CARBON CAPTURE AND STORAGE FROM FOSSIL FUELS AND BIOMASS – COSTS AND POTENTIAL ROLE IN STABILIZING THE ATMOSPHERE

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Abstract. The capture and storage of CO_2 from combustion of fossil fuels is gaining attraction as a means to deal with climate change. CO_2 emissions from biomass conversion processes can also be captured. If that is done, biomass energy with CO_2 capture and storage (BECS) would become a technology that removes CO_2 from the atmosphere and at the same time deliver CO_2-neutral energy carriers (heat, electricity or hydrogen) to society. Here we present estimates of the costs and conversion efficiency of electricity, hydrogen and heat generation from fossil fuels and biomass with CO_2 capture and storage. We then insert these technology characteristics into a global energy and transportation model (GET 5.0), and calculate costs of stabilizing atmospheric CO_2 concentration at 350 and 450 ppm. We find that carbon capture and storage technologies applied to fossil fuels have the potential to reduce the cost of meeting the 350 ppm stabilisation targets by 50% compared to a case where these technologies are not available and by 80% when BECS is allowed. For the 450 ppm scenario, the reduction in costs is 40 and 42%, respectively. Thus, the difference in costs between cases where BECS technologies are allowed and where they are not is marginal for the 450 ppm stabilization target. It is for very low stabilization targets that negative emissions become warranted, and this makes BECS more valuable than in cases with higher stabilization targets. Systematic and stochastic sensitivity analysis is performed. Finally, BECS opens up the possibility to remove CO_2 from the atmosphere. But this option should not be seen as an argument in favour of doing nothing about the climate problem now and then switching on this technology if climate change turns out to be a significant problem. It is not likely that BECS can be initiated sufficiently rapidly at a sufficient scale to follow this path to avoiding abrupt and serious climate changes if that would happen.

1. Introduction

Carbon capture and storage from fossil fuels is by many seen as a key technological option to reduce CO_2 emissions (see e.g., Parson and Keith, 1998; World Energy Assessment, 2001; Williams, 2001). But it should be noted that the carbon releases from biomass conversion might also be captured and stored (see Ishitani and Johansson (1996); Ekström et al. (1997); Williams (1998); Keith (2001); Azar et al. (2001); Möllersten and Yan (2001); Obersteiner et al. (2001); Keith and Rhodes (2002)). If so, the biomass energy system would deliver CO_2 neutral energy carriers

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such as heat, electricity or hydrogen at the same time as it removes CO_2 from the atmosphere. We refer to this concept as Biomass Energy with Carbon Capture and Storage (BECS). If widely applied, the global energy system as a whole could become an instrument to remove CO_2 emissions from the atmosphere on a continuous basis (as long as storage capacity is available). There are other ways of removing CO_2 from the atmosphere, e.g., through afforestation or direct capture from the air, but we have not included these options in this study.

The aim of this paper is to analyse the potential role that carbon capture and storage from fossil fuels and BECS technologies might play in meeting ambitious global climate targets. We do this by

- estimating the cost of carbon capture from fossil fuels and from bioenergy (including scale-related potential additional storage and transportation costs);
- calculating the cost of meeting two stabilization targets for atmospheric CO_2 (350 and 450 ppm[1]) under various assumptions about the possibility to use carbon capture and storage technologies with fossils fuels and with biomass.

We use a global energy–economy model, GET 5.0, to calculate the costs. The model, and scenario assumptions, are described in Section 2. In Section 3, we present technology cost parameters, and focus in particular on the cost of carbon capture from fossil fuels and biomass energy. In general, biomass conversion facilities can be expected to be smaller than fossil fuel plants, and these smaller plant scales may lead to higher CO_2 transportation and capture costs. These costs are estimated explicitly. In Section 4, we focus on issues related to the potential for biomass energy, fossil fuels, hydro, nuclear and wind and solar energy and the potential to store CO_2. In Section 5, we present our results. Some concluding remarks are offered in Section 6.

2. Model Description and Scenario Assumptions

To analyse the global energy system and the potential role of carbon capture and storage technologies we have used GET 5.0, a global energy model developed by Azar and Lindgren (see earlier publications e.g., Azar et al., 2003). The model is a linear programming model that is globally aggregated and has three end-use sectors, electricity, transportation fuels, and heat (which includes low and high temperature heat for the residential, service, agricultural, and industrial sectors). Primary energy supply options include coal, oil, natural gas, nuclear power, hydro, biomass, wind, solar heat, solar electric and solar hydrogen. Conversion plants exist that may convert the primary energy supplies into secondary energy carriers (e.g., hydrogen, methanol, heat, electricity, natural gas for vehicles and gasoline/diesel). The costs and conversion efficiencies of these conversion plants are given in Section 3 below. The model also includes exogenously set maximum expansion rates for different primary energy supplies and energy technologies.

The model is set up to meet exogenously given energy demands while meeting a specific atmospheric concentration target by the year 2100 at the lowest energy system cost (net present value costs over the period 2000–2300). Optimization is inter-temporal and capital invested in one period remains roughly 30 years (declines exponentially with a life time of 30 years).

Electricity and heat/process heat demands are exogenous to the model and taken from the ecologically driven scenario C1 in IIASA/WEC (see Nakicenovic et al., 1998). Minor modifications were carried out so as to match with actual values for the year 2000 for electricity and primary energy supplies with data taken from BP World Energy Statistics, and the scenarios were extended to the year 2300[2]). The reason for choosing scenario C1 is that it is a low-energy demand scenario. Although the scenario should not be seen as a projection of the future, it is reasonable to believe that the energy demand in the future could be as low as depicted in the C1 scenario if we opt for low-stabilization targets (450 ppm or below). In a sensitivity analysis, a higher energy demand scenario is also tested. Heat/process heat is defined as all stationary uses of fuels that neither aims at generating electricity nor transportation fuels. The C1 transportation scenario is not sufficiently detailed for our analysis, so we developed our own transportation scenario by assuming that the increase in the amount of person kilometers traveled is proportional to GDP growth (in purchasing power parities (PPP) terms). Full details of the model and the demand scenarios are available in Azar et al. (2000, 2003).

Technology is also assumed to be exogenously given. In most cases, e.g., capital costs and conversion efficiency for electricity and heat are assumed constant at their "mature levels" (as given in Table I). For the transportation sector, exogenous declines in fuel cell costs are assumed.

Biomass energy is assumed to be carbon neutral. In reality, bioenergy can be either CO_2 neutral, positive or negative, depending on how land use is affected by the biomass source. If the biomass is replanted, the carbon releases from combustion are recaptured and the biomass energy system is generally CO_2 neutral. If forests are cleared to make way for bioenergy plantations, then substantial initial emissions are associated with the establishment of the system. If, on the other hand, biomass energy plantations are established on lands with sparse vegetation, there might be an initial build up of carbon on the land (both in the soil and the standing biomass). See Schlamadinger et al. (2001) for more detailed descriptions of the impact on biospheric stock of carbon of different biomass energy systems.

The carbon impact of bioenergy systems also depend on the input of fossil fuels in the production, transport and conversion of the biomass. If inefficient systems, e.g., ethanol production from corn in the US, are used then rather high carbon emissions per unit of biofuel will be obtained (Kheshgi et al., 2000, Berndes et al., 2001). On the other hand, there are also bioenergy systems that perform much better, e.g., heat production from short rotation forests. In such systems, the energy used as input for production do not amount to more than 5% of the production of useful energy carriers (Börjesson, 1996). It is for technical and economic reasons very

TABLE I
Assumed efficiencies and capital[a]

	Electricity Production[b,f]				Hydrogen Production[c]				Heat Production[d]				Methanol production[e]	
	No C capture		With C capture		No C capture		With C capture		No C capture		With C capture		No C capture	
	Eff. (%)	$/kW$_e$	Eff. (%)	$/kW$_e$	Eff. (%)	$/kW$_{H_2}$	Eff. (%)	$/kW$_{H_2}$	Eff. (%)	$/kW$_{th}$	Eff. (%)	$/kW$_{th}$	Eff. (%)	$/kW$_{MeOH}$
Coal	45	1100	35	1500	65	700	60	900	90	300	80	500	60	1000
Oil[f]	50	600	40	1000	75	400	70	600	90	100	80	300		
Natural Gas	55	500	45	900	80	300	75	500	90	100	80	300	70	600
Biomass[f]	40	1200	30	1700	60	800	55	1000	90	300	80	500	60	1000
Hydrogen[f]	55	500							90	100				

[a]The efficiencies indicated here are on a higher heating value basis. For technologies involving carbon capture, efficiency penalties are incurred, as shown in the table. Carbon capture rate is assumed to be 90% of the flow (meaning that 90% of the carbon input to the plant is recovered as CO_2 for disposal), although some suggest higher rates.

[b]The cost estimates for coal and natural gas based electricity are rounded numbers from World Energy Assessment (WEA, 2000, p. 292). The WEA estimates lie well in line with Freund and Davison (2002) for natural gas. Freund & Davison report a wide range of cost estimates for coal, some of which are higher than the numbers assumed here.

[c]For H_2 production from coal (through gasification technology), Williams (2001) estimates the cost at 700 USD/kW$_{H_2}$ without carbon capture and 900 USD/kW$_{H_2}$ with carbon capture. The conversion efficiency (coal in, H_2 out) is estimated at 65% without carbon capture and 60% with carbon capture. (These efficiency estimates are lower than in Williams, 2001, by around 5 percentage points. Williams analysis includes some net electricity production in the plant that can replace coal for electricity generation in other plants.) Performance and cost of natural gas conversion to H_2 with and without CO_2 capture are based on Foster-Wheeler (1996), as cited by Williams (2001). For a plant capacity of 1000 MW$_{H_2}$, Williams gives higher-heating value efficiencies for converting natural gas to H_2 of 81% with CO_2 venting and 78% with CO_2 capture. Williams shows a total installed capital cost of $262 million with CO_2 venting and $429 million with CO_2 storage. We round the cost numbers upwards to be on the conservative side.

