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Interim Report **IR-02-042**

Biomass Energy, Carbon Removal and Permanent Sequestration — A 'Real Option' for Managing Climate Risk

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20 June 2002

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Abstract

The United Nations Framework Convention on Climate Change (UNFCCC) calls for stabilization of greenhouse gases (GHGs) at a safe level, and it also prescribes precautionary measures to anticipate, prevent, or minimize the causes of climate change and mitigate their adverse effects. In order to achieve this goal, such measures should be cost-effective and scientific uncertainty on threats of serious or irreversible damage should not be used as a reason for postponing them. In this sense, the UNFCCC can be understood as a responsive climate management scheme that calls for precautionary and anticipatory risk management, where in a continuous sense-response mode, expected climate-related losses are in an uncertainty augmented analysis balanced against adaptation and mitigation costs.

In this paper we investigate a component of a wider technological portfolio of climate risk management. In particular, we will investigate the properties of biomass-based sequestration technologies with respect to their potential role in climate risk management. We use the theory of modern asset pricing, commonly known as real option valuation, in order to assess this technology on global and long-term scales. Biomass energy can be used to produce both carbon neutral energy carriers, e.g., electricity and hydrogen, and at the same time offer a permanent CO_2 sink by capturing carbon from the biomass at the conversion facility and permanently storing it in geological formations. To illustrate the long-term potential of energy-related biomass use in combination with carbon capture and sequestration, we performed an *ex post* analysis based on a representative subset of the Intergovernmental Panel on Climate Change (IPCC) reference scenarios developed with the MESSAGE-MACRO modeling framework. The cumulative carbon emissions reduction in the 21st century may exceed 450 gigatons of carbon, which represents more than 35% of the total emissions of the reference scenarios, and could lead, in cases of low shares of fossil fuel consumption, to net removal of carbon from the atmosphere (negative emissions) before the end of this century. The long-run technological potential of such a permanent sink technology is large enough to neutralize historical fossil fuel emissions and cover a significant part of global energy and raw material demand. The economic potential might turn out to be smaller, if the signposts of climate change do not require that negative emissions, as a real option, need to be exercised.

The main policy conclusion is that investments in both expanding the absorptive capacity for carbon (expanding carbon stocks) and research and development (R&D) investments for developing negative emission technologies as a viable technology cluster should not only be (socially) priced against all other mitigation technologies by simple Net Present Value calculation (working only with the average expected loss), but according to a real option valuation given the full uncertainty spectrum of expected (economic) losses due to human induced climate change. The questions of how much and when sinks have to be committed as real options for robust climate management depend on the properties of the climate signal and the nations' degree of risk aversion — both are yet to be fully quantified.

Acknowledgments

Our appreciation is extended to everyone who contributed to this paper as well as to previous drafts.

We are grateful to the National Institute for Environmental Studies (NIES), Japan for their partial financial support of this work.

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1 Introduction

Climate change is often considered as one of the most serious environmental problems facing mankind today. This concern triggered the international negotiations that led to the United Nations Framework Convention on Climate Change (UNFCCC, 1992). The convention calls for a "*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*".

However, it should be kept in mind that the UNFCCC does not attempt to define the concept of dangerous interference with the climate system. Precise calculations of what is "dangerous" is not possible, since (a) the degree of climate change associated with any level of greenhouse gases (GHGs) in the atmosphere is subject to a variety of uncertainties; and because (b) the level of risk that is "acceptable" or "dangerous" is based on value judgment (Azar and Rodhe, 1997; Schneider and Thompson, 2000). Science can provide estimates about expected climatic changes and associated ecological and societal impacts but, ultimately, the question of what constitutes dangerous anthropogenic interference must be settled in the political arena using the best scientific assessments available about the likelihood of various potential outcomes.

Azar and Schneider (2001) emphasize that climate policy approaches that aim at a single stabilization target and try to cost-optimize emission trajectories towards that target, is a highly incomplete analysis owing to the large uncertainties that are present at almost every aspect of the climate problem. In fact, because of these uncertainties, analysis must be offered across a wide range of potential outcomes and value statements simply to span the "possibility space" — something like a single optimal calculation cannot possibly accomplish given the current uncertainties. In our view, it is wise to keep many doors open — analytically and from the policy perspective. This includes keeping the possibility of meeting low stabilization targets open (Azar and Schneider, 2001). As more is learned of the costs and benefits in various states of the world and as political preferences become better developed and expressed, interim targets and policies can always be revised (e.g., Lempert and Schlesinger, 2000).

