Environmental Externalities of Geological Carbon Sequestration

Effects on Energy Scenarios

Koen Smekens and Bob van der Zwaan

NOTA DI LAVORO 58.2004

MARCH 2004

CCMP – Climate Change Modelling and Policy

Koen Smekens, *Energy Research Centre of the Netherlands (ECN), Policy Studies Department*
Bob van der Zwaan, *Energy Research Centre of the Netherlands (ECN), Policy Studies Department and Harvard University, John F. Kennedy School of Government*

Environmental Externalities of Geological Carbon Sequestration Effects on Energy Scenarios

Summary

Geological carbon sequestration seems one of the promising options to address, in the near term, the global problem of climate change, since carbon sequestration technologies are in principle available today and their costs are expected to be affordable. Whereas extensive technological and economic feasibility studies rightly point out the large potential of this 'clean fossil fuel' option, relatively little attention has been paid so far to the detrimental environmental externalities that the sequestering of CO_2 underground could entail. This paper assesses what the relevance might be of including these external effects in long-term energy planning and scenario analyses. Our main conclusion is that, while these effects are generally likely to be relatively small, carbon sequestration externalities do matter and influence the nature of future world energy supply and consumption. More importantly, since geological carbon storage (depending on the method employed) may in some cases have substantial external impacts, in terms of both environmental damage and health risks, it is recommended that extensive studies are performed to quantify these effects. This article addresses three main questions: (i) What may energy supply look like if one accounts for large-scale CO_2 sequestration in the construction of long-term energy and climate change scenarios; (ii) Suppose one hypothesizes a quantification of the external environmental costs of CO_2 sequestration, how do then these supposed costs affect the evolution of the energy system during the 21st century; (iii) Does it matter for these scenarios whether carbon sequestration damage costs are charged directly to consumers or, instead, to electricity producers?

Keywords: Geological carbon storage, External costs, Energy scenarios

JEL Classification: O33, O38, Q43

The authors thank the EU-funded VLEEM-2 project for the opportunity offered to perform this analysis within its program of long-term energy scenario research. They also acknowledge the EU-funded TranSust project, whose meetings provide the means to communicate the results of MARKAL studies to a wider community of energy and sustainability researchers. Bob van der Zwaan is grateful to the STPP program of the Belfer Centre for Science and International Affairs, Kennedy School of Government at Harvard University, for the stimulation received to undertake this and other research and writing projects. For inspiring discussions on the subject matter of carbon capture and storage, and comments to this paper, both authors are grateful to Heleen de Coninck, Howard Herzog, David Keith and Ari Rabl.

Address for correspondence:

Bob van der Zwaan
Energy Research Centre of the Netherlands (ECN)
Policy Studies Department
P.O. Box 37154 - 1030 AD
Amsterdam
The Netherlands
E-mail: vanderzwaan@ecn.nl or bob_vanderzwaan@harvard.edu

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 minimize the risks induced by substantial climate change (UNFCCC, 1992), carbon dioxide concentrations should be stabilized, preferably during the 21st century and probably at a level not exceeding much more than twice the pre-industrial level (IPCC, 1996). Adaptation to the consequences of climate change will almost certainly be necessary. "Geotechnical engineering" of the atmosphere, to counteract the radiative effects of increased levels of greenhouse gases, is probably undesirable. Removal of carbon dioxide from the atmosphere through the employment of biological sinks may likely contribute to only a limited extent to mitigating climate change. Thus, reducing anthropogenic greenhouse gas emissions substantially below the levels that would be implied by a "business-as-usual" scenario is imperative. In order not to exceed a doubling of the atmospheric carbon dioxide concentration, global carbon emissions from fossil fuel combustion in 2050 must not exceed those in 1990, and should decrease to about a third of 1990 levels by the end of the century (see, for example, Fetter, 1999). Given current and likely near-term future energy consumption increases and corresponding emission evolution patterns, this challenge is large.

The challenge, however, can be met. Many different measures must be exploited simultaneously to realize it, among which a control of global population growth, decreasing levels of energy use per unit of Gross Domestic (World) Product (GDP or GWP), and decreasing levels of carbon emissions per unit of energy use. Whatever means may to some extent contribute to alleviating the global warming problem, most specialists view a (partial) decarbonisation of energy use a necessity. For decreasing the carbon intensity of energy consumption, no panacea exists. Hence, all non-carbon emitting options should probably, for the moment at least, remain part of an energy mix as diversified as possible. Among these are very different (both conventional and still relatively unconventional) energy resources, such as hydropower, nuclear energy, renewables and decarbonised fossil fuels. Hydropower possesses a number of environmental drawbacks and is unlikely to be expandable so as to maintain its current relative share in an increasing world energy supply. Nuclear energy's future is unclear, since it faces a variety of problems related to radioactive waste, reactor accidents, nuclear proliferation, economic competition and public perception (Sailor *et al.*, 2000). Renewables (such as wind, solar and biomass energy) seem promising in many respects, but when and to what extent they can significantly contribute to global energy supply remains to be seen, impeded for the moment by relatively high costs and/or large land-use or resource requirements, and because it is unresolved whether renewables can be effective in ascertaining energy supply security (Turner, 1999). Therefore, expanding the decarbonisation of fossil fuels to options beyond a transition from carbon-intensive fossil fuels (coal and oil) to carbon-poor ones (natural gas) is currently receiving enhanced attention (Reichhardt, 1999; EIA/DOE, 2004; IEA/OECD, 2000a and 2000b; IEA-GHG, 2004).

The decarbonisation of fossil fuels through carbon dioxide capture and sequestration in the ocean or deep underground could contribute significantly to reducing anthropogenic greenhouse gas emissions (Marchetti, 1977; Parson and Keith, 1998; UNDP, 2000; Gielen, 2003). 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 already been demonstrated, notably through their use for a number of other industrial purposes (Hendriks, 1994; Williams, 1998). Technologies for carbon dioxide transport, via pipelines or with tankers, and for its compression or solidification, needed for storage, are all known in principle. Whereas deep-ocean storage is still at a relatively early stage of development and is likely to remain controversial, it has been shown that geological carbon sequestration is feasible and probably acceptable today (Herzog *et al.*, 2000). The Earth's geological storage capacity, in depleted natural gas and oil fields, aquifers and coal-beds, is likely to be large (Socolow, 1997; Bachu and Gunter, 1999; Lako, 2002). Carbon storage might, already in the short term, play an important role in mitigating global warming and protecting mankind against the detrimental regional and local effects of climate change (UNDP, 2000; IPCC, 2001). Therefore, energy analysts start presently to include carbon capture and storage alternatives in abatement scenarios for their integrated assessments of climate change. Still, insufficient attention has so far been paid to possible external environmental effects of carbon storage.[1] This paper attempts to contribute to filling the gap existing in this respect in the current literature.

In section 2 of this article we recapitulate what we think could be some of the major environmental externalities of geological carbon sequestration. Leaving a detailed technology externality calculation for future research, in section 3 we postulate some rationalized hypotheses concerning the order of magnitude of possible environmental impacts, in terms of external costs, of CO_2 sequestration. In section 4 we present our analysis results regarding the nature of long-term energy and climate change scenarios if one accounts for CO_2 sequestration (i), if one incorporates external costs of geological carbon storage (ii), as well as concerning the way in which damage costs are included in energy models, i.e. whether they are charged to energy consumers or, instead, to electricity producers (iii). Section 5 provides our major conclusions, describes a few recommendations and lines for further research, and discusses possible implications of our findings for policy making *vis-à-vis* future large-scale geological carbon sequestration.

2. Environmental externalities of geological carbon sequestration

Whereas the prospective benefits of carbon sequestration are significant, notably because it possesses the potential to catalyse a transition to a hydrogen economy, a number of important questions related to environmental hazards and safety risks remain (for a taxonomy of the various risks involved with geological carbon storage and potential impacts, see also van der Zwaan *et al.*, 2001; Wilson *et al.*, 2003). In scientific, political and non-governmental communities, a closer inspection of these external effects now starts to receive momentum.[2] At present, information about the potentially detrimental external environmental effects of carbon sequestration is far from complete. Uncertainties associated with negative sequestration impacts – that ideally ought to be addressed before carbon storage is employed at a large scale – abound, and their nature and extent are insufficiently understood. Without attempting to be exhaustive, we indicate below some of the geological storage externalities that we suspect could play a role in the future. We do not try to assign probabilities to these various potential impacts, or to quantify the uncertainties dominating their significance, given the lack of our current understanding of carbon sequestration external impact mechanisms. However inadequate our present knowledge about the external effects of carbon storage may be, we do not judge that this inadequacy is reason for not trying to include external costs in energy policy analyses. Instead, we postulate in the next section some hypotheses on these environmental impacts (means lacking for the moment to do better), which we rationalize and that could thus be considered crude 'guesstimates' to at least some extent. Subsequently, in section 4, we include them in our scenarios.

---

[1] The IPCC (Working Group III), in an envisaged Special Report on Carbon Dioxide Capture and Storage, is currently in the process of assembling a comprehensive overview of carbon storage options, including their detrimental environmental impacts.

[2] For a presentation on views and preoccupations of environmental NGO's regarding CO_2 capture and storage, see, for example, www.ipieca.org/downloads/climate_change/Oct03_workshop/3_Anderson.ppt.

Deep geological carbon storage can acidify water present at large depths underground. Natural gas and oil fields have a proven containment integrity record for millions of years. Still, storing carbon dioxide in such fields (once depleted, or while depleting) could have an acidification impact on underground waters. In a similar way, water in deep underground aquifers could undergo acidifying effects by CO_2 injection (Chen *et al*., 1999). In both cases, groundwater pollution of nearby freshwater aquifers may result, if the containment of the aquifers into which CO_2 is injected is breached. This could affect the quality of drinking water, if the latter is obtained from sources fed by the polluted groundwater. Enhanced Coal-Bed Methane (ECBM) recovery and Enhanced Oil Recovery (EOR) carbon storage can in principle pose similar groundwater pollution effects (Wong *et al*., 1999; Liu *et al*., 1999). A related problem is that the process of reservoir fluid/gas displacement by CO_2 insertion, and the resulting modification of the hydrodynamic properties of underground geological layers, can have a negative impact on the water extraction potential of certain sources. Perhaps more importantly, as a result of CO_2 injection in geological layers, their integrity could be disturbed. In the case of aquifers this could lead to the brine they contain migrating to other layers in contact with freshwater aquifers serving as source for drinking water.

As a result of underground carbon sequestration, structural changes could occur in geological formations, as well as modifications of the thermodynamic properties – and even dissolution – of underground geological layers. Both such geological modifications and the CO_2 injection process itself could involve seismic activity or soil cave-ins, with uncertain aboveground impact, depending both on site and option chosen.[3] Altered chemical properties of geological formations as a consequence of carbon sequestration, or the build-up of localized high pressures, could affect the stability of the geological layers above. Resulting from a large range of possible geo-chemical reactions of carbon dioxide with underground geological structures, cocktails of gases can be formed, the bearings of which to either the underground or aboveground environment (including plants, animals and humans) are largely unknown today. All these matters can affect or have pervasive consequences on habitat conditions.

It is not improbable that carbon dioxide gas could gradually - and without being noticed - migrate and slowly leak from where it is stored (Ha-Duong and Keith, 2003). This threat ranks high among the potential risks of geological carbon storage, since it could seriously hamper its suitability as global warming mitigation alternative. Since natural gas has long been stored in geological formations, one could draw a parallel and conclude that long-term secure sequestration of carbon dioxide seems feasible. Given that the physical and chemical properties of CO_2 are different from those of CH_4 (the latter being chemically more inert than the former), however, it may not be guaranteed that its artificial storage underground retains integrity forever. Especially regarding options other than depleted gas and oil fields, such as aquifers and coal beds, long-term storage effectiveness aspects are uncertain. Migration times vary according to the sequestration option considered, and depend on the characteristics of the geological formation of the site specified (NITG, 2004). The leakage time frame that typifies each option and site, and the compatibility of that time frame with global warming mitigation efforts (determined by the features of the natural carbon cycle), is determinant for the option’s suitability to preclude or postpone presumed climate change effects.

Probabilities for catastrophic well blowouts (e.g. during injection) may be exceedingly small and the associated risks negligible in comparison to those involved with carbon seeps, but the eventuality that artificially stored carbon dioxide gas could escape rapidly, in large amounts at once, may not be left unmentioned. Sudden carbon releases could in principle have global warming effects - if large enough - as well as severe accidents with human casualties. Although the hazards involved are likely to be only local and temporary, they could be pervasive. However

---

[3] Note that, inversely, carbon dioxide sequestration could be employed to restore (re-pressurize) natural or artificial surface soil cave-ins, e.g. resulting from pressure decreases generated by fossil fuel mine/field depletion.

inappropriate a comparison may be between artificially stored CO_2 and amounts built up in some natural cases, a frightening phenomenon remains the natural disaster that occurred in Cameroon in August 1986. Carbon dioxide welled up from deep in Lake Nyos, and was responsible for killing, by asphyxiation, 1,700 people and their livestock (Holloway, 2000). This concerned a very unique and unfortunate case, different in many ways from CO_2 stored underground by Man, but it should not be fully neglected, and shows that one has in principle to be weary of unexpected potential risks.[4] Accidental releases of CO_2 should also be considered regarding high-pressure CO_2 transportation, which would become part of the carbon sequestration solution. CO_2 pipelines exist already, and specialists ascertain that their safety record can be considered better than that of natural gas pipelines. Multiple safety devices are built-in throughout the various stages of CO_2 transportation methods, but risks for personal accidents as a result of pipeline defaults and sudden CO_2 releases, e.g. for workers involved in network maintenance or for people living in the vicinity of pipelines or CO_2 compression installations, are not zero. If CO_2 transportation via pipelines is operationalized at large scales, such risks will augment accordingly. Land-use issues may then also increasingly play a role of significance.

3. Damage costs

How does one go about quantifying the qualitative observations made above regarding the potential externalities of geological carbon sequestration? In principle, to evaluate the impact and damage cost of any pollutant, one needs to 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 disposed or emitted, (2) a calculation of the dispersion of the pollutants, (3) a calculation of the impact of these pollutants, and (4) the monetary valuation of the costs of these impacts. The impacts and costs must then be summed over all impact types and receptors of concern. For the fossil fuel chain including carbon sequestration, part of the damage cost arises from combustion in power plants (corresponding to the pollutants that are not captured but emitted into the atmosphere), while the other part arises downstream from power generation, that is, as a result of the environmental externalities of geological carbon sequestration. For most energy resources, such 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, however, have so far not included calculations on externalities resulting from geological carbon sequestration. The scientific knowledge required for externality calculations for carbon sequestration, e.g. regarding migration of carbon-induced products through underground layers, is still largely absent. Without data on geological chemical diffusion, these calculations cannot be performed, and even if they were available today, it would fall beyond the scope of this paper to perform these (extensive and detailed) calculations here.