[d]Capital costs and conversion efficiencies for heat production from biomass, coal and natural gas without carbon capture are derived from Gustavsson et al. (1995), Wahlund et al. (2000), and Azar et al. (2003). In order to estimate the additional costs to capture CO_2 from heat plants, we use data from flue gas capture in power plants. The additional capital cost for the capture in a coal-fired power plant is around 500 USD per kg CO_2 captured per hour (David and Herzog, 2000). For NGCC with flue gas CO_2 capture the cost is around 850 USD per kg CO_2 captured per hour (David and Herzog, 2000). After introducing these costs, we get a total of 520 USD/kW heat delivered from coal with carbon capture, and for natural gas the corresponding calculation gives 300 USD/kW heat. The conversion efficiency for all fuels into heat without capture is assumed to be 90%. Flue gas CO_2 capture in the heat production plants requires 0.8 kWh heat per kg CO_2 captured to regenerate monoethanolamine (Göttlicher and Pruschek, 1997). This corresponds to 25% of the heat releases if coal is used, and 15% if natural gas is used. We assume that parts of these energy losses can be reused at a lower temperature, so that the conversion efficiency into heat drops by 10 percentage points. This lower efficiency also leads to higher capital costs and these are taken into account in the estimates given above. Further, there is a demand for electricity to compress the CO_2 assumed equal to 0.12 kWh_e per kg CO_2 captured (Göttlicher and Pruschek, 1997). This corresponds to 4% of the higher heating value in coal and biomass and 2.5% for natural gas. The use of carbon capture in the heat sector leads to a higher electricity demand in the model than when no carbon is captured.
[e]Methanol production costs are taken from WEA (2000, p. 296).
[f]For oil conversion, unit costs are assumed to be slightly higher than for natural gas, but lower than for coal and biomass. Also conversion efficiencies are in between those for natural gas and coal. For hydrogen conversion to electricity and to heat, efficiency and cost are assumed to be the same as for natural gas conversion. Biomass, which may have a rather high moisture content, would have a lower conversion efficiency (on a higher heating value basis) into heat than coal, oil and natural gas, unless flue gas condensation would be applied. The additional cost of flue gas condensation is estimated at 10% of overall capital costs, and is thus less than the uncertainty range in our numbers, hence no cost adder has been included for flue gas condensation. Biomass to hydrogen and biomass to electricity plants cost the same per kW fuel input as for coal. The efficiency of biomass conversion to electricity and hydrogen are assumed to be 5 percentage points lower than that for coal. Thus, the cost per kW_e or kW_{H_2} is scaled with the conversion losses.
[g]Plants cogenerating heat and electricity are assumed to cost 100 USD/kW_e more than plants that only produce electricity (for all cogeneration plants). The conversion efficiency into electricity is five percentage points lower than in plants that only produce electricity, and the total efficiency is set at 90% (without carbon capture) and 80% (with carbon capture).

unlikely that poorly performing systems can ever make any significant contribution to the global energy system. Further, in the future, with increasingly lower carbon emissions in the global energy system, the carbon emissions associated with this energy use will diminish. For that reason, we have assumed that biomass energy, in the absence of carbon capture and storage, is CO_2 neutral.

The model then estimates CO_2 concentrations as a function of CO_2 emissions, through the use of the model by Maier-Reimer and Hasselman (1987) of the ocean–atmosphere carbon cycle. Different assumptions on how biota will respond to changes in CO_2 and climate might significantly affect the actual concentration we would end up with by the end of the century (IPCC, 2001a). We have assumed that there is a net uptake in biota corresponding to an uptake of 1 Gton C/year that drops to 0.6 Gton C/year over the next hundred years (regardless of the stabilisation target). Average biota uptake (not related to land-use changes) in the 1980s was an estimated 1.9 Gton C/year, but with wide variations (IPCC, 2001a). We assume a land-use change contribution that diminishes (roughly linearly) from 1 Gton C in the year 2000 to zero by the year 2060. These assumptions make our carbon cycle model in line with IPCC estimates of cumulative carbon emissions to meet the 350 and 450 ppm stabilization targets.

An energy–economy model like ours makes it possible to explore quantitatively the role and cost-efficiency of various technologies given various carbon emission constraints, carbon storage availabilities, biomass resource availabilities, and different parameter values for other technologies.

Our model – like any other model of the global energy system – is a simplification of reality in many ways, e.g., the number of available technologies is limited, demand is price-inelastic, decisions in the model are only based on price considerations, and there is no uncertainty about future costs, climate targets or energy demand levels, etc.

Nevertheless, the model is useful when it comes to comparing the costs between scenarios for three main reasons: (i) The set of energy technologies included in the model covers the major energy conversion pathways (electricity, heat/process heat and transportation fuels) and we have assumed representative values for each of these technology pathways; (ii) the relative costs of different technologies are most important when it comes to choosing between them; and (iii) we generate a large number of scenarios based on both stochastic and systematic variations of parameter values, and this sensitivity analysis shows that the results do not critically depend on the exact parameter values.

3. The Cost of Energy Carriers With and Without CO_2 Capture

There are numerous studies of the potential future cost of electricity, hydrogen and heat with or without capturing and storing CO_2 (see e.g., WEA (2000), and references in Table I). Table I summarizes the cost numbers we have chosen for our study (the numbers reflect what the technologies can be expected to cost when they are mature, say around 2020–2030). They are based on estimates from the literature, complemented with our own estimates. We have used round numbers compared to those in the original studies (to avoid the impression that we are more accurate than it is possible to be). Fixed plus variable annual O&M cost is assumed to be equal to 4% of the specific investment cost for each technology in Table I.

There is a wide range of conversion efficiencies and cost numbers when it comes to producing electricity from coal and natural gas, but our model captures the inherent relative costs and efficiency numbers between the different technology options. For instance, electricity production from coal and biomass is inherently less efficient than electricity production from natural gas. Further, the capital costs for coal and biomass fired power plants are inherently higher than for natural gas fired power plants.

Similar observations can be made when it comes to hydrogen and heat production.

3.1. FUEL COSTS

In the model, we have assumed that coal costs 1 USD/GJ, crude oil 3.5 USD/GJ, natural gas 2.5 USD/GJ and biomass 2 USD/GJ.[3] If biomass is used in plants with carbon capture and storage, we assume longer transportation distances to the plant (since larger plants are desirable to capture economies of scale), and the costs would then be 2.5 USD/GJ.[4] In our model we stipulate upper limits on fossil fuel resources and potential biomass supplies, as discussed in Section 4. This implies that scarcity rents arise when fuels become scarce, so the energy prices in the model rise from the price levels noted above and reach roughly 20 USD/GJ (including carbon taxes) within wide ranges depending on the scenario and the fuel toward the end of the century.[5] Hydrogen produced from solar energy by splitting water into hydrogen and oxygen is assumed to cost 23 USD/GJ based on a capital cost of 2000 USD/kW_{H_2}.

3.2. FROM WHICH ENERGY CONVERSION FACILITIES CAN CARBON BE CAPTURED?

Carbon capture and storage is more effective and less costly when carried out in large plants. This tends to favor carbon capture and storage from fossil fuels used in large plants, e.g., power plants (see Table II). It is less feasible to capture CO_2 from small-scale or mobile emission sources such as cars. In our model we assume that carbon can be captured from all fossil fuel and biomass conversions related to electricity and hydrogen production. For reasons related to scale and logistics, we have assumed that no more than 30% of the global energy use for heat and process heat can be equipped with carbon capture and storage technologies. “Heat and process heat” plants appropriate for carbon capture include pulp mills, refineries,

TABLE II
CO_2 emissions from various plants

Plant	“Typical” size	CO_2 emissions (kg/s)
Coal fired power plant	500–1000 MW_e	130–260
Natural gas fired power plant	300 MW_e	40
Pulp mill (typical large biomass conversion facility)	1500–3000 ton pulp per day	36–72
District heating station	10–100 MW_{heat}	1–10

Source: Own calculations.

and plants where carbon is used as an industrial raw material (steel mills) and consumed as anode material (aluminum plants).

Most of the biomass in the world is currently used in traditional ways (for cooking) and this is inherently a very small-scale technology. Also in industrialized countries biomass is often thought of as a small-scale technology. This is because most biomass conversion uses residues, which are dispersed geographically and thus incur high transportation costs if large quantities must be secured. In the future, one might expect small-scale uses to continue to be important, e.g., residential heating where the biomass is burnt as wood fuel or pellets. Under these conditions, scale considerations rule out CO_2 capture and storage from biomass.

But there are larger-sized operations in use, and these can be expected to become even more important in the future. Currently, pulp mills are major point sources of biomass-derived CO_2, as are district heating plants. For instance, a typical (chemical) pulp mill (1500–3000 tons of pulp per day production), produces 36–72 kg CO_2/s from energy use of biomass by-products of pulp production (black liquor and bark).

3.3. THE COST OF CO_2 TRANSPORTATION AND STORAGE

Because of the large volumes involved, pipelines would be preferred for the transportation of CO_2 to a storage location once it has been captured. Transport of CO_2 can best be done at elevated pressure, e.g. 80 to 140 bars. Compression and pipeline transport of CO_2 is feasible and technically proven. In addition, the use of large tankers might be economically attractive for long-distance transportation of compressed/liquefied CO_2 over water.

We investigated economies of scale effects on the cost of CO_2 transportation and storage by using a model issued by the IEA GHG R&D Programme (IEA, 2002). The costs of transportation and on-shore storage were calculated for a set of CO_2 flow rates and transportation distances[6] (Figure 1).

In a globally aggregated model it is not possible to include issues of scale in detail. Instead, we chose the following rough approach. The CO_2 transportation and storage cost is around 10 USD/ton CO_2 from plants which release carbon at

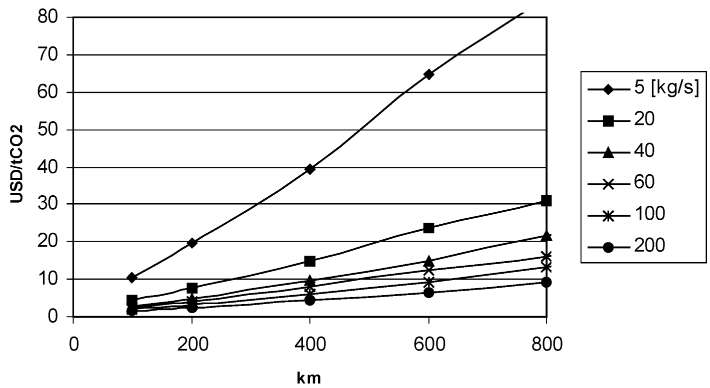


Figure 1. Cost of CO_2 transportation and storage for on-shore injection wells.

a rate of 100 kg CO_2/s (typical large fossil fuel fired plants) if transported 600 km (see Figure 1), and this is the value that we use for CO_2 storage from fossil fuel fired power plants.

