovered through EOR processes proves more competitive than the gas recovered through ECBM, e.g. since in Europe the former competes mostly with oil from the Middle East and the latter mostly with gas from closer-by Russia. The order between EOR and ECBM can be further justified by the observation that over the coming decades geological coal seams in Europe may prove inappropriate as long-term reliable CO_2 storage medium, e.g. resulting from insufficient porosity characteristics.

Since the quantities of CO_2 captured are so large in scenarios (b) and (e), and to some extent in scenario (c), EOR and ECBM do not suffice to store all CO_2 underground. Gradually therefore also aquifers and depleted oil and gas fields are phased in, sequentially in this

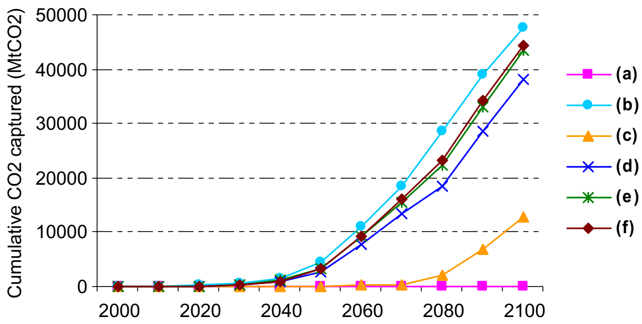

Fig. 4 Cumulative amount of CO_2 captured in the electricity sector (including both fossil-based and biomass-based power plants, expressed in $MtCO_2$) in scenarios (*a*)–(*f*)

order, on the basis of their assumed costs and potentials. EOR and ECBM, on the one hand, precede aquifers and depleted oil and gas fields, on the other hand, given the economic benefits of fuel recovery in the case of the former. Of course, the extent to which ECBM methane becomes competitive with foreign gas, e.g. as imported from Russia, and thereby can substitute for depleting domestic gas resources, will affect the deployment prospects for ECBM. In our case, these are admittedly rather optimistic because we assume fairly large fuel benefits that make up for the relatively high costs associated with the recovery process itself. Other factors that will play key roles in the deployment sequence of the various CO_2 storage options are the expected storage potentials, the interactions of CCS opportunities with the rest of the energy system, and the potential environmental risks associated with the different storage options. Furthermore, if different leakage rates prove applicable to different storage options, this will also importantly affect their deployment: for EOR and depleted oil and gas fields, storage integrity seems a priori more likely to be guaranteed than for ECBM and aquifers.

If it is optimal to capture CO_2 on a large scale, in particular the power sector is subjected to CCS, as demonstrated by the CO_2 capture and storage plots for scenarios (b) and (e) in Fig. 3. Figure 4 shows the cumulative amount of CO_2 captured and stored in the electricity sector, including both fossil-based and biomass-based power plants, in scenarios (a)–(f). Figure 4 confirms for the power sector what applies to the energy system at large, i.e. that in the base case (without climate target) the amount of CO_2 captured is negligible, and this amount in scenario (c) is relatively modest (since the leakage rate, of 1%/year, is too high). In all other (climate-constrained) scenarios, the cumulative quantity of power-sector CO_2 captured and stored in Europe is large, close to 40,000 $MtCO_2$ by the end of the century when the leakage rate is 0.5%/year and between 40,000 and 50,000 $MtCO_2$ by 2100 when the leakage rate is at the 0.1%/year level. The difference in cumulative amount of captured and stored CO_2 as associated with electricity generation in the year 2100 between the cases of 0.1%/year and no leakage is around 10%. For all sectors of energy use combined, in 2100, the cumulative amount of CO_2 retained underground is about 44,000 and 55,000 $MtCO_2$ with a leakage rate of 0.5 and 0.1%/year, respectively, while the corresponding cumulative amount of CO_2 leaked back into the atmosphere is approximately 7,000 and 2,000 $MtCO_2$ in these two cases.

What are, in our cost-minimisation setting, the marginal costs of CO_2 emissions? Figure 5 (left graph) shows the shadow prices (or dual costs, in constant (2000) €) associated with CO_2 emissions under the constraint of 550 ppmv for the five different climate control scenarios. In all five scenarios, irrespective of the CO_2 leakage rate, these marginal costs of CO_2 emissions remain below 50 €/tCO_2 until about 2060, after which they steadily rise to reach a level of more than 150 €/tCO_2 by 2100. The differences in marginal CO_2 costs between the different leakage scenarios are small and remain within at most the 40 €/tCO_2 range in 2100 for the two outer cases with leakage rates of 0 and 1%/year, respectively. The right graph of Fig. 5 depicts for these scenarios the total annual welfare or GDP loss as a result of the imposition of the stringent climate constraint of 550 ppmv. As measure for GDP, we take the sum of the calculated consumers' and producers' surplus. Welfare loss, i.e. in our case the loss of European GDP, is expressed as the percentage change of GDP in the scenario under consideration with respect to that in the base case (see also [21]). Again, the differences in welfare loss between the different leakage scenarios are small and remain within a variation of about 0.1%. Overall, and until the end of the century, reaching our strict climate change control target will not cost more than 0.5% of European GDP annually, and probably much less, especially until about 2080. Note that these costs are significantly lower than those reported