Still, however, we think it may be insightful to perform an energy scenario analysis including not only carbon sequestration technologies, but also the external costs that could be associated with them. Lacking either theoretical or experimental data regarding external impacts, we have chosen to make some hypothetical assumptions concerning their costs. By including these in our scenario analysis, we hope to trigger work directed towards the proper calculation of external costs of carbon storage, or at least towards a more careful, but perhaps still crude,

---

[4] In the case of Lake Nyos, CO_2 rises up from deep volcanic activity and via groundwater beneath the lake dissolves in the lake’s lower water layers. Lake Nyos does not turnover, however, so that CO_2 gas saturates the bottom water until some trigger (e.g. a storm or earthquake) provokes the deep water to suddenly move upward. This resulted in 1986 in CO_2 coming out of solution in large quantities, and erupting, like champagne uncorked, into an 80 m high jet of water and CO_2. The CO_2 gas, heavier than air, subsequently rolled down the hills in a large cloud, asphyxiating everything it found on its way.

estimation of them. Deriving rough but reasoned guesses of what external costs of carbon sequestration could be would allow getting better feeling for their consequences for energy-climate modelling, as well as for their policy relevance. For the moment, however, we cannot do much more than simply postulating a set of numbers. We will, nevertheless, attempt to somewhat justify our 'manna-from-heaven' figures in this section. Thus, while avoiding to undertake a detailed geological carbon storage externality calculation *à la* ExternE – we will leave such work to future research activities – we attempt to somewhat validate our hypothetical quantification of the (order of magnitude of the) external costs associated with the environmental impacts of CO_2 sequestration.

For this justification, we rely on the numbers generated by Rabl and Spadaro (1999), which are based on ExternE (1998), for the externalities resulting from the use of the three fossil fuels based on technologies employed during the 1990s and 2000s. For these two time periods, the Rabl and Spadaro (1999) figures are quoted in table 1. We use these, as well as their comparison with the corresponding numbers for renewables and nuclear energy, as reference for our hypothetical figures on coal, oil and gas externalities for the 2010s and thereafter. For the latter time period we assume that geological carbon sequestration is added to the use of fossil fuels. Our postulated estimates for the damage costs, involved in fossil fuel use, of carbon sequestration are also presented in table 1. The figure of 0.2 ¢/kWh hypothesized for the external geological storage costs for fossil technologies in the 2010s is assumed neither to vary over the technology considered nor over time from 2010 onwards. The main reason is that externality costs at large, and our postulates in particular, are subject to great uncertainties and may vary by even an order of magnitude depending on the option under consideration. Since these uncertainties are dominant, we merely perform a "*suppose that... what then...?*" analysis with these fixed and constant figures.[5]

Damage costs (¢/kWh)	**Total**	**PM_{10}, SO_2, NO_x**	**Global Warming**	**CO_2 Sequestration**
Coal 1990s	13.3	10.5	2.8	-
Coal 2000s	3.8	1.1	2.7	-
Coal 2010s	***1.3***	***0.6***	***0.5***	***0.2***
Oil 1990s	10.0	8.2	1.8	-
Oil 2000s	3.2	1.4	1.8	-
Oil 2010s	***1.3***	***0.7***	***0.4***	***0.2***
Gas 1990s	2.8	1.6	1.2	-
Gas 2000s	1.5	0.3	1.2	-
Gas 2010s	***0.6***	***0.2***	***0.2***	***0.2***

Table 1. Damage costs for fossil fuel chains in the EU. Carbon sequestration is included in 2010. Note that production cost of base load electricity in the EU is in the range of 2.5 to 5 ¢/kWh. Source: ExternE (1998), for 1990s and 2000s, and author's hypotheses, for 2010s and thereafter.

---

[5] For future work we intend to perform a proper sensitivity analysis, in which we vary our externality assumptions over e.g. an order of magnitude and analyse the effect of this variation on our scenario results. Within the present knowledge of uncertainty concerning these figures, we do not judge it sensible to distinguish between different external sequestration costs for e.g. gas and coal, although natural gas usage emits only about half of the carbon dioxide of coal power generation.

In postulating the figures of table 1 for the damage costs of coal, oil and natural gas with 2010 technologies, we have made the following assumptions. First, it is unlikely that all external costs in the two first categories can be avoided: not all particulate matter (PM_{10}, of size smaller than 10 μ), SO_2, NO_x emissions, on the one hand, and global warming (mainly as a result of CO_2 emissions), on the other hand, will be eliminated when pollution removal and carbon capture are applied. This explains why non-zero figures remain for these two entries for 2010 technologies.[6] Second, it is supposed that in 2010 damage costs due to particulate matter, SO_2 and NO_x will be further reduced to about 50% of current damage costs, given the improvement in capture technologies that still takes place. Third, it is assumed that in 2010 damage costs due to global warming will be reduced, through carbon capture and sequestration, to about 20% of current costs, given that 80% GHG emission reduction can probably be implemented relatively soon and cost-effectively (Hendriks, 1994). Technologies that can reach capture levels that near the 100%-level exist (IGCC seems the most likely route forward for new power plants, which reduces emissions at the plant by easily 95%): but we want to be realistic in that not all greenhouse gas emissions are likely to be avoided completely anytime soon, mainly for economic reasons.

Furthermore, the damage costs of carbon sequestration are expected not to exceed the range of those for renewables and nuclear energy. The latter have been calculated to be about 0.2 ¢/kWh (Rabl and Spadaro, 2000).[7] We think it is reasonable to make conservative assumptions regarding the damage costs of carbon capture and sequestration – resulting from e.g. carbon dioxide dissipation, sudden releases of carbon dioxide, acidification of underground water, and the chemo-geophysical modification of underground geological layers – in which their level does not surmount (and is at most of the same order of magnitude as) the average damage costs of renewables and nuclear energy. Two main arguments can be given to back this assumption.

First, like with nuclear energy, the use of fossil fuels with carbon sequestration involves the geological storage underground of by-products of the energy chain (for the nuclear case, see, for example, Milnes, 1985). But that is probably where the comparison stops: for radioactive nuclear waste one has relatively small quantities of highly toxic products, whereas for carbon sequestration one has very large quantities of CO_2 with low toxicity. Indeed, the magnitude of material disposed is vastly less for nuclear energy and the material is vastly more dangerous than with fossil fuel use with carbon storage. For both, one multiplies a big number by a small one, but it is unlikely that the result of it equals in these two (inverse) cases. One cannot claim, therefore, that the corresponding costs could be the same, or even of the same order of magnitude. The nature of the products involved is too different, especially considering the health effects of chemically active reactants, for carbon storage, *vis-à-vis* those of radioactive substances, in the case of nuclear energy. Chemical acidification is likely to be much less hazardous to the environment and harmful to humans than radioactive contamination. Hence, damage costs for carbon sequestration are probably smaller than those for nuclear energy, that is, for radioactive waste disposal. Estimates for the latter (however controversial these might be) can be considered a pessimistic upper bound for guesses of the former, thereby justifying our conservative choice of 0.2 ¢/kWh for carbon storage damage costs.

---

[6] Of course, in the case of SO_2 emission reductions, almost all SO_2 can technically be removed with either amine or IGCC systems (for PM_{10}, NO_x and CO_2 it is more difficult to achieve total removal). But it will not easily be considered cost-effective to reach such close-to-zero limits.

[7] For wind and PV, high and low estimates fall within a width of some 0.1-0.2 ¢/kWh, while for biomass damage costs amount to about 0.1-0.6 ¢/kWh, depending on the technology chosen. For nuclear energy, damage costs are distinguished between short-term and long-term, amounting to values below 0.1 and around 0.2 ¢/kWh, respectively. On average, therefore, a value of 0.2 ¢/kWh seems to be reasonable for the damage costs of these renewable and fission alternatives.

Our second argument derives from our assertion that the total costs of electricity (including all external costs) for different energy technologies will perhaps become the most important determinant for the permissible (internal and external) costs of sequestration. If external costs are to be internalised (this is now official EU policy), and if external costs for carbon sequestration prove to be – and remain – much higher than those for renewables (supposing that at least some renewable energy options will reach competitive break-even with fossil fuels including carbon storage in the not too distant future), carbon sequestration will not see the daylight on any large scale because of a lack in economic interest. Wind power, for example, is at present becoming competitive at various locations, while on average still being more costly to generate than conventional (fossil-fuelled) electricity. It can be reasonably expected that wind energy production costs continue to decrease over the coming years, while its external costs may remain about 0.2 ¢/kWh. Other renewable energy resources, such as PV, are still considerably more expensive than fossil-based electricity, but are also expected to continue to be subject to economic learning. Capturing, transporting and sequestering CO_2 may increase competitive fossil energy production costs by a factor of two, when e.g. about 80% of the CO_2 released is avoided. In other words, competitive costs of fossil-based power production including sequestration may approximate renewable energy production costs over the decades to come, so that - on the basis merely of production costs - a comparable electricity price results for these two distinctive alternatives. But this does not yet account for damage costs. Damage costs of carbon sequestration may then surely not exceed the (renewable) 0.2 ¢/kWh level of external costs, in order for carbon sequestration to remain competitive with these cheap renewable options (and given that fossil fuels with carbon sequestration still involve some of the remaining external costs other than those related to sequestration). We assume that those carbon sequestration technologies will emerge that are both environmentally attractive and are able to survive in competitive markets, which justifies our choice for the above quoted (conservative) upper-bound values of external sequestration damage costs.

4. Long-term energy scenarios

If in the future the energy system is going to be subjected to stringent climate constraints, the use of coal for power generation will be put into disadvantage, even in comparison to its fossil-fuel-based counterparts (oil and natural gas). Clearly, when ambitious global warming goals are to be met, the role of coal in our energy mix should be significantly reduced. Scenario analyses demonstrate that coal indeed loses importance under these conditions. With much of its emissions being avoided through carbon capture and storage, however, this picture dramatically changes: coal can largely continue to play the important role it does today. But with coal retaining a large share of global energy consumption, a proper analysis should be performed of its full external environmental impact, not only in terms of the generation of mining wastes and its continued contribution to global warming and local air pollution, but also in terms of the possible damage effects of geological carbon sequestration. What is the effect of including damage costs for carbon sequestration on the construction of long-term energy supply scenarios? To answer this question, we have used the MARKAL model. Before presenting our modelling results, the main features are described of the MARKAL version we employed.

4.1 The MARKAL model

MARKAL is a commonly used bottom-up model for energy system analysis based on cost optimisation. The model algorithm has been expanded over the years, resulting today in a number of possible extensions that can be employed in combination and in conjunction with the basic version. But its major 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 for the entire modelling timeframe under consideration.[8] The version often used nowadays for policy analysis studies is the one with endogenised technological learning and price elasticities. Its geographical coverage is Western Europe (WEU), that is, the 15 EU countries *anno* 2003, expanded with Norway, Switzerland and Iceland. This area is treated as a single region, so there is no specific country dis-aggregation.

The emissions considered for this study are the CO_2 emissions from both fuel combustion and industrial processes. Emission removal is considered both through carbon sequestration in geological storage options and via uptake by land use, agriculture and forestry. The model distinguishes 6 geological CO_2 storage options: aquifers, Enhanced Oil Recovery (EOR), Enhanced Coal Bed Methane (ECBM) recovery (2 different options, at different depths) and depleted oil and gas fields (2 options: on-shore and off-shore). They are each 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 21 technologies are modelled: 10 in the electricity sector (coal, oil and natural gas based), 6 in industry (mainly in ammonia, iron and steel production), and 5 in the fuel conversion sector (in the production of hydrogen from fossil fuels).[9] Figure 1 illustrates the basic functioning of MARKAL, with the supply side at the left, the conversion and transformation phases in the middle, and the end use at the right.

Some features, assumptions and limitations of MARKAL deserve additional attention. The model does not incorporate trade, changes in import-export balances of electricity, rebound or other feedback effects at the macroeconomic level resulting from price changes, e.g. induced by the incorporation of external costs. Assumptions with respect to implementation barriers of technological options, as well as various socio-political considerations, can be inserted, but have not been regarded as relevant for this study. Although MARKAL may cover other pollutants and other greenhouse gases (GHGs) than CO_2, within the context of the present study the analysis has been restricted to carbon dioxide only (accounting presently for about 80% of all GHGs in Western Europe). This implies that only the global warming and sequestration parts of the external costs of table 1 have been considered for our energy scenario inspection. For older technologies from the 1990s, these represent only the smaller part of total external costs. For recently and future installed technologies, however, the global warming impacts are expected to involve generally the largest among the three sources of external costs. Since the emphasis in the current analysis lies on the effects of the inclusion of CO_2 sequestration external costs in electricity production, it is the cost difference as a result hereof that matters mostly (rather than the absolute value of remaining external costs).

---

[8] It is a linear programming bottom-up energy technology model, using GAMS and a linear solver (CPLEX or OSL). The time frame by the model version used covers the 1990-2100 period, and the programme is solved in 10-year steps. The database linked to the use of MARKAL contains about 70 different demand categories at the end-use-side, and in total more than 900 energy technologies at the supply-side (involving both existing and future options).

[9] Note that for the analysis presented in this paper, no carbon sequestration à la the Sleipner project is included, that is, in which CO_2 is captured from natural gas field exploitation and subsequently re-entered in underground layers.

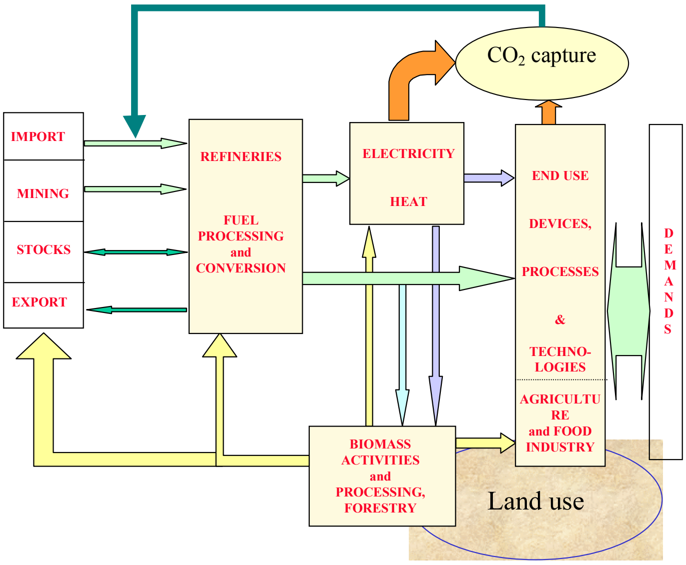

Figure 1. Flow diagram of MARKAL with carbon capture and sequestration. The upper (dark green) arrow indicates that some storage activities have energy recovery as co-benefit.