The CO_2 transportation and storage cost for a plant which releases carbon at the rate 20–40 kg CO_2/s is 15–25 USD/ton CO_2 for a transportation distance of 600 km. We use the value 20 USD/tonCO_2 for biomass fired plants.

An important consideration is that our cost assessment assumes dedicated single pipelines for each project. If a CO_2 grid with trunk pipelines becomes a reality, similar to the case for natural gas, allowing numerous CO_2 emitting point sources to be connected to a CO_2 transport network, the average scale of the transportation system would increase, thus decreasing the average cost.

3.4. TOTAL COSTS PER UNIT OF ENERGY AS A FUNCTION OF AN ASSUMED CARBON TAX/CARBON PERMIT PRICE

In Figures 2–4, we show the cost of electricity, heat and hydrogen from various technologies (using the technology costs given above) as a function of an assumed carbon tax/permit price. Transportation and storage costs as estimated above at 10 and 20 USD/ton CO_2 for carbon captured from fossil fuels and biomass, respectively, have been included in the graphs.

The figures show that with increasing carbon taxes/permit prices, carbon capture and storage applied to coal fired technologies become competitive with conventional coal technologies at around 100 USD/ton C. But at that tax/permit price, conventional natural gas-fired technologies can still provide energy at a lower price. It is only when the carbon tax reaches 100–200 USD/ton C that capture and storage of carbon with natural gas technologies becomes competitive with conventional natural gas fired technologies (for heat, electricity and hydrogen production). For such carbon taxes/permit prices, biomass (with or without carbon capture and storage) also becomes competitive for heat, electricity and hydrogen production.

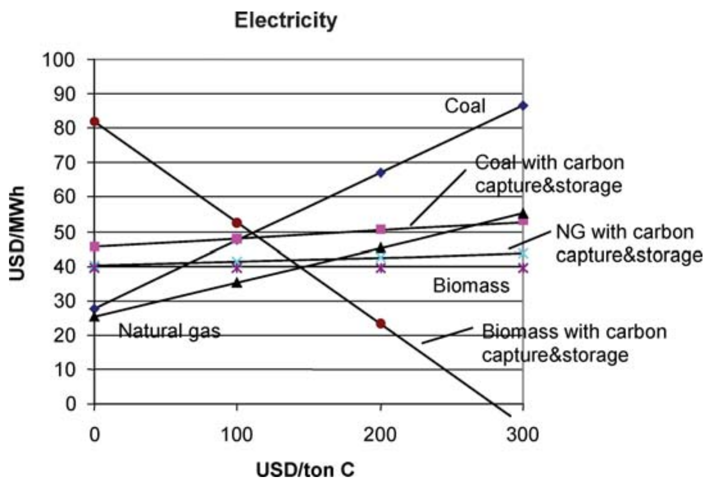


Figure 2. The cost of electricity from fossil fuels and biomass is shown as functions of the carbon tax/permit price. Data from Table I.

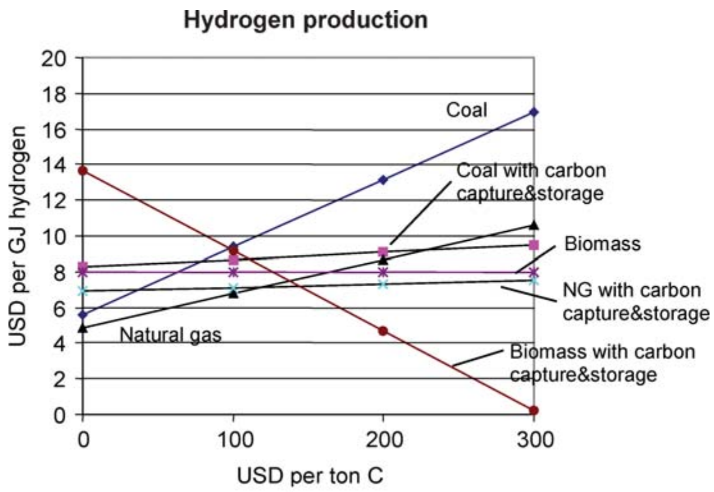


Figure 3. The cost of hydrogen from fossil fuels and biomass is shown as functions of the carbon tax/permit price. Data from Table I.

Under the assumption that the CO_2 from the biomass-fired plants is captured and stored, electricity/hydrogen/heat production costs will drop if the plant owner gets paid for capture and storage of the carbon. Graphs showing this feature have been presented previously by Azar et al. (2001) and Keith and Rhodes (2002). At a carbon tax/permit price of 300 USD/ton C, biomass-based electricity can be produced at no cost since the revenues from the carbon capture and storage cover the plant cost, the biomass cost and the O&M costs.[7]

For the sake of comparison with the above carbon values, estimates of the carbon tax (or permit price) required to meet the Kyoto protocol when participation of the

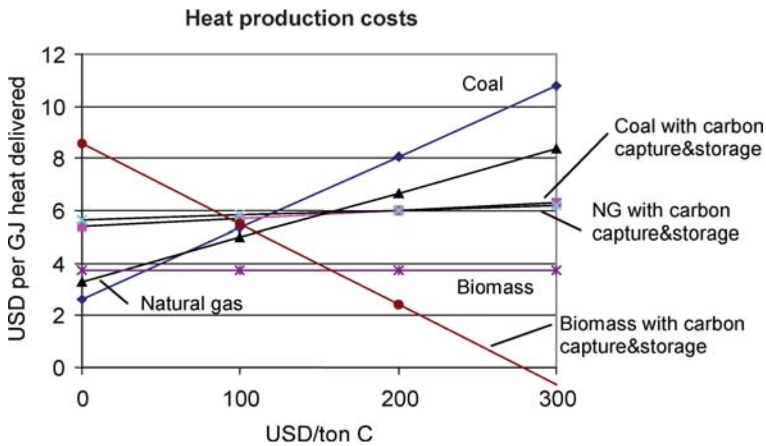


Figure 4. The cost of heat from fossil fuels and biomass is shown as functions of the carbon tax/permit price. Data from Table I.

United States was expected was less than 100 USD/ton C by most models (see IPCC 2001c, 537). Permit prices are expected to be lower as a consequence of President Bush's decision to withdraw from the protocol.[8] For further comparison, it can be noted that the Swedish carbon tax on the transportation sector and on household and district heating, is currently roughly 400 USD/ton C.

4. Global Energy and Carbon Storage Potentials

4.1. BIOENERGY POTENTIALS

Potential bioenergy supplies can be divided into two broad categories: (i) wastes and residues, including organic municipal waste and residues and by-products of food and materials production and processing and (ii) dedicated energy crops. The energy value of residues generated world-wide in agriculture and the forest-products industry amounts to more than one third of the total commercial primary energy use at present (Hall et al., 1993, p. 607, Wirsenius, 2003). Dedicated plantations include sugar crops and perennial herbaceous crops and short rotation woody crops. Yield levels in the tropics might reach (on average on well managed plantations) 15 ton dry matter/ha/year, or 300 GJ/ha/yr, but one should be hesitant to assume that these numbers can be achieved on average over large tracts of lands, in particular if degraded lands are targeted (as a means of avoiding competition with food production or the destruction of pristine ecosystems).

How much biomass we can get for energy purposes depends on income, the size of the global population and how people's preferences for meat, nature and landscapes develop over time. It also depends on how climatic change will affect forestry and agriculture. Some argue that degraded lands could be targeted with these plantations, others are concerned about social and environmental conflicts that may arise if/when dedicated plantations come to compete with food production for agricultural lands. For various perspectives on these issues, see Hall et al. (1993); Carrere and Lohman (1996); Azar and Larson (2000); Larson and Kartha (2000); Victor and Ausubel (2000) and Azar (2004).

In this paper, we will assume that up to 500 Mha of land are (or will be made) available for bioenergy plantations and that the average yield is 200 GJ/ha/year (or about 10 dry t/ha/year). It may be noted that this is around six times current global industrial roundwood production. The area is equivalent to a third of the current global crop land, or a sixth of global pasture land. Thus, the impact on global land use can be very large. We will also assume that up to 100 EJ/year can be obtained from residues (see Berndes et al., 2003, for a survey of 17 assessments of global biomass energy potentials).

Thus, in this study, we assume that the maximum potential for bioenergy (residues plus dedicated plantations) is 200 EJ/yr (including traditional biomass uses), although in the real world one can very well imagine a situation where only half or perhaps 50% more than this might be obtained.

4.1.1. *The Maximum Potential for Carbon Capture From Biomass*

A biomass potential 200 $\pm$ 100 EJ/yr corresponds to roughly 5 $\pm$ 2.5 Gton C/yr, and this is thus the maximum carbon capture potential from biomass assumed in this study. In reality, however, the potential is likely to be lower for reasons related to scale and capture efficiency. First a considerable share of this biomass will most likely be used in applications where CO_2 capture and storage are not possible, e.g., small-scale facilities. Second, the carbon capture at the conversion facility will not be complete (it is generally assumed to be around 90%, although higher numbers are achievable).

4.2. ENERGY SUPPLY POTENTIALS

We assume that the ultimately recoverable resources of oil and gas correspond to 12 000 and 10 000 EJ, respectively. This is roughly twice BP's estimate of the reserves of these resources in the year 1998, see WEA (2000, pp. 143–145). Coal is basically unlimited for all energy policies related to the 21st century. Nuclear is constrained in the model to its current level, and hydro is maximised at close to its current level. The potential for solar energy is basically unlimited if energy storage possibilities are available, and we assume that hydrogen plays that role. Intermittent wind and solar are maximised at 30% of the electricity demand.

4.3. CARBON STORAGE POTENTIALS

A key issue is where CO_2 should be stored. Suitable candidate underground CO_2 storage locations are exhausted natural gas and oil fields, not exhausted oil

TABLE III
Potential for carbon storage underground

Underground storage	Storage capacity (Gton C)
Deep aquifers with structural traps	30–650
Deep aquifers without structural traps	<14000
Depleted oil and gas fields	130–500
Coalbeds	80–260
Enhanced oil recovery	20–65

Source: Grimston et al. (2001).

fields (so-called enhanced oil recovery), deep unminable coal layers, and deep saline aquifers (water-containing layers). See Halloway (2001) and Grimston et al. (2001) for discussions and estimates of the global potential for underground storage. In Table III, we reproduce the assessment of Grimston et al. Ocean storage is also possible, but may be more controversial than underground storage.[9]

Finally, much research remains before carbon storage can be applied at the Gton C scale. Surprises – physical or political – may appear that rule out the use of below-ground or ocean CO_2 storage, and therefore we analyze two cases in our base runs: no carbon capture (for the sake of comparison) and up to 600 Gton C storage (which seems plausible given the estimates in Table III). This constraint neither affects overall net present value costs nor the amount of carbon that is captured over the next 100 years, but it has implications for the energy system after the year 2100 and onwards. We also assume that there is a maximum rate of increase in carbon capture and storage of 100 Mton C/year/year. This restriction is removed in a sensitivity analysis.