There is a widespread impression that such revisions of climate policies can only be made upwards, but here we present a technological option that:

- will make it possible to meet more stringent CO_2 concentrations than many people today think is possible, and
- allow for some "climate risk management" that would make it possible to reduce atmospheric concentrations of GHGs in response to expected negative impacts, if this turns out to be necessary.

While the first point is interesting with respect to questions of intergenerational equity, the second refers to a more complex option model for climate risk management. Negative emission technologies derive a big part of their value from their inherent optionality. In other words, with technologies of 'last resort' at hand it is necessary to have a detailed real option model, which makes sure that maximum welfare is extracted from this technology. This refers to a technology that is on the 'margin', i.e., with high marginal costs and lots of flexibility. In contrast, the primary mitigation technologies have to be constantly 'on-line' in order to smoothly reach a preset emission target.

Biomass energy can be carbon 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 (see, e.g., Schlamadinger *et al*., 2001) for more detailed descriptions of different biomass energy systems).

However, the carbon releases from biomass conversion can also be sequestered and stored in geological deposits, in much the same way as carbon sequestration and storage is being discussed for fossil fuels (see, e.g., Parson and Keith, 1998). In this case, the biomass energy system will become a negative carbon emissions system as long as there are enough carbon storage possibilities. We refer to this as Biomass Energy Carbon Sequestration (BECS).

Thus, if widely applied this technology will make it possible to both displace fossil fuels (and thereby reduce CO_2 emissions) and remove CO_2 from the atmosphere on a continuous basis. This does not mean that we can emit a lot now, and then reverse the concentrations rapidly if this turns out to be necessary, because the removal rate is not fast enough to be of any significance for time scales of less than 50 years. Furthermore, the sink capacity is limited by physical, social, economic, and environmental constraints. As an illustration, a maximum removal rate of 5 Gton C/yr would mean that it could take as long as 70 years before historical emissions, some 350 Gton C from 1850 to 2000, are reversed — assuming that no other emissions take place over this period.

In this paper, we first discuss the potential for biomass, storage, and the potential impact on global CO_2 fluxes. Furthermore, we will also explore, in more abstract terms, how robust and comprehensive climate risk management could be used to effectively deal with the scientific, economic, and political uncertainties of the climate change problem and identify BECS's role under such a risk management regime.

2 BECS and Real Option Theory

Modern asset pricing, commonly known as real options valuation, has been used as an alternative to discounted cash flow methods (DCM) in many industrial applications, in particular in the energy sector, to improve the representation of project structure within project valuation models. In contrast to widespread industrial practice all IPCC emission scenario models still use DCM in appraising technology trajectories over the 21st century. It is believed that such analysis is not fully adequate in an environment of highly uncertain patterns of climate change and other socioeconomic and technological uncertainties. The conclusions from analysis using modern asset pricing might be radically different from that of DCM, as we have witnessed in many practical industrial cases (see, e.g., www.realoptions.org).

The real option calculation is based on models developed for financial options. Myers (1973) observed that the theory on financial options could be used to value investment opportunities in real markets — the markets for products and services. The value of keeping one's options open is clearest in investment-intensive industries where decisions are done on incremental steps. Of course, also for the validation of technological options on climate change, the real option calculation can be very valuable. With respect to the uncertainty of climate change signals we need to decide whether to invest now into various mitigation technologies, to take preliminary steps reserving the right to invest in the future, or to do nothing. Because each of these choices creates a set of payoffs linked to further choices down the line, all climate management decisions can be thought of in terms of options. The option valuation recognizes the value of learning. This is important because strategic decisions are rarely one-time events, particularly in the case of climate change where the greenhouse effect interacts with other processes affecting the climate like El Niño. Discounted cash-flow analysis, which relies on all-or-nothing, "go/no go" decisions for the cost competitive amount of a particular technology in emission scenarios and does not properly recognize the value of strategic learning[1] before a full commitment is made, is for that reason often inadequate. In fact, DCM's inadequacy can be stated in the precise terms of the real options model. Of the many variables in a real option model, DCM analysis recognizes only two: the present value of expected cash flows and the present value of fixed costs. Option valuation offers greater comprehensiveness, capturing discounted value plus the value of flexibility — that is, the expected value of the change in discounted value over the option's life.