Cost reductions of technological options are assumed to evolve through learning curves. This assumption 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 installed capacity. Learning curves are based on observed phenomena in the past, and applied in our MARKAL version to future technological cost developments. 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 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 MARKAL 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.

A weak point of traditional MARKAL models is that 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. Of the two approaches that 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 significant differences that exist between the two in computer calculation times.[10] 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 and product service prices. A main advantage of the model is that it is still based on linear equations, allowing rapid calculations. With non-linear demand equations, with current machines and calculation capacity at least, it would not be possible to run our complex WEU model. Figure 2 shows the (simplified) equilibrium that is achieved in traditional MARKAL models. Figure 3 shows the equilibrium that is achieved in the model version we use, with elastic demands.

---

[10] Note that both MARKAL-MACRO and MARKAL-ED are attempts to bridge the worlds of bottom-up versus top-down modelling. For example, these models constitute a first step towards allowing for the study of welfare effects with the bottom-up approach, through a calculation of changes in consumer plus producer surplus.

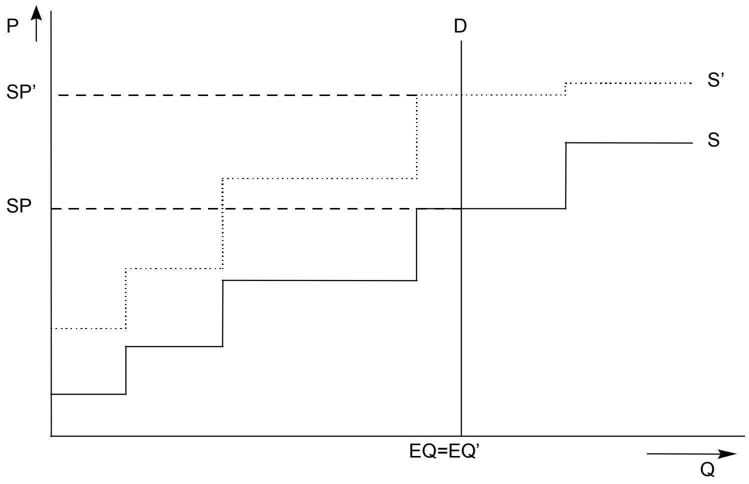

Figure 2. Supply (S and S') and demand (D) price-quantity equilibrium in traditional MARKAL models. EQ=EQ' indicates the equilibrium quantity (Q); SP and SP' are the shadow prices (P).

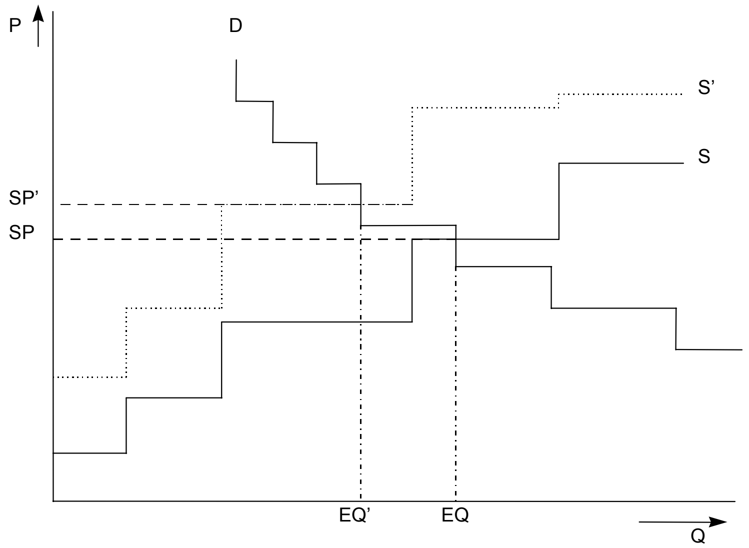

Figure 3. Supply (S and S') and demand (D) price-quantity equilibrium in our MARKAL-ED model for Western Europe. EQ and EQ' indicate the equilibrium quantities (Q); SP and SP' are the shadow prices (P).

As depicted in both figures 2 and 3, all supply and demand curves are linearized in MARKAL (typically a 20-step function), allowing the use of a linear algorithm to solve the programme. Supply curves are derived from the database of supply options and their characteristics. In traditional MARKAL models (figure 2), energy demand is independent of its price, so that the demand function is a vertical line. In MARKAL-ED (figure 3), the demand decreases if the price increases, so that the demand function is a curve with a downward slope. Equilibrium between supply (S) and demand (D) is reached in point EQ, which is the same for both figures in the base case calculation without GHG emission penalties. If GHG penalties are introduced, the supply curve moves upward, because all emissions in the supply chain are penalised (S changes to S'). In the case of fixed demand (figure 2), this has no consequences for the demand (EQ=EQ'). However, shadow prices increase (from SP to SP') in both figures. In the case of elastic demand (figure 3), demand decreases and a new equilibrium price and quantity are achieved, below the EQ' prices and quantities in the case of fixed demand (figure 2). The precise form of the demand function used in our analysis, applied to all energy resources and technologies, is:

$$D_{i,p}/D_{i,b} = (P_{i,p}/P_{i,b})^{ei}$$

in which:

$D_{i,p}$ = demand for energy i after introduction of GHG penalty
$D_{i,b}$ = demand for energy i in the base case
$P_{i,p}$ = energy price i after introduction of GHG penalty
$P_{i,b}$ = energy price i in the base case
ei = price elasticity for energy i

While it is known that price elasticities may diverge considerably (see, for example, Franssen 1999), even within a single demand category, we have assumed that all elasticities in our model are fixed at a value of -0.5. Long-term demand elasticities typically lie within bounds between -0.1 and -2.5. Still, most long-term demand elasticities usually range from -0.1 to -0.5. Our value of -0.5 is considered to represent an upper limit for the impact of demand elasticities, given the fact that our model also simulates other demand reduction and increase effects (e.g. through endogenised technological learning). The high value for elasticities is compensated by e.g. rather stringent limitations on the rate at which energy demand may vary.

4.2 Results

Before looking in detail into the consequences of adding damage costs for CO_2 sequestration in our model, we attempt to answer the first question we pose ourselves: how does energy production change if one includes carbon sequestration technologies in long-term scenarios? We look at the energy system, and the electricity generation scheme in particular, as calculated both before and after the introduction of carbon sequestration technologies. Two sets of scenarios are presented, to illustrate the effect of adding CO_2 sequestration options. The first set (figures 4a and 4b) includes a base case and a CO_2 reduction scenario, as derived before CO_2 sequestration was included in the MARKAL database. The base (or reference) case is a business-as-usual scenario, without the imposition of a climate constraint. The reduction case illustrates a stabilisation scenario by 2100 at 550 ppmv atmospheric carbon dioxide concentration, modelled through a cumulative limit on the total amount of emissions between 2000 and 2100, the year in which the required maximum concentration level is reached. The second comparative scenario set (figures 5a and 5b) involves the same two (business-as-usual, respectively stabilisation) scenarios, but this time with sequestration technologies included (but still without external damage costs). All four figures show the total amount of electricity production (in TWh) by means of production (fuel source). For each of them, the price-elastic version of MARKAL is used for the stabilisation scenario, in order to avoid rigid demand levels under a severe climate objective.

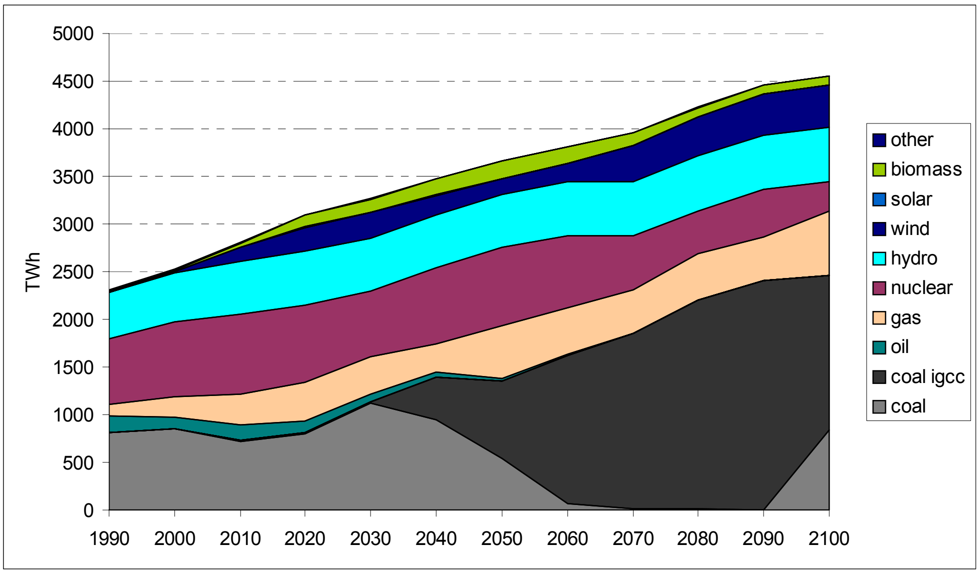

Figure 4a. Electricity production by energy source in the base case scenario (no carbon sequestration technologies included).[11]

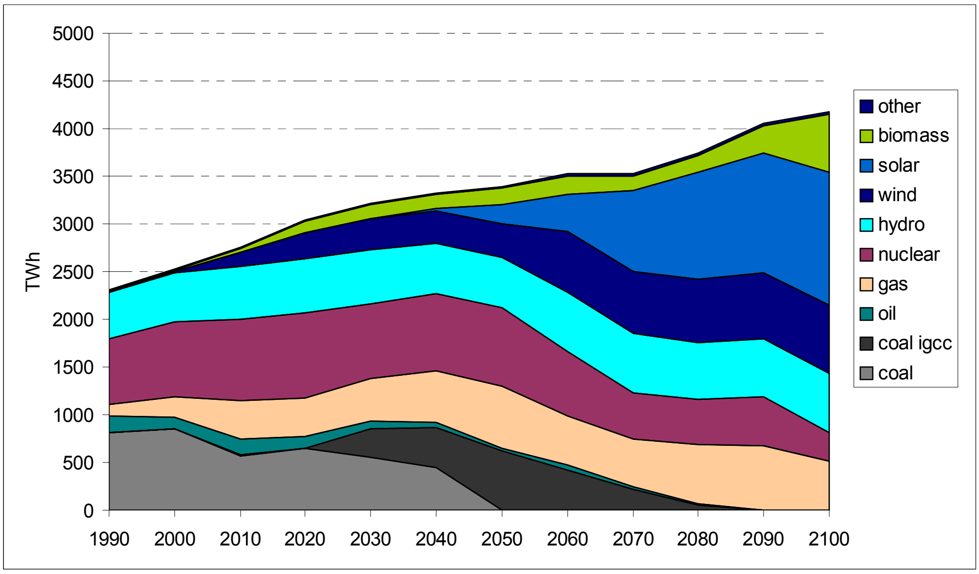

Figure 4b. Electricity production by energy source in the climate-constrained scenario (no carbon sequestration technologies included).

From figure 4a, one observes that in the reference case renewables (mainly wind and some biomass) emerge early, and subsequently remain almost constant at a relatively modest share. Hydropower remains roughly stable, while nuclear energy decreases slightly. The use of natural gas increases significantly, but by far the largest increase occurs in the production of electricity through cheap coal technologies. From 2030 onwards, the major production source is coal through the advanced type Integrated Gasification Combined Cycle (IGCC). In the 550 ppmv stabilisation case, depicted in figure 4b, both the total production decreases and the production mix changes. The decrease in energy demand, and thus production, results from the use of elastic demand curves, and is induced by an increase in energy prices that allows meeting

---

[11] Note that this and following figures should be interpretable in black-and-white: the energy contributions in the graph appear in the same order, from top to bottom, as in the corresponding explanatory box. Still, they remain most illustrative in full colour.

the climate constraint. Nuclear energy remains available because it involves zero carbon emissions. Hydropower remains roughly stable: it has no room for expansion within Western Europe, so it cannot contribute more to power production. Under the climate constraint, coal disappears completely, even with the advanced IGCC technology, while wind and solar energy increase substantially. To compensate for the increased power production from intermittent renewables like wind and solar energy, biomass and natural gas use also increases.

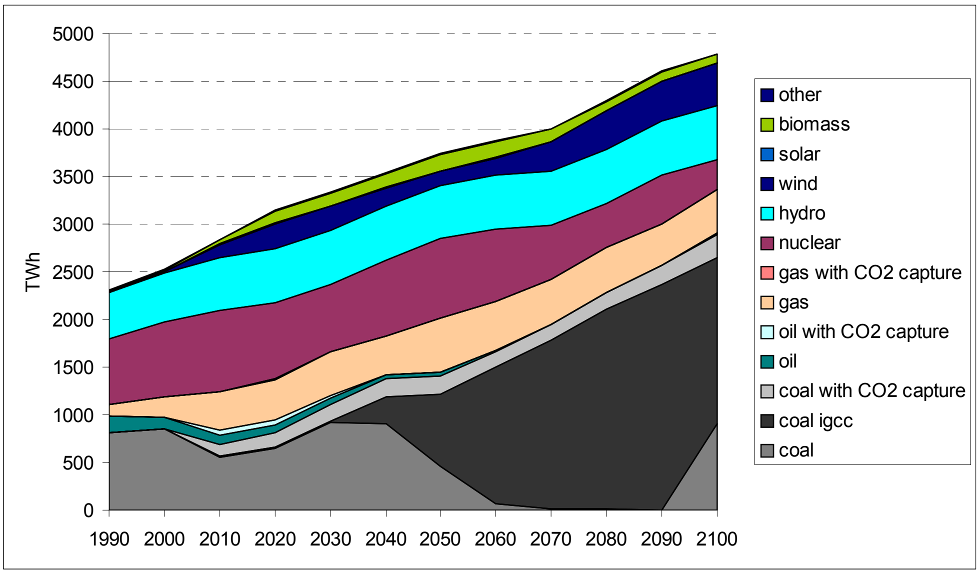

Figure 5a. Electricity production by energy source in the base case scenario (with carbon sequestration technologies).