One risk that we have not dealt with in our model is the possibility of leakage of the stored CO_2. Clearly, leakage rates have to be much smaller than 1% for carbon capture and storage to play a large and meaningful role in meeting stringent climate targets. (If 1% of 600 GtC leaks every year, total emissions from leakage would amount to as much as 6 GtC/year, which is roughly equal to current total global CO_2 emissions from fossil fuels.) For more details on the leakage question, see Pacala (2002) and Ha-Duong and Keith (2003).

5. Results: Global Energy Scenarios and Cost Estimates for Atmospheric Stabilization at 350 and 450 ppm CO_2

In this section, we present our energy scenarios and cost estimates for stabilizing atmospheric concentrations of CO_2 at 350 and 450 ppm, respectively. Three main cases are investigated:

Case 1: Carbon capture and storage is not allowed (no capture).
Case 2: Carbon capture and storage is allowed but only from fossil fuels (fossil capture).
Case 3: Carbon capture and storage is allowed from fossil fuels and biomass (fossil and biomass carbon capture allowed, BECS).

5.1. WORLD PRIMARY ENERGY SUPPLY SCENARIOS

In Figure 5a–f, we depict the world primary energy supply for the different scenarios.

A general feature for all scenarios is that biomass increases to its maximum potential by 2060–2080. The combined contribution from wind and solar electricity (PV or solar thermal) is constrained to 30% of the electricity demand in the model (for intermittency reasons) and reaches this level by the middle of the century. Compared to the global primary energy demand, the contribution of these sources may look small, but by the year 2050 in the 350 ppm no capture scenario, there are more than 5000 TWh/year of electricity from wind (in round numbers about three million 1 MW_e wind turbines, or twice the current nuclear contribution) and half that amount from solar cells.

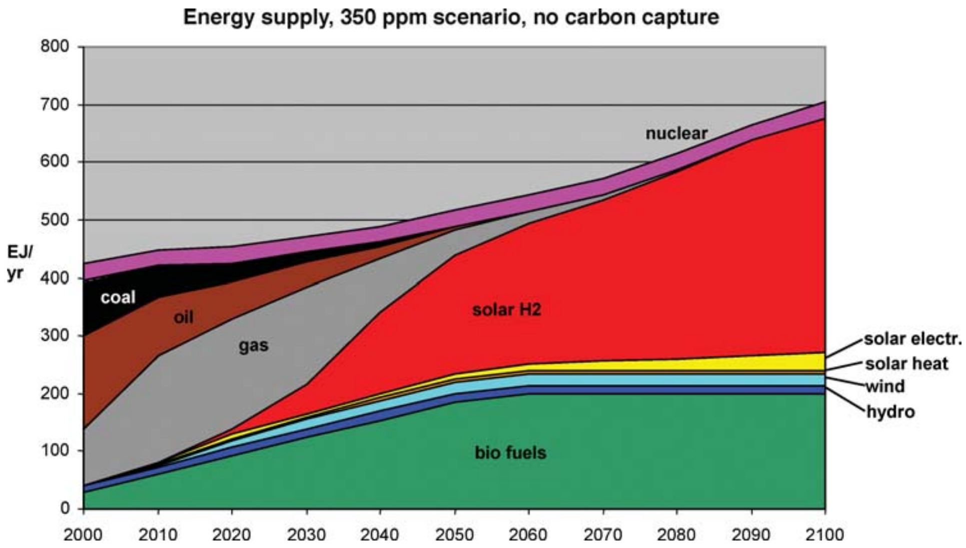
In all of the 450 ppm scenarios and in the two 350 ppm scenarios that allow carbon capture, all oil and natural gas resources assumed available in the model are essentially exhausted by the end of this century. In the 350 ppm scenario without carbon capture, considerable amounts of oil and some gas remain since the carbon constraint is so stringent (360 Gton C can be emitted between 1990 and 2100). Total oil and gas resources assumed available in our model amount to around 400 Gton C, so all of it cannot be burned, in particular given that it takes some 40 years to phase out coal in this scenario.

In both 450 ppm scenarios with carbon capture, the contribution of coal to the global energy system by the year 2100 is larger than the entire global energy system today. The contribution of coal is also substantial in the two 350 ppm scenarios in which carbon capture is allowed.

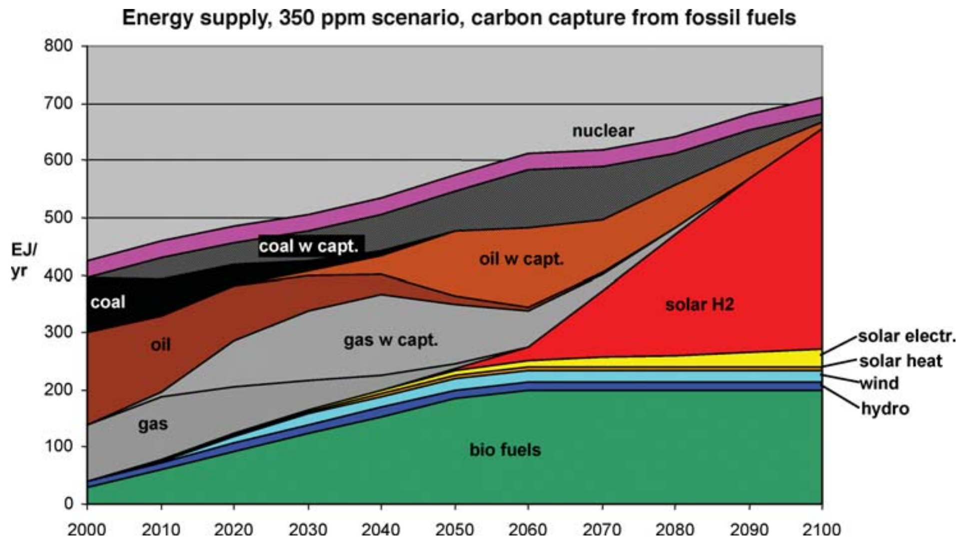
Biomass energy with carbon capture and storage is utilized in both the 350 and 450 ppm scenarios that allow this option, but it enters the energy system two decades later in the 450 ppm scenario than in the 350 ppm scenario.

Solar hydrogen, i.e., hydrogen derived from solar energy either through electrolytic or thermochemical conversion of water, which functions as a back-stop technology for the energy system, enters the energy system in all cases. (The hydrogen can be used not only as a transportation fuel, but also to produce heat and electricity.) It plays a completely dominant role in the 350 ppm scenario with no carbon capture, and a very minor role in the 450 ppm scenario with carbon capture from both fossil and biomass.

In the transportation sector, oil remains the dominant fuel until the middle of the century, and then a transition toward hydrogen takes place. The more stringent the



(a)



(b)

Figure 5. (a) Scenario for 350 ppm target: carbon capture and storage is not allowed. (b) Scenario for 350 ppm target: carbon capture and storage is allowed but only from fossil fuels. (c) scenario for 350 ppm target; capture of CO_2 from fossil fuels and BECS. (d) Scenario for 450 ppm target: carbon capture and storage is not allowed. (e) Scenario for 450 ppm target: carbon capture and storage is allowed but only from fossil fuels (fossil capture). (f) Scenario for 450 ppm target: capture of CO_2 from fossil fuels and BECS.

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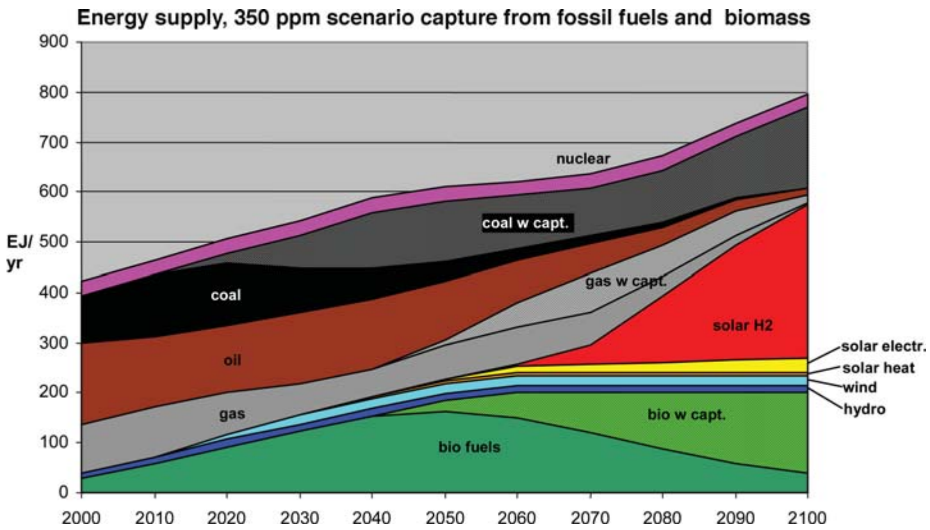
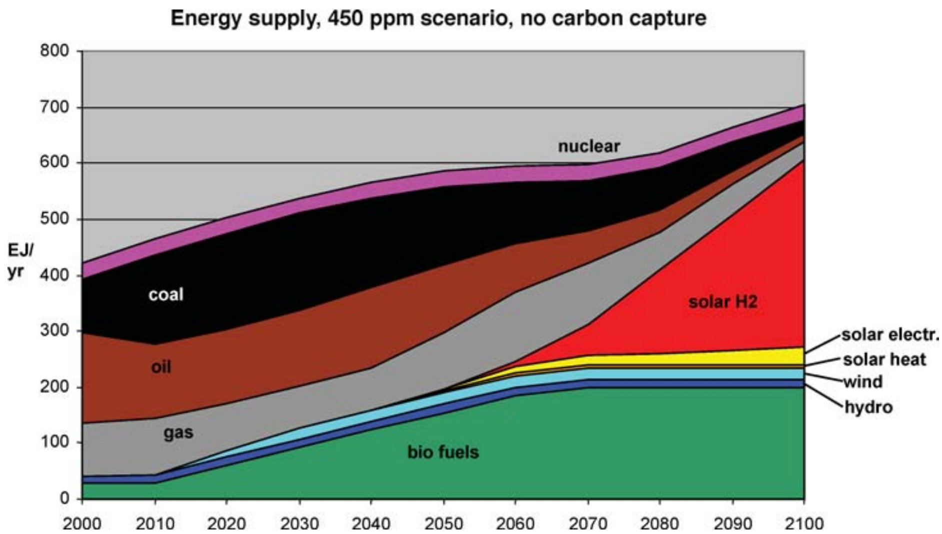