Some kinds of flexibility are common to financial and real options. In each case, an option holder can decide whether to make the investment and realize the payoff, and if so, when to invest — this is important since the payoff will be optimal at a particular

[1] The concept of learning in the context of real options is to be distinguished from the learning curves entering the emission scenario models.

moment. These are essentially reactive kinds of flexibility: an option holder responds to environmental conditions to maximize the payoff.

When we talk about the reactive flexibility of a real option, however, we are ultimately talking only about its advantages as a valuation tool. The further, and typically larger, payoff comes from the proactive flexibility to increase the value of an option, once acquired. This opportunity arises from the fact that, while a financial option is acquired and exercised in a deep and transparent market, real business situations usually feature a limited number of players — each able to influence a few specific levers that control the value of real options — interacting with one another. This is also true for the behavior between large-scale energy systems on the one side and energy systems and adaptation measures with respect to climate change on the other. Thus, national decision makers can use their skills to improve an option's value before they actually exercise the option, making it worth more than the price paid to acquire or create it. In the case of BECS, the creation of a real option involves, *ante factum*, targeted research and development (R&D) efforts and in some cases reservation of land for biomass production. Note, however, biomass can be used for several purposes one of which is as an energy carrier. The same biomass can, however, also be employed as a 'real option' on a multiplicity of markets leveraging increased flexibility. In this way, the cost of the real option BECS might actually turn out to be rather minimal if a real option calculus is employed when benchmarking technologies.

Detailed empirical calculations appraising the real option value of BECS have not yet been carried out. In this report we will give some preliminary information on the main features of BECS with respect to a more thorough real option calculus and give qualitative and some preliminary quantitative valuations. Furthermore, we argue that BECS, due to the fact that it is currently the only sound technology that could be used to remove carbon from the atmosphere on large scales, shall be a vital part of a robust technological portfolio hedging climate risks. It should be noted that a real option approach valuing different technological options as real options is consistent with portfolio approaches. Future research will concentrate on the quantification of these items.

2.1 Thinking in Terms of Real Options

There are a number of compelling reasons for technology strategists and modelers of technological change to grasp the main insights behind real options. While option-pricing models are indeed a superior valuation tool — the usual use of the theory — real options can also provide a systematic framework serving as a strategic tool. In this report we seek to provide such a framework and try to convey that thinking in terms of real options could have real implications on the way we value mitigation technologies. A more thorough treatment on computing exercise strategies of mitigation options is given in Obersteiner *et al*. (2002)

The basic principle of real options can, in the most simple way, be illustrated by the formulation of a financial option. The price of a financial option is typically estimated by the application of the Black-Scholes formula. The original formula calculates the theoretical option value — the present value of the expected option payoff — under the assumption of no dividend payments, taxes, or transaction costs. The value of a financial option is calculated as follows:

$$Se^{-\delta t}\{N(d_1)\} - Xe^{-rt}\{N(d_2)\}$$

where

$$d_1 = \frac{\left\{\ln((S/X) + \left(r - \delta + \frac{\sigma^2}{2}\right)t\right\}}{\sigma\sqrt{t}},$$

$$d_2 = d_1 - \sigma\sqrt{t}$$

and where *S* is stock price, *X* is exercise price, δ is dividends, *r* is risk-free interest rate, σ is uncertainty, *t* is time to expiry, and *N(d)* is cumulative normal distribution function. *N(d1)* equals the proportion of shares required to replicate the call option and *N(d2)* equals the probability that the call option will be exercised on expiry.

The real-market equivalents of these factors are as follows:

- **Stock price (*S*)**: the present value of cash flows expected from the investment opportunity in a real technology on which the option is purchased.
- **Exercise price (*X*)**: the present value of all the fixed costs expected over the lifetime of the investment opportunity.
- **Uncertainty (σ)**: the unpredictability of future cash flows related to the asset; more precisely, the standard deviation of the growth rate of the value of future cash inflows associated with it.
- **Time to expiry (*t*):** the period for which the investment opportunity is valid. This will depend on technology (a product's life cycle), competitive advantage (intensity of competition), and contracts (patents, leases, licenses).
- **Dividends (δ):** the value that drains away over the duration of the option. This could be the cost incurred to preserve the option (by staving off competition or keeping the opportunity alive), or the cash flows lost to competitors that invest in an opportunity, depriving later entrants of cash flows.
- **Risk-free interest rate (*r*)**: the yield of a riskless security with the same maturity as the duration of the option. Increases in stock price, uncertainty, time to expiry, and risk-free interest rate raise the option value. Increases in exercise price and dividends reduce it.