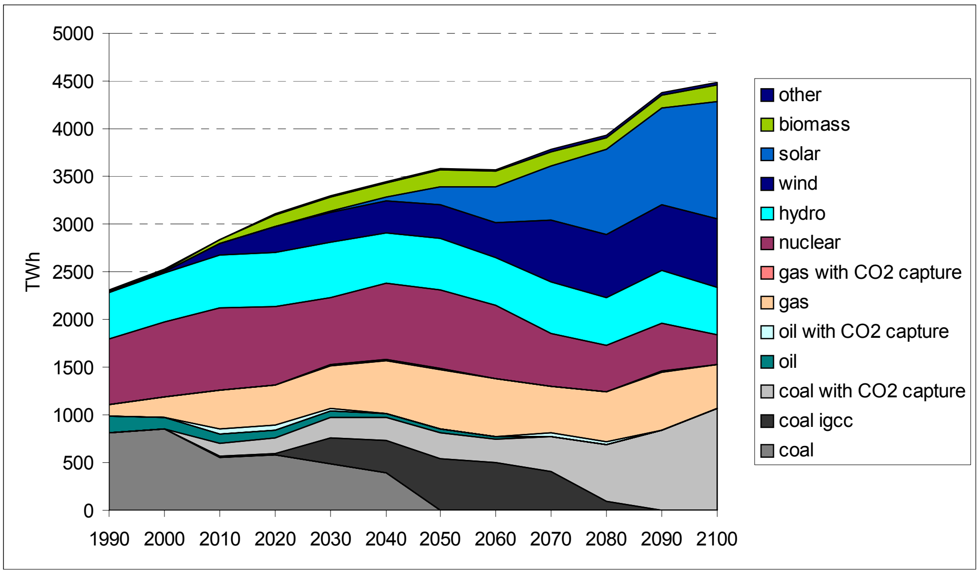

Figure 5b. Electricity production by energy source in the climate-constrained scenario (with carbon sequestration technologies).

From figure 5a, one sees that even without climate constraint it becomes worthwhile to invest in coal with CO_2 capture rather early in time, while oil and natural gas based electricity production with capture remains marginal throughout the entire simulation period. The reason for the use of coal with carbon capture to become profitable is that the CO_2 captured is used for

ECBM. Through the recovery of methane by the injection of CO_2 in coal beds, it becomes cost-effective to invest in coal power plants that include carbon capture and sequestration, in addition to the vast use of coal through IGCC. Otherwise, figures 4a and 5a differ little from each other. Note that one may judge it remarkable, and even unlikely, that ECBM will make carbon capture profitable without carbon constraints; in our case it appears as an opportunity largely as a result of our parametric assumptions on fuel prices. As can be seen from figure 5b, in the climate-constrained scenario, allowing for geological carbon storage implies that coal remains an electricity option for the rest of the century at a fairly constant share (and coal is not phased out like in figure 4b). Coal with carbon capture is developed to a large extent, especially during the last decades of the 21st century. Again, the reason is that CO_2 is injected in coal seams to extract methane, which on its turn is fed into the energy system. In this stabilisation case, compared to the stabilisation scenario without carbon capture, coal-based electricity production with CO_2 capture replaces some of the renewables (biomass and solar energy). Again, one observes that overall electricity supply in figure 5b is lower than in 5a. The reason is that in the 550 ppmv stabilisation case, a reduction has to be realised of up to 40-60% of annual carbon emissions by the end of the century. This reduction will affect seriously energy prices, and hence end-use behaviour, demand and production. A fixed price-insensitive demand would over-estimate future energy use under severe climate constraints, and also pose a heavier burden on the energy system as a whole in meeting these constraints.

If one applies the external costs from table 1 to electricity production costs, and assumes 0.2 €ct/kWh external costs for all other production options (renewables, nuclear and hydropower), it is not surprising that both the overall production level and the electricity production mix changes. The differences between scenarios with and without external costs prove important. For our purpose, most interesting is to look at the results in two external cost cases, namely with and without CO_2 sequestration costs. Figure 6 illustrates (in the BAU case) how the introduction of global warming external costs influences the total production of electricity, as well as the nature of the resulting production mix. The figure depicts in particular how the share (or rather, contribution) of some energy resources decreases (options that result in bars above the 0-line) and the share of others increases (bars below the 0-line).[12] As can be derived from the difference between the bars above and below the x-axis, the total power production is lowered slightly as a result of incorporating external global warming costs (between 0.5 and 2.0%). As can be seen from the figure, in terms of the production mix, the use of coal with conventional technologies is reduced, but the part lost is mainly replaced by the use of coal through IGCC. Also the use in production of natural gas and wind is increased modestly. The use of nuclear energy is slightly increased in the short term, but loses in importance in the longer run, according to our modelling results.

---

[12] Note that in figures 6, 7 and 8, we want to present the effect (on electricity supply, resulting from including external costs) in terms of the *reduction* of contributions from different energy resources, so that *decreases* appear as *positive* columns (and *vice-versa*).

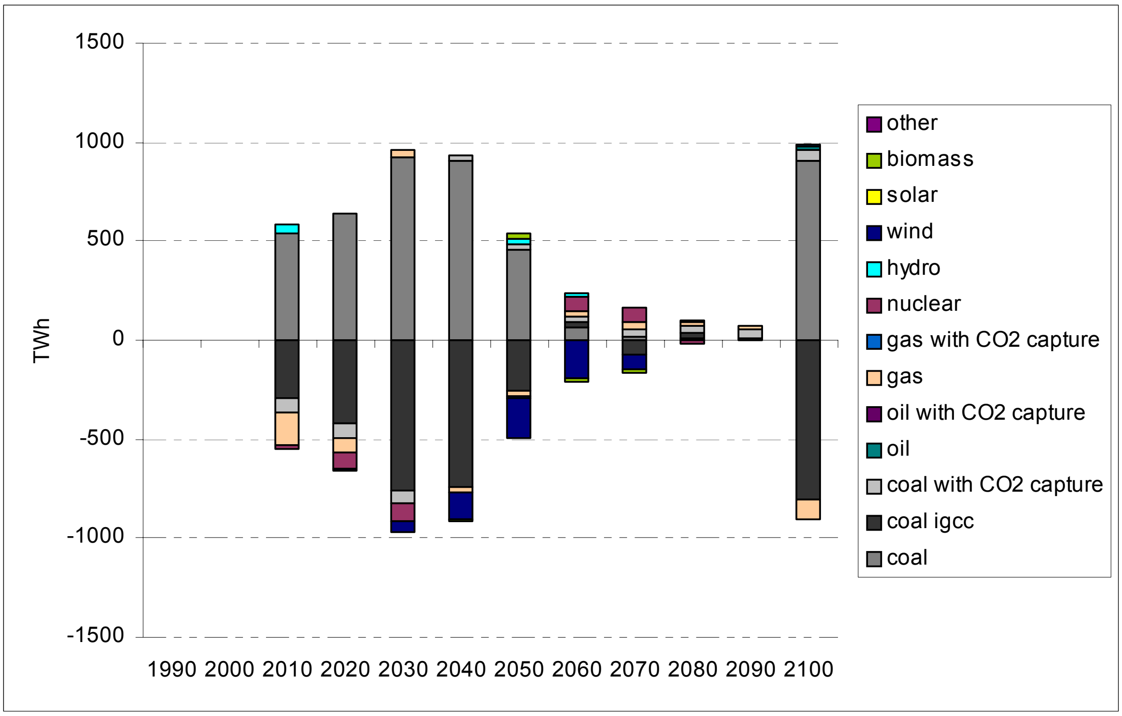

Figure 6. Overall and energy-specific reduction in electricity production after applying global warming external costs (BAU case).

Figure 7 displays the changes induced when, in addition to global warming external costs, also external costs for CO_2 sequestration are applied (again for the BAU case). First of all, one observes that the total change in electricity generated (all externalities in comparison to global warming externalities only) is relatively small, about an order of magnitude smaller than in the case of figure 6 with the introduction of global warming costs only (in comparison to no external costs). Both in the cases of no inclusion of external costs and the incorporation of global warming external costs only, the use of coal with carbon capture and sequestration was able to develop to some (rather small) extent. When also sequestration external costs are accounted for, coal-based production with CO_2 capture loses part of its share, as can be seen from the bars above the 0-line in figure 7. The share lost is mostly replaced by coal based on IGCC and the use of natural gas (and to a lesser extent also biomass). Overall (and understandably), the shift of technologies results in a total production level that is lower than in the case with only global warming external costs, the difference being on average 4 TWh/yr. This reduction comes on top of an average reduction of 35 TWh/yr after the inclusion of global warming external costs only. Thus, the inclusion of external costs for CO_2 sequestration has a further dampening effect on power generation, while the price difference between various electricity generation sources becomes less pronounced. As can be seen from figure 7, the overall electricity production reduction is largest at the end of the time horizon, and lowest in the very beginning. This means that, while the effects of including external sequestration costs are felt during the entire modelling time frame, the effects are significantly larger at the end of the 21st century than when they start being applied. This is a specific feature of our version of the MARKAL model used.

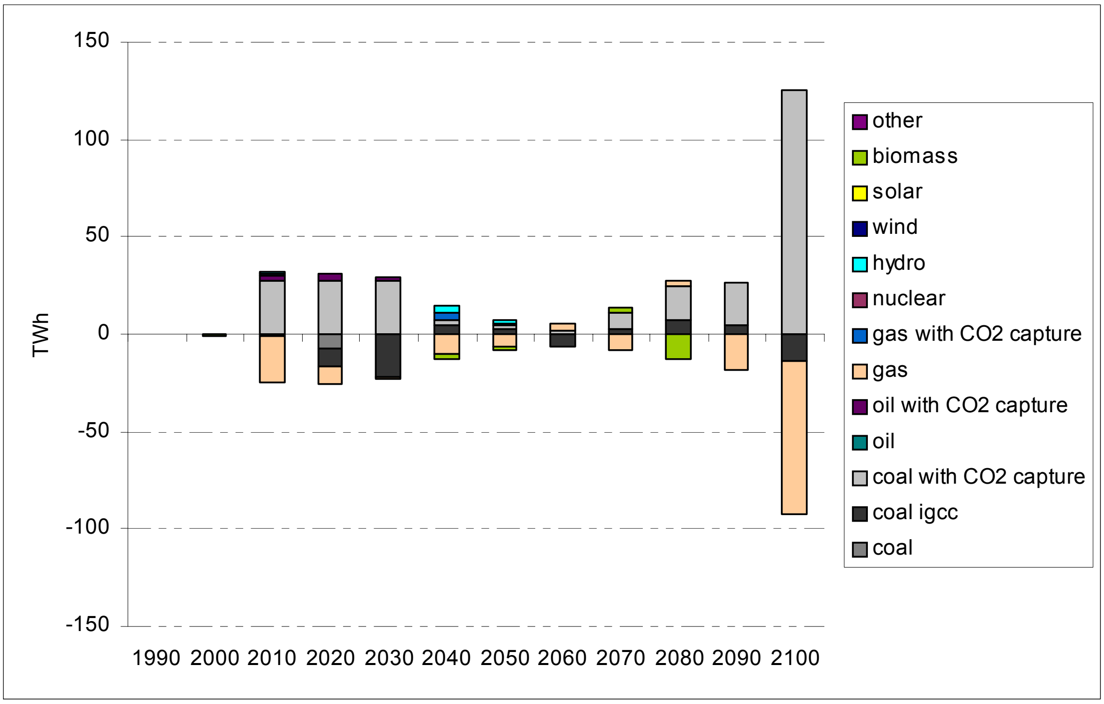

Figure 7. Additional overall and energy-specific reduction in electricity production after also including CO_2 sequestration external costs (BAU case, producer-side).

For both figures 6 and 7, the external costs are implied at the producers level as add-on to the fuel cost used as input in power plants. However, two variants can be considered, one where the external costs are distributed over power producers by adding it to fuel costs (as done for figures 6 and 7), and one where the external costs are distributed over the end-users as add-on to electricity prices. In the second case, the system not only optimises demand, but does so while taking into account increased delivery prices of electricity as set by producers. This, naturally, results in a lesser demand, and, as a consequence, a lower level of production. The difference, like in the first case, in total power generation (in a business-as-usual scenario) between with and without (global warming plus carbon sequestration) external costs lies in the order of 40 TWh/yr, or about 2% of total production. As a matter of fact, since the overall reduction in demand as a result of additionally including carbon sequestration is about 8 TWh/yr on average in the second case, the production level change as a result of the inclusion of all externalities lies this time slightly above 40 TWh/yr. The detailed results are depicted in figure 8. One sees that the features observed in this (consumer) case are roughly similar to the ones as found in the first (producer) case (compare figures 7 and 8). For example, coal-based power production including carbon sequestration is partly substituted by IGCC coal power production, the latter becoming more attractive due to the smaller impact of external sequestration costs on the output price of electricity. Also natural gas based production profits from the changed difference in production costs per kWh, and increases its share. If IGCC technologies gain in importance, it indeed seems logical that the use of natural gas should do so too, given the comparability of these two technologies.

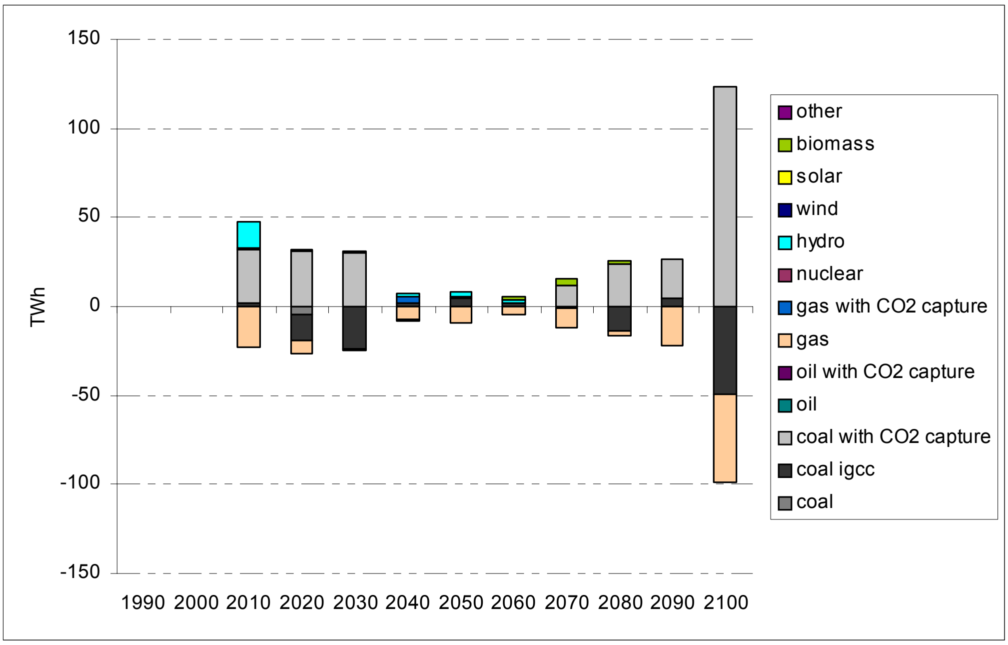

Figure 8. Additional overall and energy-specific reduction in electricity production after also including CO_2 sequestration external costs (BAU case, consumer-side).