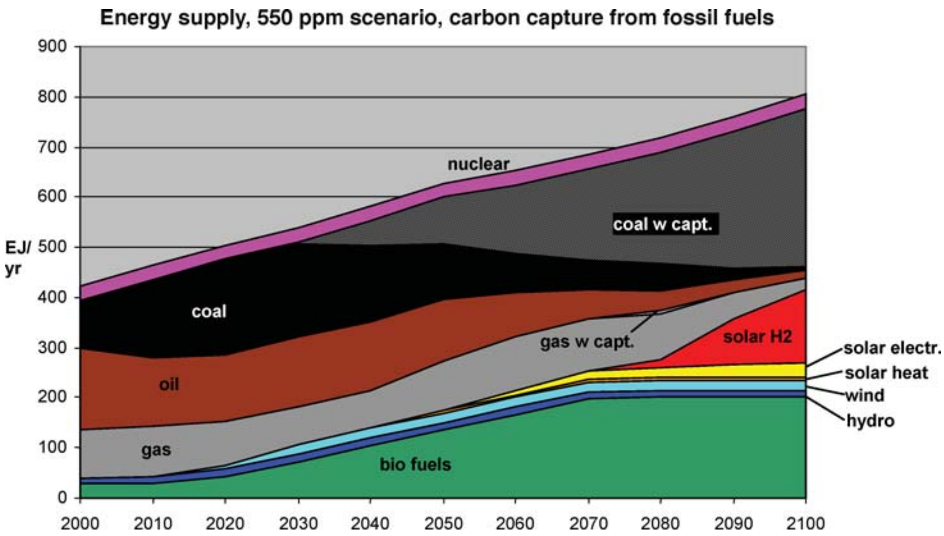
(c)



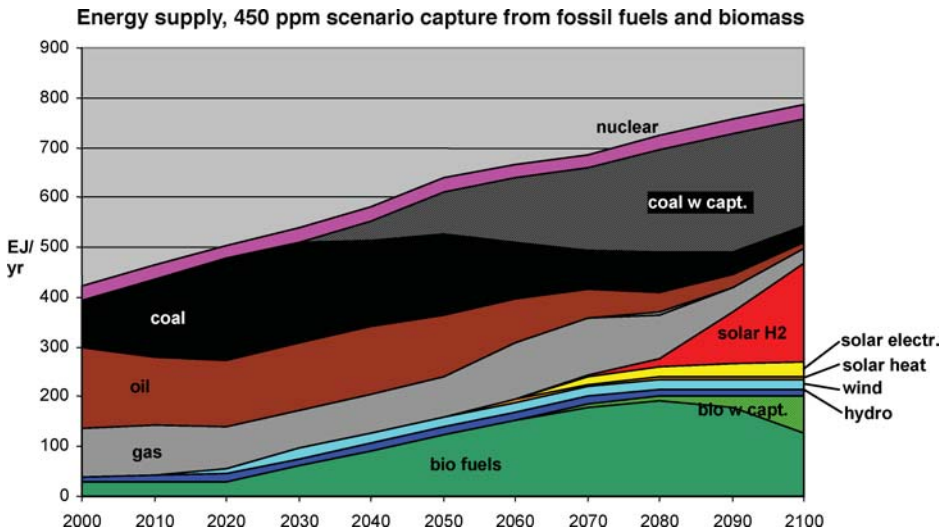
(d)

Figure 5. (*Continued*)

scenario and the less carbon capture and storage is allowed, the heavier the reliance on hydrogen. One interesting feature is that the possibility to use BECS opens up the option to use coal-based diesel fuels or natural gas in the transportation sector and still keep overall global emissions at zero. This may happen if hydrogen technologies remain expensive or if the expected gain in energy efficiency of hydrogen in fuel cells is not significantly higher than electric hybrid vehicles. In the 450 ppm



(e)



(f)

Figure 5. (*Continued*)

scenarios presented above, natural gas provides a significant part of the fuel for cars for a few decades around 2060. The hydrogen is primarily derived from solar energy, but there is also some contribution from fossil fuels (the extent to which this happens depends on the scenario). More detailed results for the transportation sector have been published in Azar et al. (2003) in which an earlier version of this model was used.

Finally, a number of very rapid transitions take place in the scenarios, in particular in those that meet a 350 ppm target, e.g., the expansion of solar hydrogen in Figure 5a, the expansion of carbon capture in the beginning of the century in Figure 5b, and the expansion of carbon capture from coal around 2030 and from biomass in the second half of the century in Figure 5c. One may debate whether such rapid transitions are feasible. In linear programming models of the energy system such as ours, expansion rate constraints are often introduced to model inertia in the system.[10] However, there are problems associated with setting such expansion rate constraints.[11] In Section 5.1, we carry out a few sensitivity analyses on this matter.

5.2. COST CONSIDERATIONS

In Figure 6, we present our estimates of the net present value cost of meeting the 350 and 450 ppm stabilization targets (over the period 2000–2100). The model is set up so that the concentration targets have to be met by the year 2100 but overshoots are allowed before the year 2100.

The costs are calculated as the difference in annual total energy system cost between a baseline scenario (in which no carbon constraints are imposed) and the abatement scenario. These annual costs are then discounted by 5%/year back to year 2000 values to give a single net present value cost for each scenario.

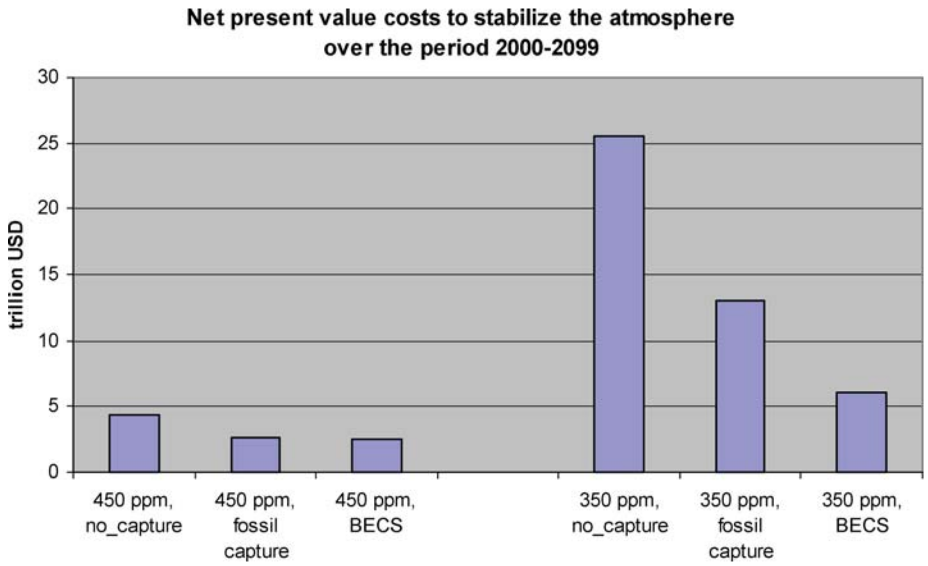


Figure 6. Net present value of extra energy systems costs to meet a 350 and 450 ppm stabilization target by the year 2100 compared to a baseline scenario with no CO_2 constraints. The discount rate is 5%/year.

Several important observations regarding the cost estimates can be drawn:

- The cost drops from 26 trillion USD to 13 trillion USD in the 350 ppm case, and from 4.3 trillion to 2.6 trillion in the 450 ppm case when carbon capture and storage from fossil fuels are allowed (compared to a case when no carbon capture is allowed). (A trillion USD is 10^{12} USD.)
- With BECS as an added option, there is a further even more significant drop in costs (percentage wise, that is) in the 350 ppm case, from 13 trillion USD to 6.1 trillion.
- However, the introduction of BECS only marginally affects the cost of meeting the 450 ppm target (compared to the case when fossil carbon capture and storage is allowed).

The reason that BECS plays an important role in the 350 ppm scenario is partly that it is less costly per ton C avoided than the introduction of solar hydrogen, and partly that it enables negative global emissions in the second half of the century, which opens up the possibility to emit more CO_2 in the near term. This point is discussed further below.

Next, we test the sensitivity of our key result – that BECS reduces the cost to meet a 350 ppm target substantially, but not the cost to meet a 450 ppm target – with respect to a number of key parameter values in the model. The additional capital costs for carbon capture technologies (as compared to the same plants without carbon capture) were assumed to vary between −50 and + 100% from the base case value of Table I (with a stochastic variation chosen so that the mean value equals the base case value). We have also varied the following parameter values: additional capital costs for solar hydrogen, electricity and heat and the additional costs for carbon storage and biomass transportation to carbon capture plants, the maximum potential of biomass, the maximum expansion rate for biomass, solar (for hydrogen production) and for carbon capture and storage technologies (uniform variation in the range ±50%). In total, 26 parameters have been varied.

The stochastic sensitivity analysis, shown in Figure 7, suggests that the cost relations between the case when BECS is allowed and the case with capture is only allowed from fossil fuels remains largely unaffected by the stochastic variation in parameters. For the 450 ppm target, the inclusion of BECS technology reduces the cost by less than 10%, while for the 350 ppm target, BECS leads to a reduction in the interval 40–60%. Larger variations are found for the 450 ppm target in the cost ratio between the fossil capture case and the no capture case, where the cost of the case with fossil capture is in the range 45–80% of the cost of the no capture case.