From this formulation it is not difficult to see how one should price alternative mitigation technologies in an uncertain environment. In more elaborate formulations uncertainties can be connected to all of these six main factors and their underlying processes. So, for example, the uncertainty of future cash flows related to the asset or technology can be a function of institutional uncertainties whether or not the global community will be able to implement sustainable climate policies in a timely manner. For other factors, e.g., the risk-free interest rate, Newell and Pizer (2000, 2001) showed, outside the real option theory, how uncertain rates increased valuations of the benefits of climate change mitigation. It can be expected that a number of papers are due to appear featuring other factors of the option valuation. Each factor in itself offers a number of interesting insights with potentially large political weight (e.g., defining the time of expiry for GHG targets).

2.2 The Role of BECS in the Terrestrial Carbon Cycle

While historical additions of carbon during industrialization have been identified to be the major causes of concern, few technologies have yet been identified that would be capable of permanently withdrawing carbon from the atmosphere within a sufficient time frame. There has been extensive scientific research to determine the potentials of enhancing the sink capacity of terrestrial and marine ecosystems beyond the natural level.[2] However, the conclusions from various groups of scientists are that enhancing the biological pump cannot be considered as a safe and robust strategy to rectify historical carbon emissions. While an enhancement of the sink capacity of marine ecosystems is associated with limited controllability, terrestrial ecosystems are identified to act as carbon sinks of rather limited capacity (saturation) and uncertain permanence (see, e.g., Schlamadinger and Marland, 2000). The potential role of bioenergy is illustrated in *Figure 1*.

The permanence and saturation arguments hold only as long as terrestrial ecosystems are regarded as isolated systems. While global terrestrial gross primary production (GPP) has been estimated to be about 120 $GtCyr^{-1}$, net biome production (NBP) of large ecosystems are considered to be slightly positive (IPCC 2000b), and thus relatively small in comparison to fossil fuel emissions. About half of GPP is used for immediate respiration, resulting in a Net Primary Production (NPP) of about 120 $GtCyr^{-1}$, while the energy stored in the remaining organic matter is dissipated in decomposition processes, resulting in a Net Ecosystem Production (NEP) of 10 $GtCyr^{-1}$, and disturbances like wild fires (*Figure 1*). From a closed ecosystem point of view, it becomes clear that there is only limited capacity available to change NBP in a sustainable manner over long periods of time since natural terrestrial ecosystems seem to attain an equilibrium of balanced or slightly positive carbon fluxes. This is mainly due to the fact that organic matter is prone to decay under natural circumstances.

It is exactly the decomposition process and some of the disturbances that are the point of incidence of BECS, the combined bioenergy/CO_2 removal/sequestration technology[3]

[2] Currently, the total uptake of CO_2 from the atmosphere is estimated to be in the range of 3.8 $GtCyr^{-1}$ where ocean uptake makes up for 2.0 ± 0.8 $GtCyr^{-1}$ and terrestrial ecosystem uptake for 1.8 ± 1.6 $GtCyr^{-1}$. It should be noted that these are the current figures of ocean and terrestrial ecosystem uptake, which can be subject to gradual but also sudden change if accumulated climate change renders ecosystems to follow a chaotic behavior (Scheffer *et al*., 2001).

[3] Other technologies that can be used to slow or stop the decay process include increased consumption of wood or other organic matter for construction purposes, depositing tree trunks in river beds (co-benefit of more structure in river beds to avoid erosion and slowing run-off of water, which has positive implications for flood control and biodiversity), and restoring the natural flow of coarse woody matter to the ocean.

(see dotted orange box in *Figure 1*[4]). The energy stored in organic matter can be used as bioenergy for human purposes and the 'concentrated' residual carbon can be sequestered after scrubbing and subsequent long-term storage in geological formations or other permanent reservoirs. Biomass production of terrestrial ecosystems can be considered as a joint production process that captures carbon from the atmosphere for long-term storage and at the same time delivers substantial amounts of energy. Given the large potential of biomass for bioenergy BECS should be regarded as the instrumental technology to conduct responsive carbon management that is conditional on a volatile and highly uncertain climate change signal. Responsive climate management, however, will turn out to be a successful strategy only if it leads to the necessary structural shifts in the energy market to less fossil carbon emissive energy technologies. It must be noted that the smaller the share and absolute size of fossil emissions the higher the leverage of BECS with respect to managing climate risk.