A comparison of both base-case variants of figures 7 and 8 – with external costs accounted for via either fuel input for power plants or for the end-users of electricity – shows that in an optimisation model like MARKAL the difference between these two distribution systems induces little change. This could be expected, because the model optimises simultaneously the supply and demand side, while taking into account price-elasticity effects on the demand side. Also, the model does not take into account behavioural effects, but merely takes a rational approach to meet constraints and to cope with cost increases, so that no large differences are to be expected between the two cases. Nevertheless, some small effects were found. These are hard to explain because of the complex interactions and competitions between technologies and energy carriers. For example, applying external costs to output power prices generates a little bit more coal IGCC electricity, and a little less biomass and natural gas. In this case, there is also a little less hydropower in the earlier periods; the system uses its maximum hydropower potential only in the case when externality costs are charged on fuel as input to power generation.

Figures 6, 7 and 8 all present our comparison results in the BAU scenario. For the 550 ppmv stabilisation case, the introduction of external costs for global warming and CO_2 sequestration has been briefly inspected as well. In most respects, our findings are very similar as in the BAU case. Including carbon sequestration externalities induces, likewise – whether accounted for at the production level or at the level of end use – an overall production that is on average slightly lower than in the case without these sequestration externalities. Also in the production mix there are changes similar to the ones encountered in the base case. Coal-based production with CO_2 capture decreases over the whole time frame, while IGCC and natural gas show a slight increase in production, especially over the first few decades. Also other production means gain in interest in this case (predominantly later in time), among which solar, biomass and hydro energy. Of course, like previously observed, the shifts in the production mix remain modest compared to the overall production level. While the shifts in the stabilisation case are perhaps slightly larger than in the base case, they show a very similar trend, indicating the robustness of our analysis results.

We end by presenting analysis results through which some final findings can be derived regarding both the effect of including externalities and the difference between the producer and consumer cases: the evolution over time of the amount of sequestered carbon dioxide and the total (remaining) amount of emitted CO_2. The amount of sequestered CO_2 is, of course, influenced by the inclusion (or not) of external costs. Figure 9 shows the annual amount of geologically stored CO_2 for each of the different scenarios assessed so far. As observed earlier, carbon sequestration already appears in the base case where no climate constraint is imposed. But the amount of CO_2 sequestered becomes significantly larger when a stringent climate policy is introduced. In both cases, the incorporation of external costs, either with or without sequestration externalities, lowers the amount of carbon sequestered in the long run. Including additional sequestration externalities lowers the amount of carbon sequestered further in comparison to the case where these externalities are not included. In the base case, it does not matter whether one charges these externalities at the producers or consumers side, while in the stabilisation scenario one can discern a small difference as a result of using these different accounting schemes.

Applying global warming external costs has the largest impact: a total cumulative reduction of sequestered carbon dioxide of 150 Mton in the base case and 420 Mton in the 550 ppmv stabilisation case (hence, over the 21st century modelled, on average 1.5 and 4.2 Mton/yr, respectively). Also adding sequestration external costs reduces the cumulative amount of carbon sequestered further with 190 Mton and 300 Mton (1.9 and 3.0 Mton/yr) for the base and 550 ppmv cases respectively. Applying external costs on end-users or fuel input involves a change in the amount of carbon sequestered, in the 550 ppmv case, of the same order of magnitude as the change incurred as a result of whether or not including carbon sequestration externalities. Overall, with an accounting for environmental externalities, sequestration becomes less part of the solution to meet climate change targets, while demand reduction, energy switches and technological change take a more important role. This illustrates the significant sensitivity of our model to price changes, even when these are small.

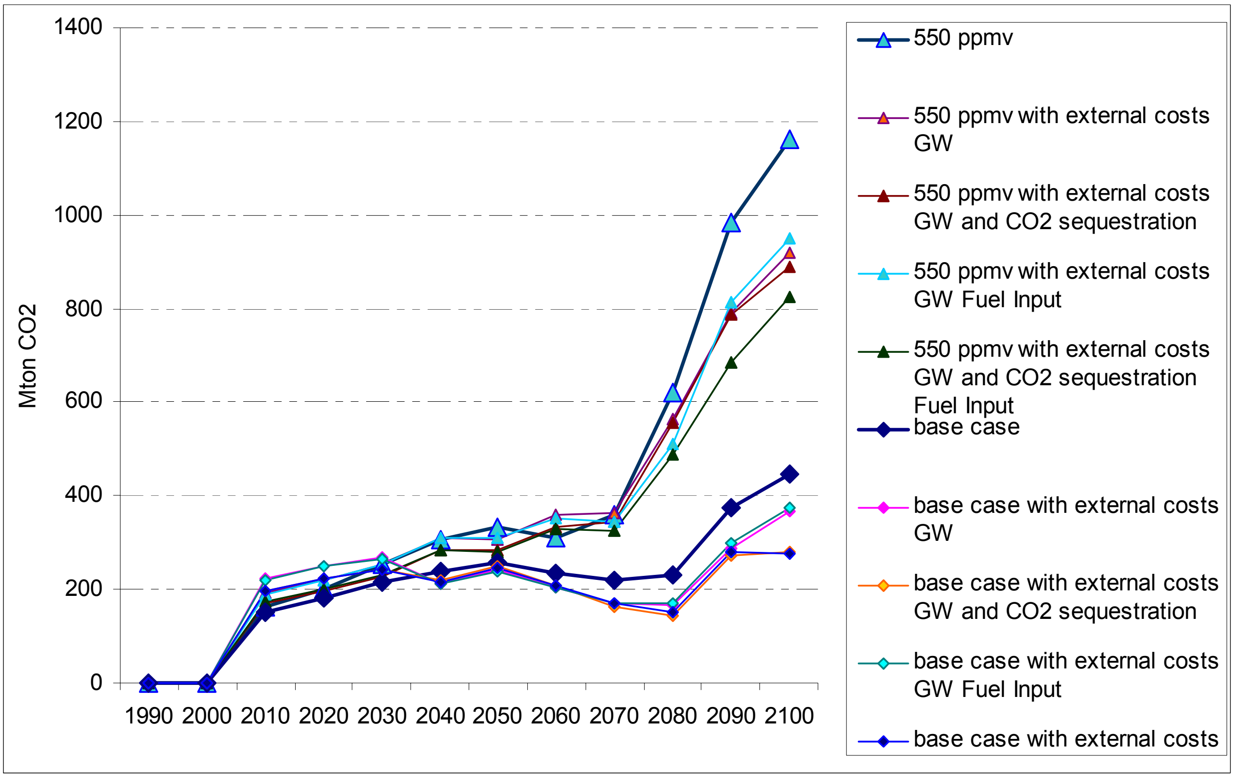

Figure 9. Total annual amount of sequestered carbon dioxide in Mton/yr.

As can be seen from figure 9, the inclusion of external global warming costs significantly lowers the amount of carbon sequestered in the long run. At first sight, this result may appear counter-intuitive, as one would perhaps expect the higher the damage provoked by carbon dioxide, the larger its sequestration. The mechanism driving the result, however, is: accounting for external costs implies in practice an increase of the costs (for either producers or consumers) - and hence in principle a decrease in attractiveness - of using fossil fuels as input for power plants. This implies that other energy options may play an enhanced role, or that the overall demand for electricity decreases due to the cost increase of electricity through the inclusion of external global warming costs. With the internalisation of climatic external costs, the use of important emitters of greenhouse gases, such as fossil-fuelled power plants, is most heavily affected, in the sense that gains are obtained in terms of avoiding detrimental greenhouse gases, but higher costs are incurred as a result of implementing carbon capture processes (that are unlikely to ever become 100% efficient). In our scenario analysis, it appears that the gains in terms of carbon emission mitigation through carbon capture are not high enough, or the additional involved costs for fossil fuels too elevated, in comparison with non-fossil options that are free of carbon emissions. A lowering of total energy production, and consequently of carbon emission and sequestration, and/or an increase in e.g. electricity from renewables might explain why we find lower carbon sequestration when including external global warming costs.

The inclusion of external costs makes a difference as well in terms of the overall carbon dioxide emission path, the impact being slightly larger in the base case than in the 550 ppmv case (see figure 10, in which external costs are accounted for at the level of the fuel input to electricity production). In the former case, carbon emissions are lowered over the entire time frame considered, as a result of including these externalities, with little difference as to whether one includes carbon sequestration external costs or not. In the latter case, a shift in time occurs in the calculated emission path, while the overall cumulative amount of emitted CO_2 (calculable through an integration over the area under the emission evolution curve) remains approximately the same. Again, there is little impact on the calculated emission level from an inclusion or not of external costs resulting from carbon sequestration. Obviously, a sharp decline in emissions results (in comparison to the base case) when one imposes the 550 ppmv carbon concentration constraint. As can be seen from figure 9, this decrease in emissions coincides with an increase in the amount of carbon sequestered underground. As we can see from a comparison between figures 9 and 10, in 2100 the amount of sequestered carbon dioxide is about the same as the remaining level of carbon dioxide emissions.

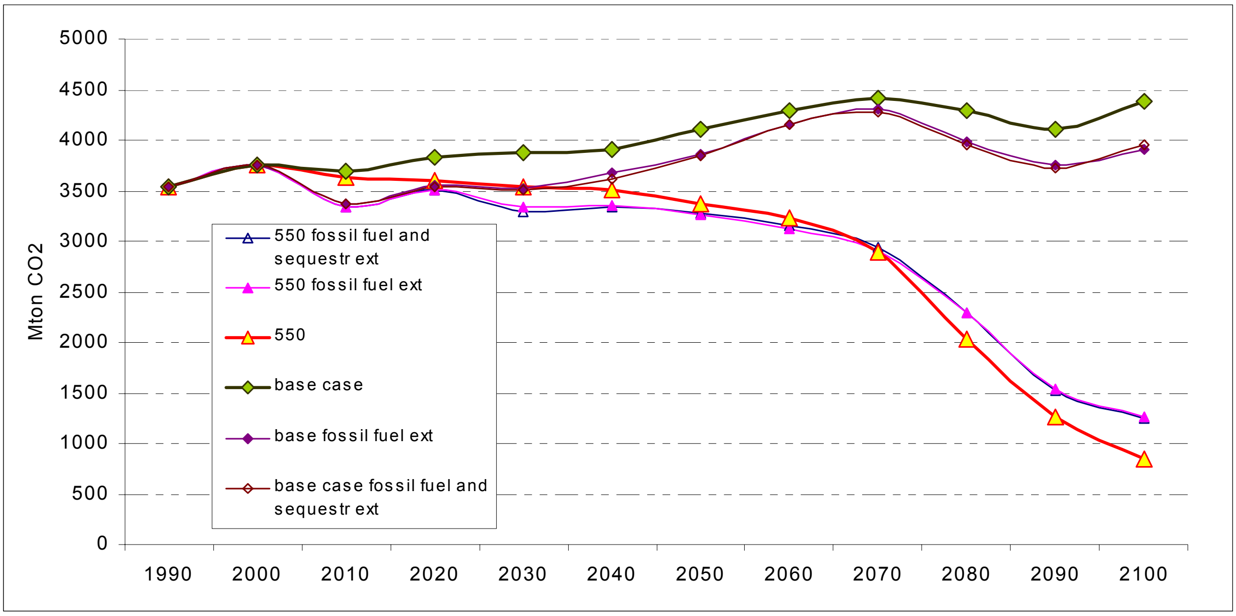

Figure 10. Total amount of remaining CO_2 emissions.

5. Discussion, conclusion and recommendations

Given the preceding presentation of our main results, the prime conclusion of this analysis is that, while external environmental effects of carbon sequestration are generally likely to be relatively small, these externalities matter, and influence the nature of future world energy supply and consumption significantly enough to pay due attention to them. More importantly, since geological carbon storage (depending on the method employed) may in some specific cases have very substantial external impacts – in terms of both environmental damage and health risks – it is recommended that extensive studies are performed to quantify these effects. As explained, the numbers postulated in table 3.1 do not involve any detailed calculation. The proper way to proceed would be to determine more precise data for all damage costs of geological carbon sequestration. Ideally, a complete impact pathway analysis would be performed, along the lines for other energy resources and technologies of the EU ExternE project (see, e.g., ExternE, 1998). We thus recommend that external damage cost calculations for carbon sequestration are included in the next phase of ongoing ExternE analyses. Also the fossil fuel cycle including carbon capture and sequestration should be analysed according to the method by which its effects are calculated in terms of emissions, dispersion, impact and the total monetary value of this impact, resulting in an overall environmental damage cost in terms of \$(or €)-cents per kWh. As long as detailed calculations remain absent, and until the moment that appropriate calculations will have been performed, we think that the numbers presented in table 3.1 can be considered rough but reasonable guesstimates.

In the beginning of this article we posed ourselves three main questions. The first one – on the nature of energy supply if one accounts for CO_2 sequestration in the construction of long-term energy scenarios – we have addressed by the presentation of the scenario results as produced with MARKAL-ED. The second question concerned the inclusion of hypotheses regarding the level of external costs, and the effect hereof on the calculation of long-term energy scenarios. As mentioned, the effect is unlikely to be very large. It certainly does not seem to be negligible, however, so that we judge it necessary that detailed calculations are performed for a proper quantification of the external environmental costs of large-scale CO_2 sequestration. Once such calculations have been made, the question of how these costs may affect the construction of long-term energy and climate change scenarios – which we answered at a first and preliminary approximation – can be revisited. Responding to our third question: it does not seem to matter significantly whether carbon sequestration damage costs are charged directly to energy consumers or, instead, to electricity producers. Surely in comparison to the inclusion of external global warming costs, the effect of choosing either of these two accounting schemes is small. The effect is expected to be of the order of magnitude of the incorporation of external costs for carbon sequestration.