In Figure 8, we compare the annual costs with the global GDP development (taken from IIASA/WEC council scenario C1, which was the basis for the energy demand scenarios, Nakicenovic et al. (1998). The IIASA/WEC numbers were given in 1990 USD, and we used a 22% price increase (US price deflator) to convert 1990 USD into year 2000 values. The rapid cost increase of the 350 ppm scenario

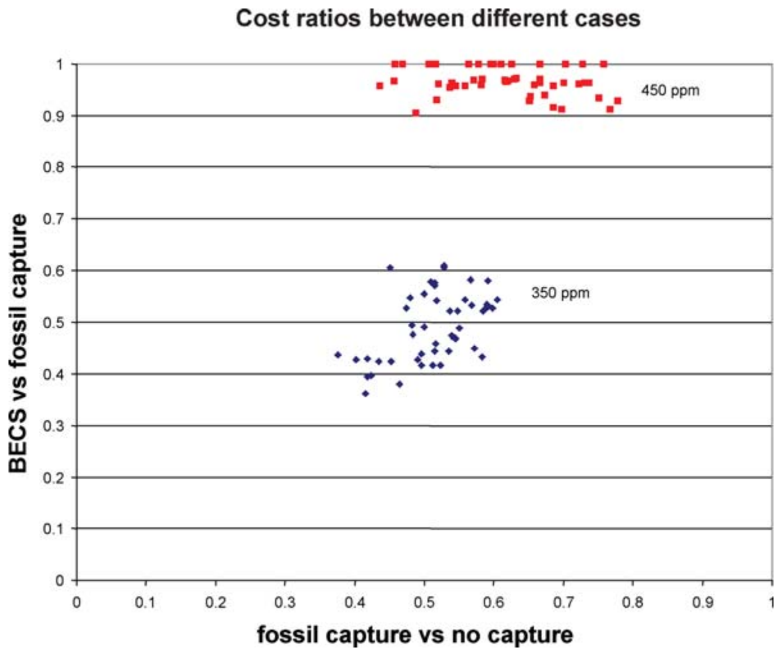


Figure 7. The diagram shows variations in cost relations based on 49 different parameter settings for each of the two stabilization targets. Parameters have been randomly generated within an interval around our base estimates. For each parameter setting, the cost to meet the two targets has been calculated for the three cases discussed in Figure 6: one without carbon capture technologies, one with carbon capture from fossil fuels only, and one that also allows capture from biomass (BECS). Each set of parameters applied to a certain target (a point in the diagram) is characterized by two cost ratios: one between the case with fossil capture and the case with no capture on the horizontal axis, and one between the BECS case and the fossil capture case on the vertical axis. The variations in parameter values leads to some variation in the relative cost reduction when carbon capture from fossil fuel is introduced, especially in the 450 ppm target, but it is clear that the introduction of BECS plays an insignificant role for the cost in the 450 ppm case and reduces costs by 40–60% in the 350 ppm case, for all parameter sets tested.

with no carbon capture allowed, stems from rapid and early investments in solar hydrogen. It is interesting to note that the no-capture scenario costs drop to roughly the same level as the carbon capture case toward the end of the century. This is partly explained by the fact that there is a rapid expansion of solar hydrogen also in the carbon capture cases, since the 350 ppm scenario is so stringent that the 90% carbon capture rate from fossil capture systems results in CO_2 emissions that are too large to allow most of the energy to come from fossil fuels with carbon capture and storage.

Although global net present value costs are estimated in the trillions and annual costs are as high as several percent of annual global GDP, these costs are rather small compared to the expected growth in GDP over the same time period. Since GDP is assumed to grow by around 2.2%/year in this scenario, the GDP is 8.5

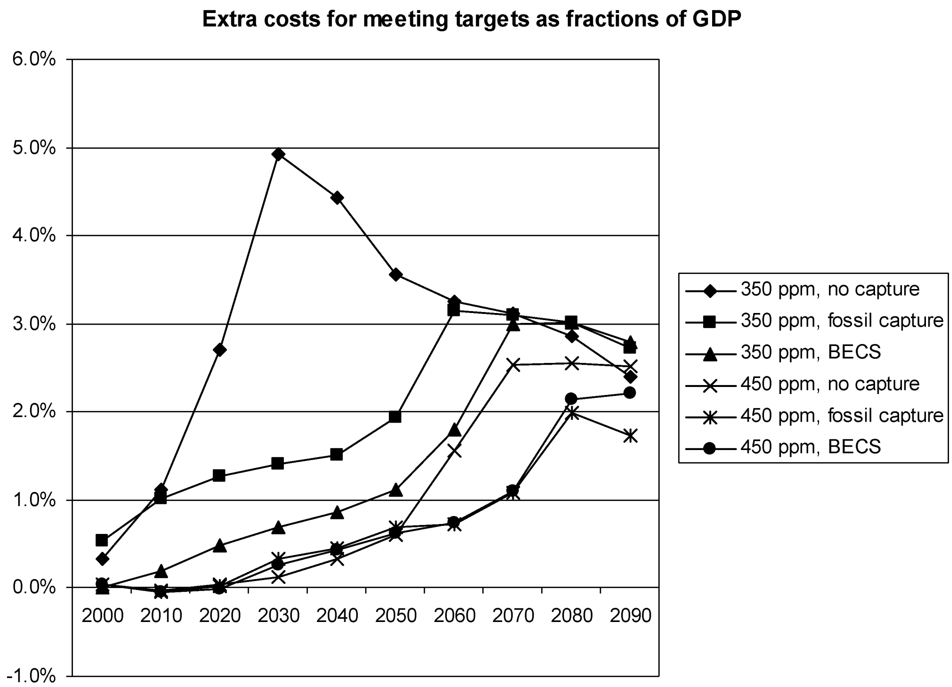


Figure 8. Extra costs for the different scenarios as fractions of GDP.

times higher by the end of the century than in the year 2000. With the 350 ppm stabilization scenario, GDP in 2100 would be 8.2 times the 2000 level,[12] a rather modestly lower income level. A more detailed discussion along these lines is given in Azar and Schneider (2002).

5.3. OPTIMAL EMISSIONS TRAJECTORIES

In Figure 9, we depict the emissions paths toward the stabilization targets. The model chooses the optimal emissions trajectory toward the stabilisation targets, and since different technological options are available, different paths and cumulative emissions are possible. It is important to note that BECS implies that we have negative emissions in the later decades of the century in the 350 ppm case. This means the cumulative emissions over the century becomes substantially higher in the BECS case than in the other cases. The reason for that stems from the fact that if we emit one ton of carbon now, only 36% will remain in the atmosphere by the end of the century and still meet the target. That means that if we can emit negatively toward the end of the century, 0.36 ton C removed in 2100 makes it possible to emit 1 ton C at present. Thus, cumulative emissions can be higher with BECS. This is one important reason contributing to making the overall costs of meeting the 350 ppm target lower with BECS.

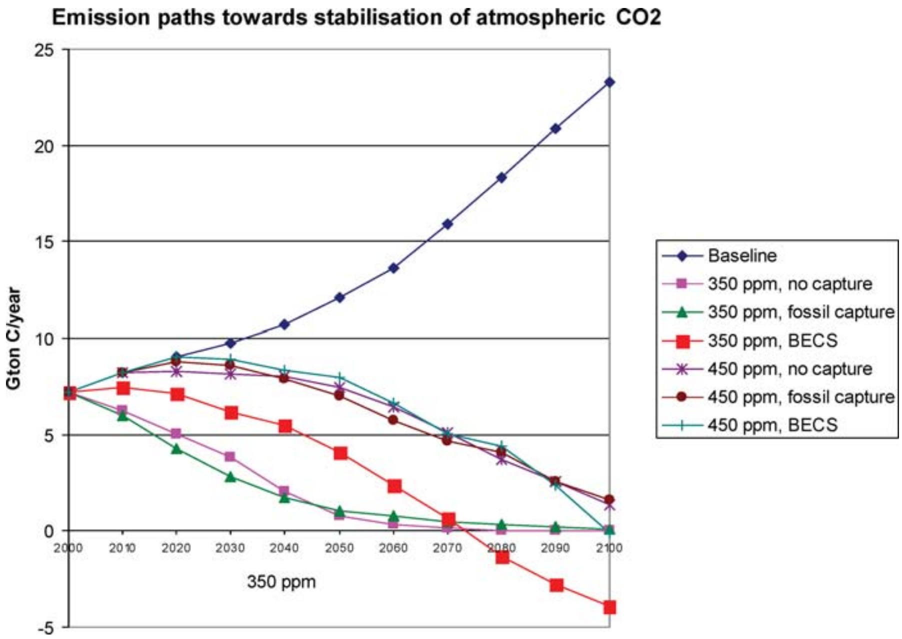


Figure 9. Optimised emission paths toward the stabilisation targets for the different scenarios including the baseline with no emission constraint.

Allowable emissions over the period 1990–2100 for the 350 and 450 ppm concentration targets are given in Table IV. For the sake of comparison, we also include estimates by IPCC (1994) and Wigley et al. (1996) of the cumulative emissions to meet these stabilisation targets. The runs in case 1 and 2 indicate that our carbon cycle model is in line with those used by IPCC and Wigley et al. and case 3 illustrates that negative emissions (or low emissions) toward the end of century may have a significant impact (primarily in the 350 ppm case) on the total amount of carbon that may be emitted over the entire period.

The drawback with BECS in the 350 ppm scenario is that the peak atmospheric concentrations will be higher (since larger emissions are allowed in the near term). Peak concentration in the 350 ppm case is 430 ppm (in the year 2040) when BECS is allowed, compared to a peak of 400 ppm (reached in 2030) when neither BECS nor carbon capture from fossil fuels is allowed (case 1).

TABLE IV

Cumulative CO_2 emissions from fossil fuel use and land use changes from 1990 to 2100 (in Gton C)

Stabilisation target	Case 1: No capture	Case 2: Fossil capture	Case 3: BECS	IPCC (1994)	Wigley et al. (1996)
350 ppm	360	353	469	300–430	360
450 ppm	755	751	786	640–800	710

5.4. FURTHER SENSITIVITY ANALYSIS

In this section, we analyse whether alternative modeling assumptions may significantly alter our conclusions as stated in bullets above.

5.4.1. *Higher Energy Demand Scenarios*

We investigated the costs for meeting climate stabilization targets for higher energy demand scenarios. We assumed a 0.5 percentage points higher annual growth rate for the energy demand resulting in a scenario reaching a primary energy supply of 1600 EJ/year and 32 Gton of annual carbon emissions in the year 2100. We then analysed the cost of meeting a 350 and a 450 ppm atmospheric CO_2 concentration target by the year 2100. In Figure 10 it is shown that the difference in costs for the 450 ppm target with and without BECS is only marginal, whereas the use of BECS reduces costs by 43% for the 350 ppm target compared to a situation in which only carbon capture from fossil fuels is used.