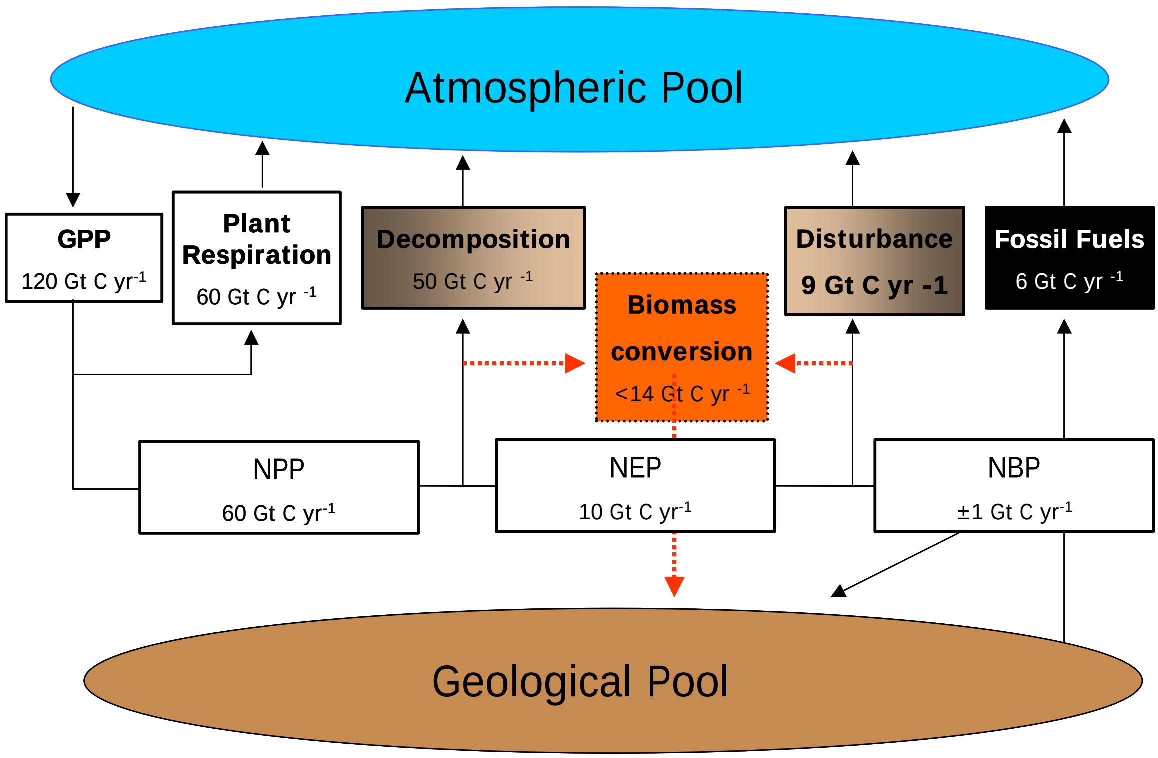

Figure 1: The potential role of bioenergy and other human use of biomass to change the net flux of carbon to the atmosphere. Sources: Adapted from Steffen *et al.* (1998), IPCC (2000b).

[4] Note that the BECS potential of <14 Gt C yr-1 must be regarded as a technical potential that ignores social, economic, and environmental constraints.

In the following paragraphs we will discuss some technological aspects of BECS, its limits and opportunities in large-scale applications. In order to be applied as a sustainable technology, BECS must:

- maintain sufficient the biological potential;
- be economically affordable;
- be efficient in using energy and materials;
- be environmentally sound; and
- be socially acceptable.

Below, we will briefly describe the CO_2 emission reduction options in terms of their sustainable and technical potential in this century. Subsequently, we will have a closer look at the possible role of BECS following the given criteria for sustainability. Throughout the following sections, it should be kept in mind that the productive resource potential of bioenergy, a significant part of BECS's life cycle, rests upon:

- the productivity of land in growing energy crops or plantations, and
- the total areas of land, of various qualities, that may over time be reallocated under pro-active land use change policies.