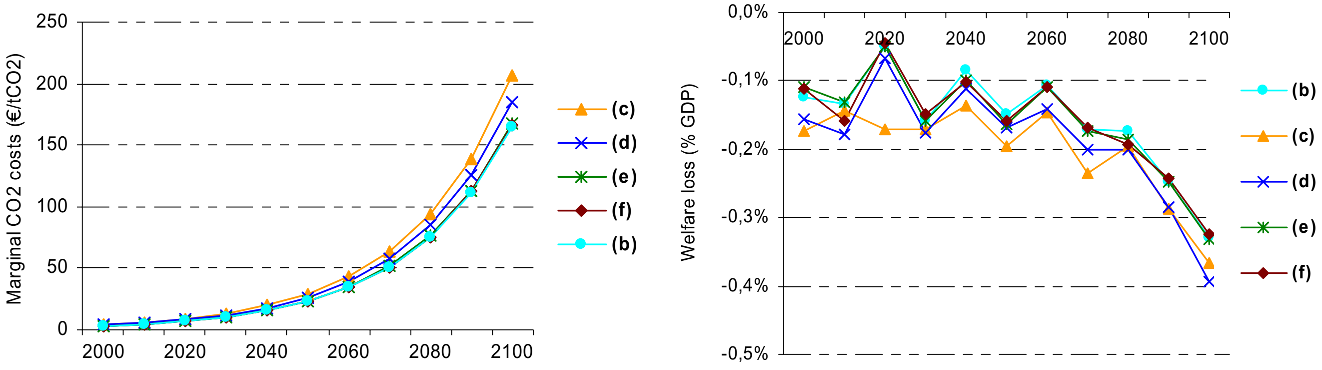

Fig. 5 Marginal costs of CO_2 emissions (*left*) and total welfare loss (*right*), expressed in (2000)€/tCO_2 and % GDP loss, respectively, in scenarios (*b*)–(*f*)

in studies conducted with some of the 'classical' top-down integrated assessment models, such as DICE, which calculates a loss of the discounted value of cumulative consumption at typically the percentage level [25]. Our results are more in line with those obtained through some of the top-down models that explicitly account for the endogenisation of technological change, like DEMETER, with which welfare losses have been calculated at around the 0.1% level (or less; see [6, 36]). In these two top-down models, however, GDP is calculated in a different way than in our bottom-up model, as the latter does not capture the impact of mitigation policies on the economy outside the energy sector.

6 Conclusions and Recommendations

Our scenario analysis has shown, first, that when no climate policy is introduced, fossil fuel use for power production in Europe with approximately its current rate of CO_2 emissions is most likely to increase considerably during at least the forthcoming decades. We thus confirm what many studies observe, for the world at large, that without climate change policies CO_2-emitting fossil fuels will continue to dominate energy production for a long time to come, and perhaps throughout most of the twenty-first century. In the base-case scenario presented in this article we assume, nevertheless, that renewables (like wind power and biomass) and eventually nuclear energy become increasingly competitive (with respect to notably the conventional use of fossil fuels) over the next few decades, in particular through learning phenomena, so that from the middle of the century onwards these energy resources can start playing a much larger role than today and bring about significant reductions in the emissions of CO_2. In this base case setting, without explicit climate change management, fossil fuels continue to provide a large share of mankind's energy needs up to 2100. Even in this no-climate-control scenario, however, it is expected that CCS technologies start playing a small role in power generation and industry, and thereby avoid a modest level of CO_2 emissions. In Europe, the first main driver of CCS deployment is expected to be the application of EOR, through which additional oil is recovered from geological reservoirs nearing depletion by CO_2 injection. 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 entail.

When a global climate policy is introduced that limits the atmospheric concentration of CO_2 to 550 ppmv, the use of non-carbon energy resources will need to be expanded considerably. We find that especially renewables (notably wind power and biomass), and to some extent nuclear energy, are among the carbon-free options whose deployment will be increased significantly, under the implementation of this stringent climate policy, and that the expansion of traditional fossil fuel usage will be halted drastically. If the climate policy introduced is the emissions ceiling in terms of a concentration limit of 550 ppmv, we see that CCS will be applied massively. While fossil-based power generation will be the main sector of application, we find that also biomass electricity production, hydrogen production and other industrial sectors will be subjected to CCS deployment. In Europe, potentials for EOR and ECBM will then not suffice to store all the amounts of CO_2 captured, so that other storage options like depleted oil and natural gas fields, as well as aquifers, will also be used. Ocean CO_2 storage or storage in deep-sea sediments 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 (see e.g. [17], respectively [13]).