Although costs are higher in this case than in our base case analysis (with lower energy demand), it is interesting to note that the cost structures are similar (compare with Figure 6). It is also interesting to note that the cost of meeting a 450 ppm scenario without carbon capture and storage is roughly the same as the cost to meet a 350 ppm scenario with fossil capture and BECS allowed.

We also estimated the share of biomass with BECS during the period 2050–2100 of total biomass use during the same period as a function of the atmospheric CO_2

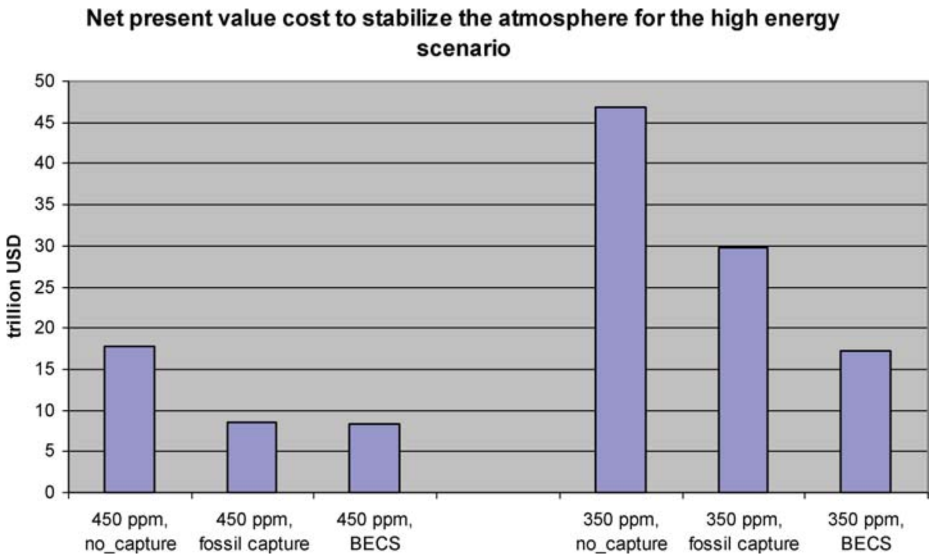


Figure 10. Net present value of extra energy systems costs in a high energy demand case. The cost is calculated as the extra energy system cost to meet a 350 and a 450 ppm atmospheric CO_2 concentration targets by the year 2100.

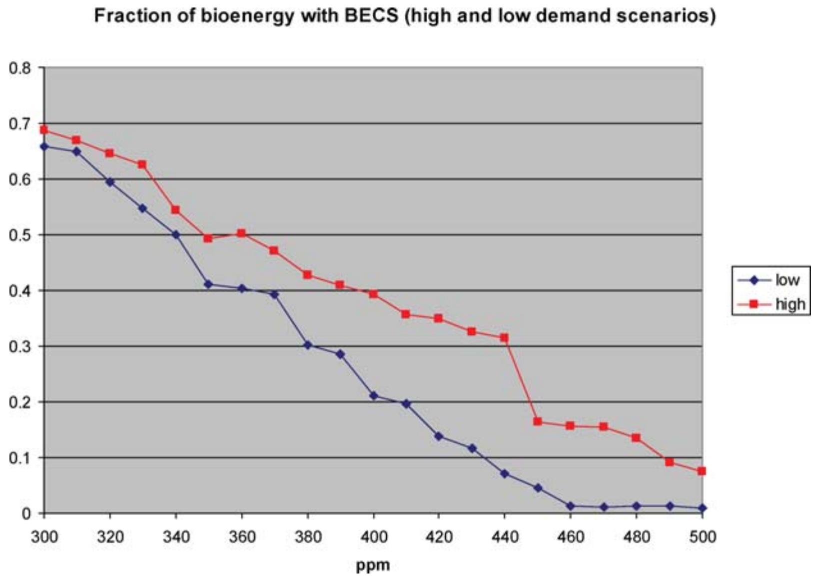


Figure 11. Share of cumulative biomass use during the period 2050–2100 with BECS for a high and a low-energy demand scenario.

target by the year 2100. The graph in Figure 11 demonstrates one of our key results that it is only for CO_2 concentration targets that are below 450 ppm that BECS plays an important role in the global energy system, and that this result holds for both a low-energy scenario (the base case) and a high energy scenario (clearly, for the latter scenario BECS is more important). It may be noted that the model is set up so that at least 20% of the total biomass used has to be used in small-scale heat facilities in which BECS cannot be applied.

5.4.2. *Low-Solar Energy Costs*

In case carbon capture and storage is not allowed in the model runs, the cost of meeting stringent CO_2 targets becomes heavily dependent on the cost of hydrogen produced from solar energy (by splitting water). In a sensitivity analysis, we lowered the cost of solar hydrogen from 2000 USD/kW_{H_2} which is our base case value, to 1200 USD/kW_{H_2}. This has a significant impact on the cost numbers, in particular in the 350 ppm case. The net present value of the cost to meet this target drops from 26 to 17 trillion USD. The cost of meeting the targets with carbon capture allowed drops too but not by as much.

5.4.3. *The Importance of the Exogenously Introduced Maximum Expansion Rate on Carbon Capture and Storage*

When the restriction of 100 Mton C/year/year on the expansion rate for carbon capture and storage is removed, the introduction of carbon capture technologies is delayed. This leads to a more rapid subsequent introduction of these technologies, and consequently an associated faster reduction of CO_2 emissions. For instance, in the 350 ppm case with BECS, carbon emissions are reduced from 5 Gton C/year in 2050 to 1.5 Gton C/year in 2060. We judge this rapid reduction as unrealistic and this observation justifies the introduction of the maximum expansion rate constraint on carbon capture and storage.

If this constraint is removed, the net present value of the cost of meeting the two stabilization targets is reduced by 32 and 23% in the 450 ppm case with and without BECS, respectively. In the 350 ppm case, the cost is reduced by 16% and 5% in the case with and without BECS, respectively. However, it may be noted that these cost estimates refer to the change in the additional energy system cost (i.e., the cost to meet the targets). The change in the total energy system cost amounts to two percent or less in all cases. Finally, it may be noted that without the maximum expansion rate constraint on carbon capture and storage, in the 450 ppm case we get around twice as much BECS by the year 2100 than what we get when the constraint is active.

5.4.4. *To What Extent does the Value of BECS Stem From the Fact That Higher Cumulative Emissions are Possible With BECS for the Same Stabilization Target?*

Earlier we concluded that the lower costs when introducing BECS in the 350 ppm case stemmed from a change in the emissions trajectory and the fact that BECS is a lower cost option than solar hydrogen. In order to separate the importance of these factors, we ran the model with both fossil carbon capture and storage and BECS as possible technology options, but stipulating the carbon trajectory to be the same as that obtained when only fossil carbon capture and storage were allowed. Under these conditions, the cost of meeting the 350 ppm target dropped from 13.0 to 10.3 trillion USD whereas the cost falls to 6.1 trillion USD when the most optimal trajectory is chosen. Thus, for the parameter values we have chosen, the change in the carbon emission trajectory is a more important factor explaining the drop in costs for the BECS option than BECS *per se*.

5.4.5. *Lower BECS Costs and the Cost to Meet the Stabilisation Targets*

In setting up our base case of the model, we assumed that there would be additional costs associated with carbon capture and storage from biomass than from fossil (0.5 USD/GJ additional biomass cost if used in plants with carbon capture, and 20 USD/ton CO_2 in storage and transportation cost versus 10 USD/ton CO_2 for fossil fuels). These numbers were deliberately chosen so as not to be overly optimistic about the prospects for BECS. But lower cost estimates cannot be excluded, for instance if a huge network of pipelines distributing CO_2 would be established (which would lower the cost of transporting biomass-derived CO_2).

In a sensitivity analysis, we set both the additional cost of transporting biomass to the conversion plants with carbon capture and the additional CO_2 transportation and storage cost to zero. In the 350 ppm scenario, where BECS is being used to a larger extent, the lowering of the BECS costs reduces overall costs by 0.5 trillion

USD. For the 450 ppm case, the difference in net present value costs (to meet the target) are marginal (0.l trillion USD), but it should be noted that the use of BECS becomes significantly larger. Basically lowering the BECS costs means that carbon capture from coal and biomass become nearly equally costly (the model prefers BECS to coal, but this switch is very sensitive to changes in the parameter values). Thus, one of our key conclusions remains: BECS is more important for the 350 ppm scenario than for the 450 ppm scenario.

5.4.6. *Unlimited Storage Capacity*
In our 350 ppm runs with carbon capture, we get large amounts of solar hydrogen, despite the fact that solar hydrogen is a more expensive technology than carbon capture from fossil fuels and or biomass. The reason is that we have set an upper limit (600 GtC) on the carbon storage capacity and the rate by which carbon storage may increase over time. If we remove these constraints, solar hydrogen does not enter.[13] The net present value of meeting the 350 ppm target becomes 4.2 trillion USD in this case (compared to our base case result 6.1 trillion USD).

6. Policy Instruments

If low-carbon emissions are to be achieved, a combination of a price policy (a carbon tax or a cap and trade system) and policies to enhance the development of emerging advanced carbon-free or energy efficient technologies will be needed (increased R&D spending, the creation of niche markets through feed in tariffs or subsidies to specific technologies, etc.). There would also be a need for energy efficiency standards, in particular in sectors or for products where markets for energy efficiency cannot be expected to function well. It is beyond the scope to describe in detail these kinds of policy instruments (see Sterner, 2002; Sandén and Azar, 2005). Instead certain observations regarding biomass energy with carbon capture and storage are offered.

A carbon tax, or a cap-and-trade system, will raise the cost of carbon emissions and therefore offer incentives to reduce the emissions of CO_2 and to increase the use of carbon-free energy sources (renewables and nuclear) and of carbon capture from fossil fuels and energy efficient technologies. Such a carbon tax would of course also have to be levied on emissions associated with biomass energy production, and this would make sure that badly performing biomass production system would not be competitive. However, a carbon tax would not provide any incentive to start using BECS.