2.2.1 Biomass potentials

Correct assessments of the global biomass potential for bioenergy use are of great importance for climate risk management and the assessment of the real option value of BECS. According to theory the 'real option', BECS, should be exercised when climate change risk boundaries and its associated losses are or are expected to exceed the costs of BECS. However, real options can only be exercised if they are prepared in advance. The estimation of biomass potentials will provide insights on how BECS could potentially be exercised and give a quantification of the limits of this real option with respect to managing climate risks.

2.2.1.1 Quantifying the potential of bioenergy and pro-active land use change

Global bioenergy consumption and production potentials are difficult to quantify. The officially most frequently cited number is that currently biomass energy provides about 55 ExaJoules (EJ), which is 14% of the world's energy while being the number one in developing countries with a share of about 34% (e.g., UNDP, 1996; FAO, 1999; IEA, 2000).[5,6] However, this number must be treated with great caution and is most likely grossly underestimated.[7]

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[5] Primary supply of combustible renewables and waste amounts to 25.3 EJ, which is equivalent to 11.2% share of total primary energy supply (in toe) according to IEA (2000). Schlamadinger *et al*. (2001) quote some 30–50 EJ/year supplied in the form of firewood, dung and other agricultural residues.

[6] It is assumed that large amounts of bioenergy consumption in developing countries are not delivered on a sustainable basis.

[7] Morocco initiated a study to investigate its real fuel wood consumptions. In 1998, a volume of 485 thousand cubic meters (CUM) were sold officially, however, the volume that was really collected and

The potential is much larger than the actual use. This fact is well documented by Berndes *et al*. (2001), who provide a thorough overview of 17 major global studies trying to quantify the potential contribution of biomass in the future global energy supply. However, the potential of biomass production combined with modern bioenergy cannot be realized without the implementation of pro-active land use change policies. The low emissions scenarios for the 21st century to be discussed below embody plantation-based bioenergy utilization of the order of hundreds of EJ during this century. In turn, this implies the cropping of large amounts of land, where it is not clear how likely such scenarios are. A catching-up program requires the early implementation of rapid capacity building in developing countries to enable the tens of thousands of land use change projects that are needed to be initiated by experts from implementing countries (Haque *et al*., 1999). These experts need to be trained in the necessary skills to implement projects at the community level, motivating the communities that live on the land to enter the market economy, as well as identifying appropriate technologies, securing finance, and demonstrating carbon benefits, etc. Furthermore, a number of sustainability constraints will have to be respected.

In the following paragraphs we will give a short discussion of the potentials and finally try to put them into perspective with climate risk management.

All forms of biomass utilization can be considered part of a closed carbon cycle. The mass of biospheric carbon involved in the global carbon cycle provides a scale for the potential of biomass mitigation options; whereas fossil fuel combustion accounts for some 6 GtC release to the atmosphere annually, the net amount of carbon taken up from the atmosphere by terrestrial plants is around 60 GtC annually (NPP) (corresponding to a gross energy content of approximately 2100 EJ yr^{-1}, of which bioenergy is a part) (*Figure 1*), and an estimated 600 GtC is stored in the terrestrial living biomass. Fischer and Schrattenholzer (2001) assess the bioenergy potential by 2050 to be in the range of 350–450 EJ yr^{-1}. A review by Hall and Scrase (1998) reports a medium-term technical potential to be in the range of 95–280 EJ/year by 2050 (see *Table 1*). In scenario studies, Hall *et al*. (2000) show biomass energy contributing 150–200 EJ yr^{-1} by 2050. Wirsenius (2000) reports that, in the renewable-intensive global energy scenario (RIGES) by Johansson *et al*. (1993) estimated that biomass-based fuels might account for nearly 40% (150 EJ) of the global fuel supply in 2050 (counting commercial fuels only). Read (1997) has plantation bioenergy supply of 500 EJ by 2070, a time horizon selected to represent a double turnover of energy sector capital stock. For biomass-based electricity, the contribution was assumed to be lower, about 18% (21 EJ) of the global electricity supply in 2050. In the biomass-intensive variant of the low CO_2-emitting energy supply system (LESS), compiled by Williams (1995), biomass was assumed to account for nearly a third (181 EJ) of global primary energy supply in 2050, and almost half (331) of the primary energy in 2100. The IEA Bioenergy Task 38 (IEA, 2001) cites IPCC (2000a) that the maximum energy that may be technically feasible to supply globally from bioenergy sources to be in excess of 1300 EJ yr^{-1}. *Table 1* provides an overview of selected bioenergy supply studies based on scenario studies and calculations of technical potentials.