It is commonly expected that without the imposition of a climate constraint the use of coal will be continued, and even considerably expanded, during the entire 21st century. Among the reasons are that coal is relatively cheap and readily available in large quantities at many locations the world over, notably in various large developing countries. Because of its polluting nature, however, both regarding local air pollution and as important contributor to global warming, the use of coal will probably be slowly discontinued over the decades to come when stringent climate objectives are to be met. An important conclusion of our analysis is that the role of coal probably remains important, even under a strict climate constraint, if carbon capture and sequestration is implemented on a large scale. Other research has come to similar conclusions (see, for example, McFarland *et al.*, 2002), the main reason being that, among the three fossil fuels, carbon capture is most easily implemented for coal technologies, thus allowing its continued use when reductions of carbon emissions are aimed at. Another finding, not reported so far in the literature, is that coal power plants may be simultaneously operated for both electricity generation and the production of CO_2 to be employed for methane extraction. Through the use of ECBM, natural gas (the cleanest of all fossil fuels) is then produced as by-product of the carbon dioxide injection process in coal seams, and can thereby be advantageously fed back into the energy system. If external damage costs for global warming are included, these findings remain roughly unchanged, the only difference being that coal with IGCC technologies (which will increasingly gain importance over the decades to come irrespective of the scenario assumed) is further favoured to the debit of conventional coal technologies. If also carbon sequestration damage costs are included, a small change can be observed from the use of coal plus carbon sequestration to the use of, predominantly, natural gas.

Some further analysis has resulted in preliminary answers regarding a number of other questions, not reported in section 4, such as what the origin of the total sequestered amount of CO_2 is. It proves that in both the base case and the climate-constrained scenario, the geologically stored CO_2 mainly originates from two sources: coal power generation and fuel conversion (that is, the production of hydrogen). Coal power generation is in both scenarios the most important source of sequestered CO_2. As we have seen, accounting for external costs induces changes in the electricity production mix. If external carbon sequestration costs are included in the analysis, especially mixes that include options with CO_2 capture and storage change. This affects, naturally, the composition of the sources of CO_2 capture. From our preliminary analysis, however, it follows that the effect of this inclusion is not very large, probably because of the relatively small expected external sequestration cost level. It may still be worthwhile to explore this subject matter further.

Where will CO_2 be sequestered? Again, we have not fully explored this question yet, but some preliminary study suggests that coal beds become the main recipient of CO_2, since this sequestration method, through ECBM, involves the beneficial recovery of methane. This finding is surprising, since ECBM is currently not seen as one of the most evident options for carbon storage. It results from our various modelling assumptions regarding (fuel) prices, and needs to be further investigated. Even in a base case scenario, ECBM is mostly followed by EOR, because of the advantageous oil recovery it implies. In a climate-constrained case higher sequestration levels should be attained, so that one is likely to observe an exhaustion of both the

ECBM and EOR potentials. This implies that storage in aquifers, as well as in depleted oil and natural gas fields, starts being employed by the end of the modelling horizon. Biological sinks are only likely to play a modest role throughout the entire 21st century. As shown from a quick inspection of the matter, the inclusion of external costs affects the sequestration options chosen in the system. The impact, however, does not seem to be very significant: in all cases, ECBM remains the predominant favourite and is used as first storage option, given the interesting option of energy recovery, while EOR comes second in line and appears later in time. Storage in aquifers and depleted oil and gas fields remains, it seems, a backstop solution. Since non-negligible effects of external cost internalisation on the nature of carbon sequestration recipients are observed, especially in the 550 ppmv stabilisation scenario, this constitutes a window for further research.

Among the other topics for future research is an analysis of welfare effects. In MARKAL, the surplus of consumption and production means can be interpreted as some measure of the welfare level of the economic system. For the short term, the imposition of a climate constraint and the inclusion of environmental externalities in energy costs involve a loss of this welfare measure. As a result of these conditions, the energy system evolves in a way different than without them, so that in the long run the welfare loss implications may not be trivial. The marginal cost of electricity, to be paid by consumers, is one of the determinants of the welfare (loss) level. This electricity cost is affected by both the climate constraint and the inclusion of externalities. External costs are thought to typically increase the marginal cost of electricity by 1.0 to 1.5 €cent/kWh, in the base case scenario. For the 550 ppmv climate-constrained scenario, the picture is more complex, as a result of the interplay between shifting investments and the presence of learning phenomena. Also this matter may be subjected to future research.

It is likely that geological carbon sequestration is going to be applied on a large scale over the decades to come. Among the various reasons is the fact that this allows continuing the present use of fossil fuels and that of their supporting infrastructures. However, carbon storage is neither a sustainable nor a renewable energy option: “true” renewables remain preferable over the longer run. The long-term deployment of renewables, however, might be negatively affected by the development of carbon sequestration today. It is therefore important, in both the scientific and policy-relevant discussion around this matter, that possible external environmental impacts of carbon sequestration are not discarded, in the same way as externalities of renewables should not be left out in assessments of their potential and desirability. In the discussion around carbon sequestration, the energy price paid for the carbon capture and storage process should also be included, as should be the observation that it prolongs the fossil fuel époque (fossil fuels remaining constrained by their limited abundance), with all the detrimental side-effects the continued use of carbon-based energy may entail. Although geological carbon storage is inherently not renewable, carbon sequestration could be considered a useful solution to bridge the 21st century, and create the time needed to let real renewable and sustainable energy sources evolve into competitive alternatives. It may thus prove a suitable technology for the development of paths leading to the sustainable use of energy.

References

Bachu, L. and W.D. Gunter, Storage capacity of CO_2 in geological media in sedimentary basins with application to the Alberta basin, in: *Greenhouse Gas Control Technologies*, P. Riemer, B. Eliasson and A. Wokaun, Eds., Elsevier, 1999.

Chen, Z. *et al*. Environmental risk assessment for aquifer disposal of carbon dioxide, in: *Greenhouse Gas Control Technologies*, P. Riemer, B. Eliasson and A. Wokaun, Eds., Elsevier, 1999.

EIA/DOE, Energy Information Administration, US Department of Energy, Washington DC, www.eia.doe.org, 2004.

ExternE, 1998, ExternE: Externalities of Energy, Vol.7: Methodology 1998 Update (EUR 19083); Vol.8: Global Warming (EUR 18836); Vol.9: Fuel Cycles for Emerging and End-Use Technologies, Transport and Waste (EUR 18887); Vol.10: National Implementation (EUR 18528), European Commission, Directorate-General XII, Science Research and Development, Office for Official Publications of the European Communities, L-2920 Luxembourg; Results also available at http://externe.jrc.es/publica.html.

Fetter, S., *Climate Change and the Transformation of World Energy Supply*, Center for International Security and Cooperation (CISAC), Stanford University, 1999.

Franssen, S., *MATTER 3.0: Relaxing the demand in the MATTER model,* mimeo, ECN / Wageningen University, 1999.

Gielen, D., "The Future Role of CO_2 Capture and Storage - Results of the IEA-ETP Model", IEA/EET Working Paper EET/2003/04, IEA, Paris, November 2003.

Ha-Duong, M., D.W. Keith, Carbon Storage: the economic efficiency of storing CO_2 in leaky reservoirs, *Clean Technologies and Environmental Policy*, **5**, 181-189, 2003.

Hamilton, L.D., G. Goldstein, J.C. Lee, A. Manne, W. Marcuse, S.C. Morris, C.-O. Wene, *MARKAL-MACRO: An overview*, Brookhaven National Laboratories, No. 48377, November 1992.

Hendriks, C.A., Carbon Dioxide Removal from Coal-Fired Power Plants, PhD Thesis, Utrecht University, Department of Science, Technology and Society, Utrecht, The Netherlands, 1994.

Herzog, H., B. Eliasson, O. Kaarstad, Capturing Greenhouse Gases, *Scientific American*, **282**, 2, 2000.

Holloway, M. *Scientific American*, 80-87, July 2000.

IEA/OECD, Capture and Storage of CO_2, What Needs to be Done?, produced for COP-6, Paris, 2000a.

IEA/OECD, *Carbon Dioxide Capture and Storage*, Paris, 2000b.

IEA-GHG, International Energy Agency, Greenhouse Gases R&D Programme, www.ieagreen.org.uk, 2004.

IPCC (Intergovernmental Panel on Climate Change), "Technical Summary" in J.T. Houghton *et al*. (eds.), *Climate Change 1995*, Cambridge University Press, 1996.

IPCC, International Panel on Climate Change, Workgroup III, Third Assessment Report, 2001.

Lako, P., Options for CO_2 Sequestration and Enhanced Fuel Supply, Monograph in the framework of the VLEEM project, ECN Report, ECN-C--01-113, 2002.

Liu, L. *et al*., Environmental impacts and risks of CO_2 injection for enhanced oil recovery in western Canada, in: *Greenhouse Gas Control Technologies*, P. Riemer, B. Eliasson and A. Wokaun, Eds., Elsevier, 1999.

Loulou, R. and Lavigne, D., ‘MARKAL Model with Elastic Demands: Application to Greenhouse Gas Emission Control’, in “*Operations Research and Environmental management*”, C. Carraro and A. Haurie, Eds., Kluwer Academic Publishers, 1996.

McFarland, J.R., J. Reilly and H.J. Herzog, Representing Energy Technologies in Top-down Economic Models using Bottom-up Information, MIT Joint Program on the Science an Policy of Global Change, Report No. 89, October 2002.

Reichhardt, T. *Nature*, **397**, 373, 1999; Nature Editorial, A timely boost to research on carbon sequestration, *Nature*, **401**, 6751, 23 September, 1999.

NITG, Netherlands Institute of Applied Geoscience, TNO, www.nitg.tno.nl /eng /projects /6_stor /index.shtml, 2004.

Marchetti, C. *Climate Change* **1**, 159, 1977.

Milnes, A.G. Geology and Radwaste. London: Academic Press, 1985.

Parson, E.A. and D.W. Keith, Fossil Fuels Without CO_2 Emissions, *Science*, **282**, 1053, 1998.

Sailor, W.C., D. Bodansky, C. Braun, S. Fetter and B. van der Zwaan, A Nuclear Solution to Climate Change?, *Science*, **288**, 1177-1178, 2000.

Socolow, R. Ed., *Fuels Decarbonization and Carbon Sequestration*, Princeton University CEES Report No. 302, 1997 (www.princeton.edu/~ceesdoe).

Rabl, A. and J.V. Spadaro, "Environmental Damages and Costs: an Analysis of Uncertainties", *Environment International*, Vol.25, 29-46, 1999.

Statoil, www.statoil.com/statoilcom/svg00990.nsf/ealias/Sleipner, 2004.

Turner, J.A., A Realizable Renewable Energy Future, *Science*, **285**, 687, 1999.

van der Zwaan, B.C.C., M. van Drunen and P. Vellinga, Geological Carbon Sequestration: A Fix for Global Warming?, Institute for Environmental Studies, IVM, Amsterdam, Report D-01/04, July 2001.

UNDP (United Nations Development Program), United Nations Department of Economic and Social Affairs, World Energy Council, *World Energy Assessment: Energy and the Challenge of Sustainability*, and chapter 8 therein: R.H. Williams, "Advanced Energy Supply Technologies", New York, 2000.

UNFCCC (United Nations Framework Convention on Climate Change), May 1992, www.unfccc.de.

Williams, R. H. Fuel decarbonization for fuel cell applications and sequestration of the separated CO2. In: Ayres R.U., editor. *Ecorestructuring*. Tokyo: UN University Press, EN-98-04, 1998.

Wilson, E.J., T.L. Johnson, D.W. Keith, Regulating the Ultimate Sink: Managing the Risks of Geologic CO_2 Storage, *Environmental Science and Technology*, **37**, 16, 2003.

Wong, S. *et al*. Injection of CO_2 for Enhanced Energy Recovery: coal-bed methane versus oil recovery, in: *Greenhouse Gas Control Technologies*, P. Riemer, B. Eliasson and A. Wokaun, Eds., Elsevier, 1999.

NOTE DI LAVORO DELLA FONDAZIONE ENI ENRICO MATTEI

Fondazione Eni Enrico Mattei Working Paper Series

Our Note di Lavoro are available on the Internet at the following addresses:
http://www.feem.it/Feem/Pub/Publications/WPapers/default.html
http://www.ssrn.com/link/feem.html