If such incentives were desired, certain modifications of the price instruments would be needed. If the carbon tax approach were taken, then cost-efficiency considerations suggest that owners of plants that capture CO_2 from biomass be paid a sum per ton of carbon stored that is equal to the carbon tax. This could be seen as a payment for the environmental service that the "negative emitter" provides. As long as total emissions are positive, governments would generate net revenues from the carbon policy. However, if global negative emissions are to be achieved (as in the 350 ppm case, see Figure 8), then governments of the world would have to raise the carbon tax on emissions and the carbon payment to those who remove carbon from the atmosphere to a level where more carbon is captured from the atmosphere and stored than is emitted. Government payments to "CO_2 removers" would then exceed the carbon tax revenues.

If a cap-and-trade system were chosen, it is reasonable to suggest that owners of plants that remove CO_2 from the atmosphere be offered permits (i.e., BECS would generate emission permits in proportion to how much carbon they capture). If global negative emissions are to be achieved, then governments of the world would have to buy (and retire) more emission permits than they hand out or sell. If the price for the permits paid by the governments were sufficiently high, owners of BECS plants would have an incentive to remove CO_2 from the atmosphere and that would, as stated earlier, generate the emissions permits that would be bought from the government. Trade in permits would be possible even if total emissions were negative, e.g., it may be that the cost-effective solution is that the transportation sector continues to use liquid hydrocarbons from coal, and compensate these emissions by buying permits generated in pulp mills with negative CO_2 emissions.

Finally, distribution of carbon reduction targets among countries could be dealt with in a similar way as distribution of positive emission targets might be dealt with, but in this case the target would be negative. For instance, assuming a global target of minus 2 GtC/year, and an equal per capita approach, then each country would have to remove 0.2 ton C/cap/year from the atmosphere (under the assumption of a global population of ten billion). A country without any significant potential for negative emissions could meet its obligations by buying permits created in a country with a large potential for BECS.

There would also need to be special policies to deal with the selection of storage sites and the possibility that there will be leaks from them (Baer, 2003, Herzog et al., 2003). It is also clear that climate policies will lead to a higher demand for biomass. This might lead to competition with food production and intrusion of biomass plantations into environmentally sensitive areas.[14] For that reason, protective policies might be needed (see Azar, 2004).

7. Conclusions

There is growing interest in carbon capture and storage from fossil fuels. Carbon capture and storage is also possible from biomass, and this has the potential to turn biomass into a continuous carbon sink while at the same time offering carbon free energy carriers (in particular heat, electricity and hydrogen).

In this paper, we have analysed the role carbon capture and storage technologies may play in meeting various atmospheric CO_2 stabilization targets through the use of a global energy–economy model (GET 5.0, developed by Azar et al., 2003). We estimate the cost of carbon capture from fossils fuels and from biomass, taking into account the smaller-scale characteristics of biomass energy systems.

We have then analysed the cost of meeting two stabilization targets: 350 and 450 ppm. It was shown that:

- The introduction of carbon capture and storage from fossil fuels could significantly reduce the total net present value cost of meeting either target (compared to a case when no capture is allowed). The added cost of meeting the stabilization target (compared to a scenario with no stabilization target) drops from 26 to 13 trillion USD in the 350 ppm case, and from 4.3 to 2.6 trillion USD in the 450 ppm case.
- When we open up for the possibility to use BECS, there is an even more significant percentage-wise drop in the added costs in the 350 ppm case, from 13 trillion USD (when carbon capture is allowed, but not from biomass) to 6.1 trillion USD (with BECS allowed).
- This significant reduction in costs suggests that it is possible to meet more stringent CO_2 concentration targets than what many people today consider possible (e.g., the 350 ppm target has generally been ruled out as infeasible).
- The introduction of the possibility of BECS only marginally affects the cost of meeting the 450 ppm target (compared to the case when only fossil carbon capture and storage is allowed).
- A detailed sensitivity analysis suggests that our key result – i.e., that BECS becomes important only for very ambitious CO_2 concentration targets – is robust to large changes in the parameter values.

Finally, a word of caution. BECS cannot be relied upon as a panacea for dealing with climate change. Further, although BECS makes it possible to remove CO_2 from the atmosphere, we should not be led to believe that we can control atmospheric CO_2 concentrations and climate on decadal timescales, since it will take at least half a century before carbon removals could have a substantial impact on the atmospheric CO_2 concentration and there is additional inertia in the climate system. Instead, BECS should be seen as an additional option that could help to reduce atmospheric CO_2 concentrations by the year 2100 to levels lower than what could be achieved otherwise (or to help reach a specific stabilization target at a lower cost). Most importantly, the implementation of carbon capture from fossil fuels and biomass depends on the availability and acceptability of storing CO_2 safely, a factor that needs to be addressed even more thoroughly over the coming decades. We also need to be careful so that efforts to promote carbon capture and storage does not lead to a significantly reduced interest in other renewables like wind and solar. Likewise, improved energy efficiency can already now start to play a significant role in the reduction of emissions. Thus, BECS should not be interpreted as an argument in favour of doing nothing in the near term.

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Notes

[1]See Alcamo and Kreileman (1996); Azar and Rodhe (1997); Azar and Schneider (2001); O'Neill and Oppenheimer (2002), for discussions about stabilization targets.

[2]We extrapolated the demands linearly from 2100 to 2130 and thereafter kept the demands fixed throughout the optimisation period. The reason why the model is run until 2300 is that we wanted to avoid boundary value problems, and also that we (in another project) investigated what the steady state solutions might look like.

[3]The natural gas and coal prices are rounded from WEA (2000) estimates of late-1990s fuel prices in the US. The oil price corresponds to 21 USD/barrel. Biomass prices are typically below 2 USD/GJ in developing countries, but higher in developed countries (WEA 2000, p. 227).

[4]Some might argue that carbon capture from biomass plants is not plausible because such plants are often small. However, studies of carbon capture from pulp mills suggest the feasibility of this technology (Möllersten and Yan, 2001; Ekström et al., 1997). In typical pulp mills, carbon emissions are around 40 kg CO_2/s. A 400 MW_{th} biomass plant has the same carbon emissions. We assume that the additional transportation cost is 0.5 USD/GJ for a large biomass plant over a small biomass plant. This corresponds to the transport cost of salix for an additional 50 km by truck (Börjesson and Gustavsson, 1996). It may be noted that the yield of biomass within a radius of 50 km, with a planting density of 10% and a harvest of 200 GJ/ha/year, would be 500 MW_{th}.

[5]We have abstained from depicting the price development over time. There are reasons to be careful when interpreting the so-called marginals of the energy balance equations in linear programming models with perfect foresight, expansion rate constraints and a stringent target that has to be met at a certain point in time, as prices. The reason for that is that an expansion constraint rate on, say, solar makes it necessary to introduce solar earlier than otherwise if a given carbon target should be met in, say the year 2100. The model then gives a high enough "price" on carbon (i.e., the carbon tax, or the permit price) in the year 2100 so that it becomes economically justifiable to introduce solar and other technologies in earlier periods in time. A very high "price" towards the end implies that a lower price is required in initial periods. In reality, however, no private company would act with such long time horizons, and therefore the internally generated prices during the initial periods in time are probably too low to generate the scenario in the real world.

[6]CO_2 injection is assumed to take place in CO_2-retaining deep saline aquifers and the depth of the injection wells was set to 1000 m. Capital costs were annualised using an interest rate of 10% and a plant life of 25 years. A capacity utilization of 90% was applied.

[7]In the graphs, we have not included the carbon emissions associated with biomass production and transportation. However, as stated above, the energy use in these activities may account to some 5% of the energy content in the biomass. If all that input energy would come from coal, then the carbon emission factor associated with biomass energy would still be lower than the emission factor for coal with carbon capture and storage (under the assumption that 90% of the carbon is captured).

The resulting increase in the cost for heat, electricity and hydrogen from biomass would be lower than the increase in the cost for these carriers if coal with carbon capture and storage is used. Thus, a more complicated modeling of the biomass energy system where the input energy would be considered, would not change the overall results of this paper (here we once again assume that badly performing biomass energy systems such as ethanol derived from corn are not used).

[8]In the absence of US participation, there is a theoretical risk that the cost will drop to very low levels or even zero because of the "hot air" in the former Soviet Union (FSU), at least under the assumption that the Kyoto–Marrakech system will operate like an entirely free market (see Nordhaus, 2001). This is however, rather unlikely, for several reasons. FSU may act as a "monopolist" and thereby increase the permit price (see Persson and Azar, 2003), and EU/Canada/Japan are unlikely to pay Russia for doing nothing.

[9]Storage in the oceans is politically sensitive, and one research project where only 20 tons of liquefied CO_2 were to be injected at the bottom of the ocean floor just outside Hawaii recently had to be cancelled before it was started because of local opposition (GECR, 2002). The project was then invited to Norway, but opposition from Greenpeace and the World Wide Fund for Nature led the government to withdraw an approval granted by the Norwegian Pollution Control Authority (Giles, 2002).

[10]As mentioned earlier, we have set the maximum expansion rate of carbon capture and storage at 100 MtC/year/year. Thus at the end of the century, at most 10 GtC/year may be captured. For solar hydrogen, the maximum expansion rate is 0.3 TW/year/year. For biomass the expansion rate is set at 0.1 TW/year/year and for all other conversion technologies 0.2 TW/year/year.

[11]If expansion constraints are too severe, more expensive technologies will enter to relieve the constraint (e.g., if the demand for energy grows very fast in a model with one low cost and one high cost technology, the high cost technology may enter even if it would be cheaper to expand the low cost option).

[12]This number is obtained by assuming that the GDP level is given by the expected GDP level minus the annual cost associated with the additional energy systems cost.

[13]There is, however, one exception to that, and that is when we run a case without BECS being allowed. Then CO_2 emissions released from plants with carbon capture and storage (assumed to be 10%) become so large that the emission constraint is exceeded. For that reason solar hydrogen enters. Thus, in this scenario, solar hydrogen enters by the middle of the century and reaches close to 400 EJ/year by the end of the century. (Note that this is a very model-specific result in the sense that a high carbon tax in the real world would mean that there would be strong incentives to increase the capture rate to levels higher than 90%. These dynamics are not modeled.).

[14]Some have expressed concern that BECS will further exacerbate this potential problem, but it should be noted that BECS also implies that emission reductions are delayed and that less solar-derived energy will be needed if the objective is to meet an atmospheric CO_2 concentration target by the year 2100. For that reason the willingness to pay for biomass in our model is actually lower in the no capture case than in the fossil capture and the BECS case.

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