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consumed was 9,566 thousand CUM (Ellatifi, 2001). The FAO database (www.fao.org) reports 770 thousand CUM, which in turn is used to calculate global consumption.

Table 1: Selected global bioenergy supply scenarios and/or potentials, EJ yr^{-1}. Sources: Hall and Scrase (1998), Fischer and Schrattenholzer (2001), IPCC (2000a,b; 2001).

Year	**2025**	**2050**	**2100**	**Potential**
Fischer and Schrattenholzer (2001)		=>		350–450 (ref 2050)
Kusumikawa and Mori(1998)			140–235	
Yamamoto *et al*. (1998)		292-317		
Leemans *et al*. 1996		181	331	
Shell (1996)	85	200–220	–	
IPCC (1996)	72	280	320	
IPCC (2000a)				1300
Hall and Rosillio-Calle (1998) (Ref. IPCC, 2000)				2900
Read (1997)		500[a]		
IPCC (2001)		441[b]		
Greenpeace (1993)	114	181	–	
Johansson *et al*. (1993)	145	206	–	
WEC (1993)	59	94–157	132–215	
Dessus *et al*. (1992)	135	–	–	
Lashof and Tirpak (1991)	130	215	–	338–675

[a] Projected for the year 2070.
[b] Projection of 'technical' energy potential from biomass.

The immediate bioenergy potential is also not negligible. The position paper by the IEA Taskforce 25 (IEA, 1998) mentions that even without additional land use for biomass there is a variety of possibilities for improved use of existing biomass resources for energy. Examples include the use of residues from forestry and agriculture, residues from the food and wood processing industry, and the biomass fraction of municipal solid waste (paper, landfill gas, disposed wood products), thus a large fraction of the globally available biomass residues (representing a potential for about 40% of present energy use of 406 EJ yr^{-1}) could be available for bioenergy. Another example is industrial waste from the pulp and paper industry. Based on a back-of-an-envelope calculation, the introduction of a BECS technology in all pulp and paper mills of the world, if they were fully run by sustainable produced bioenergy could reduce on a net basis global carbon emissions by about 9%. IEA (1998) also mentions, that the resource size of recoverable crop, forest and dung residues has been estimated to offer a yet untapped supply potential in the range of 40 EJ yr^{-1}, which could meet about 10% of the present global primary energy demand. Moreover, they mention that the difference between the annual growth increment and actual harvest from the world's forests is believed to be substantial. Kraxner *et al*. (2001) show that the harvestable yield in a typical temperate forest ecosystem could be increased by up to 30–60% through improved thinning methods and overlapping rotation methods, while at the same time complying with all criteria for sustainable forest management, leaving the genetic pool unchanged and creating a better adapted stock for climate impacts. Tree improvement methods with autochthonous genetic material could add another 30%. Likewise, hazard reduction methods of natural disturbances like fire were never considered in terms of their biomass production potential for bioenergy purposes. The potential of marine ecosystems and many other potential biomass production systems to produce biomass for energy have also not been included in any of the projections.

Another important source of biomass for bioenergy are dedicated energy crops like tree plantations. The FAO (1999) indicate that energy forestry/crops (only temperate and tropical areas) essentially through land-use change have the potential to reduce emissions of between 0.5–1.6 GtC yr^{-1}, equivalent to between 8–27% of current global consumption. The IPCC (2000b) report on Land Use, Land-Use Change, and Forestry (LULUCF) identifies a much higher potential from energy crops in the range of 4.4 GtC yr^{-1}. Schlamadinger *et al*. (2001) estimate the bioenergy potential from energy plantations to be in the range of 68 to 256 EJ. Berndes *et al*. (2001) report that the biomass supply from plantations in 2050 range from 47 to 238 EJ yr^{-1} in the studies reviewed.