NOTE DI LAVORO PUBLISHED IN 2003

PRIV	1.2003	*Gabriella CHIESA and Giovanna NICODANO*: Privatization and Financial Market Development: Theoretical Issues
PRIV	2.2003	*Ibolya SCHINDELE*: Theory of Privatization in Eastern Europe: Literature Review
PRIV	3.2003	*Wietze LISE, Claudia KEMFERT and Richard S.J. TOL*: Strategic Action in the Liberalised German Electricity Market
CLIM	4.2003	*Laura MARSILIANI and Thomas I. RENSTRÖM*: Environmental Policy and Capital Movements: The Role of Government Commitment
KNOW	5.2003	*Reyer GERLAGH*: Induced Technological Change under Technological Competition
ETA	6.2003	*Efrem CASTELNUOVO*: Squeezing the Interest Rate Smoothing Weight with a Hybrid Expectations Model
SIEV	7.2003	*Anna ALBERINI, Alberto LONGO, Stefania TONIN, Francesco TROMBETTA and Margherita TURVANI:* The Role of Liability, Regulation and Economic Incentives in Brownfield Remediation and Redevelopment: Evidence from Surveys of Developers
NRM	8.2003	*Elissaios PAPYRAKIS and Reyer GERLAGH*: Natural Resources: A Blessing or a Curse?
CLIM	9.2003	*A. CAPARRÓS, J.-C. PEREAU and T. TAZDAÏT*: North-South Climate Change Negotiations: a Sequential Game with Asymmetric Information
KNOW	10.2003	*Giorgio BRUNELLO and Daniele CHECCHI*: School Quality and Family Background in Italy
CLIM	11.2003	*Efrem CASTELNUOVO and Marzio GALEOTTI*: Learning By Doing vs Learning By Researching in a Model of Climate Change Policy Analysis
KNOW	12.2003	*Carole MAIGNAN, Gianmarco OTTAVIANO and Dino PINELLI (eds.)*: Economic Growth, Innovation, Cultural Diversity: What are we all talking about? A critical survey of the state-of-the-art
KNOW	13.2003	*Carole MAIGNAN, Gianmarco OTTAVIANO, Dino PINELLI and Francesco RULLANI* (lix): Bio-Ecological Diversity vs. Socio-Economic Diversity. A Comparison of Existing Measures
KNOW	14.2003	*Maddy JANSSENS and Chris STEYAERT* (lix): Theories of Diversity within Organisation Studies: Debates and Future Trajectories
KNOW	15.2003	*Tuzin BAYCAN LEVENT, Enno MASUREL and Peter NIJKAMP* (lix): Diversity in Entrepreneurship: Ethnic and Female Roles in Urban Economic Life
KNOW	16.2003	*Alexandra BITUSIKOVA* (lix): Post-Communist City on its Way from Grey to Colourful: The Case Study from Slovakia
KNOW	17.2003	*Billy E. VAUGHN and Katarina MLEKOV* (lix): A Stage Model of Developing an Inclusive Community
KNOW	18.2003	*Selma van LONDEN and Arie de RUIJTER* (lix): Managing Diversity in a Glocalizing World
Coalition Theory Network	19.2003	*Sergio CURRARINI:* On the Stability of Hierarchies in Games with Externalities
PRIV	20.2003	*Giacomo CALZOLARI and Alessandro PAVAN* (lx): Monopoly with Resale
PRIV	21.2003	*Claudio MEZZETTI* (lx): Auction Design with Interdependent Valuations: The Generalized Revelation Principle, Efficiency, Full Surplus Extraction and Information Acquisition
PRIV	22.2003	*Marco LiCalzi and Alessandro PAVAN* (lx): Tilting the Supply Schedule to Enhance Competition in Uniform-Price Auctions
PRIV	23.2003	*David ETTINGER* (lx): Bidding among Friends and Enemies
PRIV	24.2003	*Hannu VARTIAINEN* (lx): Auction Design without Commitment
PRIV	25.2003	*Matti KELOHARJU, Kjell G. NYBORG and Kristian RYDQVIST* (lx): Strategic Behavior and Underpricing in Uniform Price Auctions: Evidence from Finnish Treasury Auctions
PRIV	26.2003	*Christine A. PARLOUR and Uday RAJAN* (lx): Rationing in IPOs
PRIV	27.2003	*Kjell G. NYBORG and Ilya A. STREBULAEV* (lx): Multiple Unit Auctions and Short Squeezes
PRIV	28.2003	*Anders LUNANDER and Jan-Eric NILSSON* (lx): Taking the Lab to the Field: Experimental Tests of Alternative Mechanisms to Procure Multiple Contracts
PRIV	29.2003	*TangaMcDANIEL and Karsten NEUHOFF* (lx): Use of Long-term Auctions for Network Investment
PRIV	30.2003	*Emiel MAASLAND and Sander ONDERSTAL* (lx): Auctions with Financial Externalities
ETA	31.2003	*Michael FINUS and Bianca RUNDSHAGEN:* A Non-cooperative Foundation of Core-Stability in Positive Externality NTU-Coalition Games
KNOW	32.2003	*Michele MORETTO*: Competition and Irreversible Investments under Uncertainty
PRIV	33.2003	*Philippe QUIRION:* Relative Quotas: Correct Answer to Uncertainty or Case of Regulatory Capture?
KNOW	34.2003	*Giuseppe MEDA, Claudio PIGA and Donald SIEGEL*: On the Relationship between R&D and Productivity: A Treatment Effect Analysis
ETA	35.2003	*Alessandra DEL BOCA, Marzio GALEOTTI and Paola ROTA:* Non-convexities in the Adjustment of Different Capital Inputs: A Firm-level Investigation

GG	36.2003	*Matthieu GLACHANT*: Voluntary Agreements under Endogenous Legislative Threats
PRIV	37.2003	*Narjess BOUBAKRI, Jean-Claude COSSET and Omrane GUEDHAMI*: Postprivatization Corporate Governance: the Role of Ownership Structure and Investor Protection
CLIM	38.2003	*Rolf GOLOMBEK and Michael HOEL*: Climate Policy under Technology Spillovers
KNOW	39.2003	*Slim BEN YOUSSEF*: Transboundary Pollution, R&D Spillovers and International Trade
CTN	40.2003	*Carlo CARRARO and Carmen MARCHIORI*: Endogenous Strategic Issue Linkage in International Negotiations
KNOW	41.2003	*Sonia OREFFICE*: Abortion and Female Power in the Household: Evidence from Labor Supply
KNOW	42.2003	*Timo GOESCHL and Timothy SWANSON*: On Biology and Technology: The Economics of Managing Biotechnologies
ETA	43.2003	*Giorgio BUSETTI and Matteo MANERA*: STAR-GARCH Models for Stock Market Interactions in the Pacific Basin Region, Japan and US
CLIM	44.2003	*Katrin MILLOCK and Céline NAUGES*: The French Tax on Air Pollution: Some Preliminary Results on its Effectiveness
PRIV	45.2003	*Bernardo BORTOLOTTI and Paolo PINOTTI*: The Political Economy of Privatization
SIEV	46.2003	*Elbert DIJKGRAAF and Herman R.J. VOLLEBERGH*: Burn or Bury? A Social Cost Comparison of Final Waste Disposal Methods
ETA	47.2003	*Jens HORBACH*: Employment and Innovations in the Environmental Sector: Determinants and Econometrical Results for Germany
CLIM	48.2003	*Lori SNYDER, Nolan MILLER and Robert STAVINS:* The Effects of Environmental Regulation on Technology Diffusion: The Case of Chlorine Manufacturing
CLIM	49.2003	*Lori SNYDER, Robert STAVINS and Alexander F. WAGNER*: Private Options to Use Public Goods. Exploiting Revealed Preferences to Estimate Environmental Benefits
CTN	50.2003	*László Á. KÓCZY and Luc LAUWERS* (lxi): The Minimal Dominant Set is a Non-Empty Core-Extension
CTN	51.2003	*Matthew O. JACKSON* (lxi)*:*Allocation Rules for Network Games
CTN	52.2003	*Ana MAULEON and Vincent VANNETELBOSCH* (lxi): Farsightedness and Cautiousness in Coalition Formation
CTN	53.2003	*Fernando VEGA-REDONDO* (lxi): Building Up Social Capital in a Changing World: a network approach
CTN	54.2003	*Matthew HAAG and Roger LAGUNOFF* (lxi): On the Size and Structure of Group Cooperation
CTN	55.2003	*Taiji FURUSAWA and Hideo KONISHI* (lxi): Free Trade Networks
CTN	56.2003	*Halis Murat YILDIZ* (lxi): National Versus International Mergers and Trade Liberalization
CTN	57.2003	*Santiago RUBIO and Alistair ULPH* (lxi): An Infinite-Horizon Model of Dynamic Membership of International Environmental Agreements
KNOW	58.2003	*Carole MAIGNAN, Dino PINELLI and Gianmarco I.P. OTTAVIANO*: ICT, Clusters and Regional Cohesion: A Summary of Theoretical and Empirical Research
KNOW	59.2003	*Giorgio BELLETTINI and Gianmarco I.P. OTTAVIANO:* Special Interests and Technological Change
ETA	60.2003	*Ronnie SCHÖB:* The Double Dividend Hypothesis of Environmental Taxes: A Survey
CLIM	61.2003	*Michael FINUS, Ekko van IERLAND and Robert DELLINK*: Stability of Climate Coalitions in a Cartel Formation Game
GG	62.2003	*Michael FINUS and Bianca RUNDSHAGEN*: How the Rules of Coalition Formation Affect Stability of International Environmental Agreements
SIEV	63.2003	*Alberto PETRUCCI:* Taxing Land Rent in an Open Economy
CLIM	64.2003	*Joseph E. ALDY, Scott BARRETT and Robert N. STAVINS*: Thirteen Plus One: A Comparison of Global Climate Policy Architectures
SIEV	65.2003	*Edi DEFRANCESCO*: The Beginning of Organic Fish Farming in Italy
SIEV	66.2003	*Klaus CONRAD*: Price Competition and Product Differentiation when Consumers Care for the Environment
SIEV	67.2003	*Paulo A.L.D. NUNES, Luca ROSSETTO, Arianne DE BLAEIJ*: Monetary Value Assessment of Clam Fishing Management Practices in the Venice Lagoon: Results from a Stated Choice Exercise
CLIM	68.2003	*ZhongXiang ZHANG:* Open Trade with the U.S. Without Compromising Canada's Ability to Comply with its Kyoto Target
KNOW	69.2003	*David FRANTZ* (lix): Lorenzo Market between Diversity and Mutation
KNOW	70.2003	*Ercole SORI* (lix): Mapping Diversity in Social History
KNOW	71.2003	*Ljiljana DERU SIMIC* (lxii): What is Specific about Art/Cultural Projects?
KNOW	72.2003	*Natalya V. TARANOVA* (lxii):The Role of the City in Fostering Intergroup Communication in a Multicultural Environment: Saint-Petersburg's Case
KNOW	73.2003	*Kristine CRANE* (lxii)*:* The City as an Arena for the Expression of Multiple Identities in the Age of Globalisation and Migration
KNOW	74.2003	*Kazuma MATOBA* (lxii): Glocal Dialogue- Transformation through Transcultural Communication
KNOW	75.2003	*Catarina REIS OLIVEIRA* (lxii): Immigrants' Entrepreneurial Opportunities: The Case of the Chinese in Portugal
KNOW	76.2003	*Sandra WALLMAN* (lxii): The Diversity of Diversity - towards a typology of urban systems
KNOW	77.2003	*Richard PEARCE* (lxii): A Biologist's View of Individual Cultural Identity for the Study of Cities
KNOW	78.2003	*Vincent MERK* (lxii): Communication Across Cultures: from Cultural Awareness to Reconciliation of the Dilemmas
KNOW	79.2003	*Giorgio BELLETTINI, Carlotta BERTI CERONI and Gianmarco I.P.OTTAVIANO*: Child Labor and Resistance to Change
ETA	80.2003	*Michele MORETTO, Paolo M. PANTEGHINI and Carlo SCARPA*: Investment Size and Firm's Value under Profit Sharing Regulation

IEM	81.2003	*Alessandro LANZA, Matteo MANERA and Massimo GIOVANNINI:* Oil and Product Dynamics in International Petroleum Markets
CLIM	82.2003	*Y. Hossein FARZIN and Jinhua ZHAO*: Pollution Abatement Investment When Firms Lobby Against Environmental Regulation
CLIM	83.2003	*Giuseppe DI VITA*: Is the Discount Rate Relevant in Explaining the Environmental Kuznets Curve?
CLIM	84.2003	*Reyer GERLAGH and Wietze LISE*: Induced Technological Change Under Carbon Taxes
NRM	85.2003	*Rinaldo BRAU, Alessandro LANZA and Francesco PIGLIARU*: How Fast are the Tourism Countries Growing? The cross-country evidence
KNOW	86.2003	*Elena BELLINI, Gianmarco I.P. OTTAVIANO and Dino PINELLI:* The ICT Revolution: opportunities and risks for the Mezzogiorno
SIEV	87.2003	*Lucas BRETSCGHER and Sjak SMULDERS:* Sustainability and Substitution of Exhaustible Natural Resources. How resource prices affect long-term R&D investments
CLIM	88.2003	*Johan EYCKMANS and Michael FINUS:* New Roads to International Environmental Agreements: The Case of Global Warming
CLIM	89.2003	*Marzio GALEOTTI:* Economic Development and Environmental Protection
CLIM	90.2003	*Marzio GALEOTTI*: Environment and Economic Growth: Is Technical Change the Key to Decoupling?
CLIM	91.2003	*Marzio GALEOTTI and Barbara BUCHNER*: Climate Policy and Economic Growth in Developing Countries
IEM	92.2003	*A. MARKANDYA, A. GOLUB and E. STRUKOVA*: The Influence of Climate Change Considerations on Energy Policy: The Case of Russia
ETA	93.2003	*Andrea BELTRATTI*: Socially Responsible Investment in General Equilibrium
CTN	94.2003	*Parkash CHANDER*: The γ-Core and Coalition Formation
IEM	95.2003	*Matteo MANERA and Angelo MARZULLO*: Modelling the Load Curve of Aggregate Electricity Consumption Using Principal Components
IEM	96.2003	*Alessandro LANZA, Matteo MANERA, Margherita GRASSO and Massimo GIOVANNINI:* Long-run Models of Oil Stock Prices
CTN	97.2003	*Steven J. BRAMS, Michael A. JONES, and D. Marc KILGOUR:* Forming Stable Coalitions: The Process Matters
KNOW	98.2003	*John CROWLEY, Marie-Cecile NAVES* (lxiii): Anti-Racist Policies in France. From Ideological and Historical Schemes to Socio-Political Realities
KNOW	99.2003	*Richard THOMPSON FORD* (lxiii*)*: Cultural Rights and Civic Virtue
KNOW	100.2003	*Alaknanda PATEL* (lxiii): Cultural Diversity and Conflict in Multicultural Cities
KNOW	101.2003	*David MAY* (lxiii): The Struggle of Becoming Established in a Deprived Inner-City Neighbourhood
KNOW	102.2003	*Sébastien ARCAND, Danielle JUTEAU, Sirma BILGE, and Francine LEMIRE* (lxiii) : Municipal Reform on the Island of Montreal: Tensions Between Two Majority Groups in a Multicultural City
CLIM	103.2003	*Barbara BUCHNER and Carlo CARRARO:* China and the Evolution of the Present Climate Regime
CLIM	104.2003	*Barbara BUCHNER and Carlo CARRARO*: Emissions Trading Regimes and Incentives to Participate in International Climate Agreements
CLIM	105.2003	*Anil MARKANDYA and Dirk T.G. RÜBBELKE:* Ancillary Benefits of Climate Policy
NRM	106.2003	*Anne Sophie CRÉPIN (*lxiv)*:* Management Challenges for Multiple-Species Boreal Forests
NRM	107.2003	*Anne Sophie CRÉPIN* (lxiv)*:* Threshold Effects in Coral Reef Fisheries
SIEV	108.2003	*Sara ANIYAR (* lxiv): Estimating the Value of Oil Capital in a Small Open Economy: The Venezuela's Example
SIEV	109.2003	*Kenneth ARROW, Partha DASGUPTA and Karl-Göran MÄLER(*lxiv)*:* Evaluating Projects and Assessing Sustainable Development in Imperfect Economies
NRM	110.2003	*Anastasios XEPAPADEAS and Catarina ROSETA-PALMA(*lxiv)*:* Instabilities and Robust Control in Fisheries
NRM	111.2003	*Charles PERRINGS and Brian WALKER* (lxiv): Conservation and Optimal Use of Rangelands
ETA	112.2003	*Jack GOODY* (lxiv): Globalisation, Population and Ecology
CTN	113.2003	*Carlo CARRARO, Carmen MARCHIORI and Sonia OREFFICE*: Endogenous Minimum Participation in International Environmental Treaties
CTN	114.2003	*Guillaume HAERINGER and Myrna WOODERS*: Decentralized Job Matching
CTN	115.2003	*Hideo KONISHI and M. Utku UNVER*: Credible Group Stability in Multi-Partner Matching Problems
CTN	116.2003	*Somdeb LAHIRI*: Stable Matchings for the Room-Mates Problem
CTN	117.2003	*Somdeb LAHIRI*: Stable Matchings for a Generalized Marriage Problem
CTN	118.2003	*Marita LAUKKANEN*: Transboundary Fisheries Management under Implementation Uncertainty
CTN	119.2003	*Edward CARTWRIGHT and Myrna WOODERS*: Social Conformity and Bounded Rationality in Arbitrary Games with Incomplete Information: Some First Results
CTN	120.2003	*Gianluigi VERNASCA*: Dynamic Price Competition with Price Adjustment Costs and Product Differentiation
CTN	121.2003	*Myrna WOODERS, Edward CARTWRIGHT and Reinhard SELTEN*: Social Conformity in Games with Many Players
CTN	122.2003	*Edward CARTWRIGHT and Myrna WOODERS*: On Equilibrium in Pure Strategies in Games with Many Players
CTN	123.2003	*Edward CARTWRIGHT and Myrna WOODERS*: Conformity and Bounded Rationality in Games with Many Players
	1000	**Carlo CARRARO, Alessandro LANZA and Valeria PAPPONETTI: One Thousand Working Papers**