In our previous publication [32], we concluded 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.[6] We now find that, with CCS along with renewables and nuclear energy the main options available for reaching climate objectives, this is still the case when CO_2 is assumed to gradually leak from where it is stored underground. The value of the leakage rate, however, matters for the extent to which CCS is deployed as one of the optimal CO_2 emission reduction options. Our main conclusion is that a CO_2 leakage rate at the 1%/year level is too high for CCS to become one of the affordable choices in the set of deployable climate change mitigation alternatives. CCS will then only be deployed to a small extent. For all values of the CO_2 leakage rate at or below 0.5%/year, however, CCS continues to be one of the economically competitive carbon-free energy options, irrespective of the fact that there is no 100% integrity of the storage medium into which CO_2 is injected. Under stringent climate policy, the accumulated quantity of CO_2 captured and stored in Europe is expected to be large, close to 40,000 $MtCO_2$ by the end of the century when the leakage rate is 0.5%/year, and between 40,000 $MtCO_2$ and 50,000 $MtCO_2$ by 2100 when the leakage rate is at the 0.1%/year level or less. Only if the leakage rate is 1%/year or higher, this amount is significantly reduced, which confirms the

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[6] We thereby provided justification for the EU strategy to promote damage cost internalisation with the purpose of limiting e.g. climate change.

common opinion that percentages constitute unacceptably high values of the leakage rate, whereas values below 1%/year, typically at the per mille level, are acceptable for CCS to be deployed on a large scale. In the latter case, it will be mostly the power sector that will be subjected to large-scale CCS application. When the leakage rate is 0.5%/year or less, the cumulative amount of CO_2 emissions retained underground represents 20–30% of the total amount of CO_2 reduced with respect to our baseline scenario. Note that the allowable CO_2 leakage rate is most likely dependent on the imposed emissions constraint: it is expected that the leakage threshold value of 0.5%/year (at which CCS just about remains an attractive mitigation option) is reduced when the 550 ppmv climate stabilisation target is rendered more stringent (down to e.g. 450 ppmv).

The marginal costs of CO_2 emissions in our modelling setting are in line with those from other studies, that is, they remain relatively low initially (typically below 50 €/tCO_2 until the middle of the century) and rise to levels of a couple of hundred €/tCO_2 by 2100. We find that the simulation of CO_2 leakage has at most a 20% effect on the value of the marginal CO_2 costs in 2100. In absolute terms, the marginal CO_2 cost difference amounts to about 40 €/tCO_2 by the end of the century when assuming a leakage rate of 1%/year instead of none. We demonstrated that the welfare costs incurred by large climate change mitigation efforts, as calculated with MARKAL for Europe, are in the middle of the range as reported in the literature, with annually at most 0.5% loss of European GDP by the end of the century. On the basis of our scenario comparison, we conclude that accounting for different values of CO_2 leakage has typically at most a 20% effect on this value of the loss in welfare.

One of our other main conclusions is that the application of CCS technologies may significantly prolong the consumption of fossil fuels and delay their decrease in use under climate control policies by at least half a century. We thus confirm what other sources in the literature have recently reported too, regarding all fossil fuels and carbon-intensive coal in particular [1, 22, 28, 31, 32, 37, 40]. We add to this overall conclusion, however, that it only holds as long as the CO_2 leakage rate associated with CCS application is 0.5%/year or less [cf. scenario (c) versus (b) or (d)–(f)]. This finding is of major importance for the future realisation of CCS projects, and should be accounted for when choosing CO_2 storage sites and designing policies to stimulate CCS deployment, as well as generic climate and energy strategies. New in our analysis with respect to the references above is that we have not only included CCS technologies in a bottom-up energy-environment model, but have also explicitly accounted for possible leakage of CO_2 stored in geological reservoirs. CO_2 leakage is among the externalities with substantial environmental and climatic impacts that the application of CCS may engender, and thus bears importance for energy policy making.

While the specific assumptions on 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, it proves that accounting for an environmental effect like leakage of geologically stored CO_2 may also significantly influence the nature of future energy supply scenarios as derived with integrated assessment modelling. We thus recommend that extensive studies be performed to further analyse leakage effects, as well as to better quantify them, before CCS is deployed on a very large scale. The site- and time-dependence of leakage as associated with CCS is likely to be high, given the large geological differences that exist between the many kinds of possible storage mediums. This site- and time-dependence constitutes another important subject for further study. Furthermore, since CO_2 leakage probably cannot be entirely avoided, one of the other fields of study would be to determine more precisely the damage costs of CCS, involving both leakage and all other environmental and/or health risks involved with underground CO_2 storage, e.g. through a complete impact pathway analysis as performed for other energy resources and technologies in various EU externalities projects [5].

Acknowledgements The authors acknowledge the EU-funded TranSust.Scan project (no. 022773 under Sixth Framework Programme priority FP6-2004-SSP-4) for having provided the means to undertake this analysis. Additional funding from the Dutch Ministry of Economic Affairs is also appreciated.

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