NOTE DI LAVORO PUBLISHED IN 2004

IEM	1.2004	*Anil MARKANDYA, Suzette PEDROSO and Alexander GOLUB*: Empirical Analysis of National Income and So2 Emissions in Selected European Countries
ETA	2.2004	*Masahisa FUJITA and Shlomo WEBER:* Strategic Immigration Policies and Welfare in Heterogeneous Countries
PRA	3.2004	*Adolfo DI CARLUCCIO, Giovanni FERRI, Cecilia FRALE and Ottavio RICCHI:* Do Privatizations Boost Household Shareholding? Evidence from Italy
ETA	4.2004	*Victor GINSBURGH and Shlomo WEBER:* Languages Disenfranchisement in the European Union
ETA	5.2004	*Romano PIRAS:* Growth, Congestion of Public Goods, and Second-Best Optimal Policy
CCMP	6.2004	*Herman R.J. VOLLEBERGH:* Lessons from the Polder: Is Dutch CO2-Taxation Optimal
PRA	7.2004	*Sandro BRUSCO, Giuseppe LOPOMO and S. VISWANATHAN* (lxv): Merger Mechanisms
PRA	8.2004	*Wolfgang AUSSENEGG, Pegaret PICHLER and Alex STOMPER* (lxv): IPO Pricing with Bookbuilding, and a When-Issued Market
PRA	9.2004	*Pegaret PICHLER and Alex STOMPER* (lxv): Primary Market Design: Direct Mechanisms and Markets
PRA	10.2004	*Florian ENGLMAIER, Pablo GUILLEN, Loreto LLORENTE, Sander ONDERSTAL and Rupert SAUSGRUBER* (lxv): The Chopstick Auction: A Study of the Exposure Problem in Multi-Unit Auctions
PRA	11.2004	*Bjarne BRENDSTRUP and Harry J. PAARSCH* (lxv): Nonparametric Identification and Estimation of Multi-Unit, Sequential, Oral, Ascending-Price Auctions With Asymmetric Bidders
PRA	12.2004	*Ohad KADAN* (lxv): Equilibrium in the Two Player, k-Double Auction with Affiliated Private Values
PRA	13.2004	*Maarten C.W. JANSSEN* (lxv): Auctions as Coordination Devices
PRA	14.2004	*Gadi FIBICH, Arieh GAVIOUS and Aner SELA* (lxv): All-Pay Auctions with Weakly Risk-Averse Buyers
PRA	15.2004	*Orly SADE, Charles SCHNITZLEIN and Jaime F. ZENDER* (lxv): Competition and Cooperation in Divisible Good Auctions: An Experimental Examination
PRA	16.2004	*Marta STRYSZOWSKA* (lxv): Late and Multiple Bidding in Competing Second Price Internet Auctions
CCMP	17.2004	*Slim Ben YOUSSEF:* R&D in Cleaner Technology and International Trade
NRM	18.2004	*Angelo ANTOCI, Simone BORGHESI and Paolo RUSSU* (lxvi): Biodiversity and Economic Growth: Stabilization Versus Preservation of the Ecological Dynamics
SIEV	19.2004	*Anna ALBERINI, Paolo ROSATO, Alberto LONGO and Valentina ZANATTA:* Information and Willingness to Pay in a Contingent Valuation Study: The Value of S. Erasmo in the Lagoon of Venice
NRM	20.2004	*Guido CANDELA and Roberto CELLINI* (lxvii): Investment in Tourism Market: A Dynamic Model of Differentiated Oligopoly
NRM	21.2004	*Jacqueline M. HAMILTON* (lxvii): Climate and the Destination Choice of German Tourists
NRM	22.2004	*Javier Rey-MAQUIEIRA PALMER, Javier LOZANO IBÁÑEZ and Carlos Mario GÓMEZ GÓMEZ* (lxvii): Land, Environmental Externalities and Tourism Development
NRM	23.2004	*Pius ODUNGA and Henk FOLMER* (lxvii): Profiling Tourists for Balanced Utilization of Tourism-Based Resources in Kenya
NRM	24.2004	*Jean-Jacques NOWAK, Mondher SAHLI and Pasquale M. SGRO* (lxvii):Tourism, Trade and Domestic Welfare
NRM	25.2004	*Riaz SHAREEF* (lxvii): Country Risk Ratings of Small Island Tourism Economies
NRM	26.2004	*Juan Luis EUGENIO-MARTÍN, Noelia MARTÍN MORALES and Riccardo SCARPA* (lxvii): Tourism and Economic Growth in Latin American Countries: A Panel Data Approach
NRM	27.2004	*Raúl Hernández MARTÍN* (lxvii): Impact of Tourism Consumption on GDP. The Role of Imports
CSRM	28.2004	*Nicoletta FERRO:* Cross-Country Ethical Dilemmas in Business: A Descriptive Framework
NRM	29.2004	*Marian WEBER* (lxvi): Assessing the Effectiveness of Tradable Landuse Rights for Biodiversity Conservation: an Application to Canada's Boreal Mixedwood Forest
NRM	30.2004	*Trond BJORNDAL, Phoebe KOUNDOURI and Sean PASCOE* (lxvi): Output Substitution in Multi-Species Trawl Fisheries: Implications for Quota Setting
CCMP	31.2004	*Marzio GALEOTTI, Alessandra GORIA, Paolo MOMBRINI and Evi SPANTIDAKI:* Weather Impacts on Natural, Social and Economic Systems (WISE) Part I: Sectoral Analysis of Climate Impacts in Italy
CCMP	32.2004	*Marzio GALEOTTI, Alessandra GORIA ,Paolo MOMBRINI and Evi SPANTIDAKI:* Weather Impacts on Natural, Social and Economic Systems (WISE) Part II: Individual Perception of Climate Extremes in Italy
CTN	33.2004	*Wilson PEREZ:* Divide and Conquer: Noisy Communication in Networks, Power, and Wealth Distribution
KTHC	34.2004	*Gianmarco I.P. OTTAVIANO and Giovanni PERI* (lxviii): The Economic Value of Cultural Diversity: Evidence from US Cities
KTHC	35.2004	*Linda CHAIB* (lxviii): Immigration and Local Urban Participatory Democracy: A Boston-Paris Comparison
KTHC	36.2004	*Franca ECKERT COEN and Claudio ROSSI* (lxviii): Foreigners, Immigrants, Host Cities: The Policies of Multi-Ethnicity in Rome. Reading Governance in a Local Context
KTHC	37.2004	*Kristine CRANE* (lxviii): Governing Migration: Immigrant Groups' Strategies in Three Italian Cities – Rome, Naples and Bari
KTHC	38.2004	*Kiflemariam HAMDE* (lxviii): Mind in Africa, Body in Europe: The Struggle for Maintaining and Transforming Cultural Identity - A Note from the Experience of Eritrean Immigrants in Stockholm
ETA	39.2004	*Alberto CAVALIERE:* Price Competition with Information Disparities in a Vertically Differentiated Duopoly
PRA	40.2004	*Andrea BIGANO and Stef PROOST:* The Opening of the European Electricity Market and Environmental Policy: Does the Degree of Competition Matter?
CCMP	41.2004	*Micheal FINUS* (lxix): International Cooperation to Resolve International Pollution Problems

KTHC	42.2004	*Francesco CRESPI:* Notes on the Determinants of Innovation: A Multi-Perspective Analysis
CTN	43.2004	*Sergio CURRARINI and Marco MARINI:* Coalition Formation in Games without Synergies
CTN	44.2004	*Marc ESCRIHUELA-VILLAR:* Cartel Sustainability and Cartel Stability
NRM	45.2004	*Sebastian BERVOETS and Nicolas GRAVEL* (lxvi): Appraising Diversity with an Ordinal Notion of Similarity: An Axiomatic Approach
NRM	46.2004	*Signe ANTHON and Bo JELLESMARK THORSEN* (lxvi): Optimal Afforestation Contracts with Asymmetric Information on Private Environmental Benefits
NRM	47.2004	*John MBURU* (lxvi)*:* Wildlife Conservation and Management in Kenya: Towards a Co-management Approach
NRM	48.2004	*Ekin BIROL, Ágnes GYOVAI and Melinda SMALE* (lxvi)*:* Using a Choice Experiment to Value Agricultural Biodiversity on Hungarian Small Farms: Agri-Environmental Policies in a Transition al Economy
CCMP	49.2004	*Gernot KLEPPER and Sonja PETERSON:* The EU Emissions Trading Scheme. Allowance Prices, Trade Flows, Competitiveness Effects
GG	50.2004	*Scott BARRETT and Michael HOEL:* Optimal Disease Eradication
CTN	51.2004	*Dinko DIMITROV, Peter BORM, Ruud HENDRICKX and Shao CHIN SUNG:* Simple Priorities and Core Stability in Hedonic Games
SIEV	52.2004	*Francesco RICCI*: Channels of Transmission of Environmental Policy to Economic Growth: A Survey of the Theory
SIEV	53.2004	*Anna ALBERINI, Maureen CROPPER, Alan KRUPNICK and Nathalie B. SIMON:* Willingness to Pay for Mortality Risk Reductions: Does Latency Matter?
NRM	54.2004	*Ingo BRÄUER and Rainer MARGGRAF* (lvxi): Valuation of Ecosystem Services Provided by Biodiversity Conservation: An Integrated Hydrological and Economic Model to Value the Enhanced Nitrogen Retention in Renaturated Streams
NRM	55.2004	*Timo GOESCHL and Tun LIN* (lxvi): Biodiversity Conservation on Private Lands: Information Problems and Regulatory Choices
NRM	56.2004	*Tom DEDEURWAERDERE* (lxvi): Bioprospection: From the Economics of Contracts to Reflexive Governance
CCMP	57.2004	*Katrin REHDANZ and David MADDISON:* The Amenity Value of Climate to German Households
CCMP	58.2004	*Koen SMEKENS and Bob VAN DER ZWAAN:* Environmental Externalities of Geological Carbon Sequestration Effects on Energy Scenarios

(lix) This paper was presented at the ENGIME Workshop on “Mapping Diversity”, Leuven, May 16-17, 2002

(lx) This paper was presented at the EuroConference on “Auctions and Market Design: Theory, Evidence and Applications”, organised by the Fondazione Eni Enrico Mattei, Milan, September 26-28, 2002

(lxi) This paper was presented at the Eighth Meeting of the Coalition Theory Network organised by the GREQAM, Aix-en-Provence, France, January 24-25, 2003

(lxii) This paper was presented at the ENGIME Workshop on “Communication across Cultures in Multicultural Cities”, The Hague, November 7-8, 2002

(lxiii) This paper was presented at the ENGIME Workshop on “Social dynamics and conflicts in multicultural cities”, Milan, March 20-21, 2003

(lxiv) This paper was presented at the International Conference on “Theoretical Topics in Ecological Economics”, organised by the Abdus Salam International Centre for Theoretical Physics - ICTP, the Beijer International Institute of Ecological Economics, and Fondazione Eni Enrico Mattei – FEEM Trieste, February 10-21, 2003

(lxv) This paper was presented at the EuroConference on “Auctions and Market Design: Theory, Evidence and Applications” organised by Fondazione Eni Enrico Mattei and sponsored by the EU, Milan, September 25-27, 2003

(lxvi) This paper has been presented at the 4th BioEcon Workshop on “Economic Analysis of Policies for Biodiversity Conservation” organised on behalf of the BIOECON Network by Fondazione Eni Enrico Mattei, Venice International University (VIU) and University College London (UCL) , Venice, August 28-29, 2003

(lxvii) This paper has been presented at the international conference on “Tourism and Sustainable Economic Development – Macro and Micro Economic Issues” jointly organised by CRENoS (Università di Cagliari e Sassari, Italy) and Fondazione Eni Enrico Mattei, and supported by the World Bank, Sardinia, September 19-20, 2003

(lxviii) This paper was presented at the ENGIME Workshop on “Governance and Policies in Multicultural Cities”, Rome, June 5-6, 2003

(lxix) This paper was presented at the Fourth EEP Plenary Workshop and EEP Conference “The Future of Climate Policy”, Cagliari, Italy, 27-28 March 2003

2003 SERIES

CLIM	*Climate Change Modelling and Policy* (Editor: Marzio Galeotti)
GG	*Global Governance* (Editor: Carlo Carraro*)*
SIEV	*Sustainability Indicators and Environmental Valuation* (Editor: Anna Alberini)
NRM	*Natural Resources Management* (Editor: Carlo Giupponi)
KNOW	*Knowledge, Technology, Human Capital* (Editor: Gianmarco Ottaviano)
IEM	*International Energy Markets* (Editor: Anil Markandya)
CSRM	*Corporate Social Responsibility and Management* (Editor: Sabina Ratti)
PRIV	*Privatisation, Regulation, Antitrust* (Editor: Bernardo Bortolotti)
ETA	*Economic Theory and Applications* (Editor: Carlo Carraro)
CTN	*Coalition Theory Network*

2004 SERIES

CCMP	*Climate Change Modelling and Policy* (Editor: Marzio Galeotti)
GG	*Global Governance* (Editor: Carlo Carraro*)*
SIEV	*Sustainability Indicators and Environmental Valuation* (Editor: Anna Alberini)
NRM	*Natural Resources Management* (Editor: Carlo Giupponi)
KTHC	*Knowledge, Technology, Human Capital* (Editor: Gianmarco Ottaviano)
IEM	*International Energy Markets* (Editor: Anil Markandya)
CSRM	*Corporate Social Responsibility and Management* (Editor: Sabina Ratti)
PRA	*Privatisation, Regulation, Antitrust* (Editor: Bernardo Bortolotti)
ETA	*Economic Theory and Applications* (Editor: Carlo Carraro)
CTN	*Coalition Theory Network*