Box 1: Biofuel Produced from Planted Land.
Source: IPCC (2000b:Fact sheet 4.21)

The biofuel scenarios captured here project a rise in use from around 60 EJ (~10 EJ from waste) in 2020 to 300 EJ (~50 EJ from waste) in 2100, with land-use implications that depend on plantation productivity. Biofuel usage would rise from 10 oven dry tons of wood (~5 tC) (~200 GJ) ha^{-1} yr^{-1} to 25 oven dry tons of wood (~12.5 tC) (~500 GJ) ha^{-1} yr^{-1} over a century, leading to land usage that would rise from 250 Mha in 2020 to 500 Mha in 2100. If these changes are realized, the potential fossil fuel offset in ~2040 would be as tabulated below:

	Area[b]	**Percent used**[c]	**Average C-capture**	**Range**[d]	**Annual Capture**[e]
Biofuel production[a]	6.2 Gha	10%	7 tC $ha^{-1}yr^{-1}$	<2.5-20 tC $ha^{-1}yr^{-1}$	4.4 $GtCyr^{-1}$

[a] Community-scaled production for small-scale gas turbine electricity generation and conversion to transport fuels (e.g., liquid-phase Fischer Tropsch processing) (5%) combined with agroforestry meeting local needs.
[b] Cropland, grazing land, degraded land plus forest area vulnerable to predicted climate change. Of this area, 5% is in concentrated (a few km in size) biofuel plantations; an additional 10% is in 50% cover agroforestry, located in settlements in the locality of the plantations. In countries with developed energy supply systems and urbanized populations, less agroforestry is envisioned, with biomass initially accumulated in a long-rotation "buffer stock" awaiting renewal of existing capital stock.
[c] Global average predicted after several decades of technological progress and management experience. A moderately conservative figure is used because species selection and management practices are assumed to be driven by multi-purpose sustainable development criteria.
[d] Low figure = current, for conventional forestry; high figure = current small-plot experience in good growing conditions.
[e] Subject to carbon content of displaced fossil fuel, which depends on fuel mix in power generation and on refinery balances in alternative fossil fuel supply system.

Based on this short review of bioenergy potentials we would like to mention that there are still diverging views on how large the real potentials are for biomass production for bioenergy use. The potentials crucially depend on assumptions on *inter alia* the biological growth potential, and land requirements such as land availability and land-use constraints. Despite the fact that the calculations of potentials for bioenergy will still require additional work, the current estimates allow for the conclusion that a combined bioenergy/CO_2 separation/disposal technology could make net removal of carbon from the atmosphere feasible, if shares of fossil fuel consumption in the global energy are comparatively small.

It must also be noted that there are two competing concepts of bioenergy potentials. First, the 'sustainable' bioenergy potential taking into account social, economic, and ecological constraints and realities; and second the technical potential that mostly, but not exclusively, concentrates on the biological growth potential given some land availability constraints for, e.g., food security. Most likely unintentionally, these two concepts of calculating the potential match the requirements for the mitigation strategies counteracting risk types one and two. The BECS technology shall be exercised as a real option depending on the nature of the underlying risk. While the 'sustainable' bioenergy potential becomes striking under a scenario of gradual climate change, the technical potential will have to be exploited to counteract and contain risks from a self-reinforcing climate change regime, despite increased social, economic, and ecological costs. In the latter case, the costs incurred will be of no regret when the climate change risk can be contained. However, neither the sustainable potential, still less the technical potential is realizable unless a timely program of pro-active land use change had been embarked on.

2.2.1.2 Stock and flow effects of new plantations

Bioenergy itself manifests a significant potential, in terms of preparedness to respond quickly to the discovery of an unexpected low threshold for a self-reinforcing climate change regime (Read, 2002). This is because biomass can be grown over a long rotation as standing timber that can be used for fuel if a low threshold (risk boundary) is revealed or can be used commercially as timber otherwise, with consequentially reduced utilization of biodiverse natural forest in meeting demands for timber (Read, 1996).

This is relevant particularly in developed countries with surplus farmland and a large stock of energy sector fixed assets where, in the event of low threshold revelation (and consequential relatively reduced biodiversity concerns) the 'buffer stock' of standing timber can be quickly substituted for coal at minimal cost (Read, 1996). Meanwhile, the radical replacement of capital equipment (including retrofitting of CO_2 scrubbers on remaining fossil fuel plants) can be accelerated and the cleared long rotation land used for intensive short-rotation biomass production. In developing countries, where the medium-term prospect is for sustainable growth based on exports of liquid biofuels that can reduce strategic dependence on Middle East oil, the stock effect of plantation establishment for biomass production as raw material for modern bioenergy is also important. This is because, in a regime of carbon crediting such as the Clean Development Mechanism (CDM) of the Kyoto Protocol, it can provide income support during a transition from unsustainable traditional patterns of land use (Read *et al.*, 2001).

The combination of stock and flow effects from plantation establishment and from fossil fuel displacement is illustrated in *Figure 2* and related Fact Sheets of the IPCC (2000b).

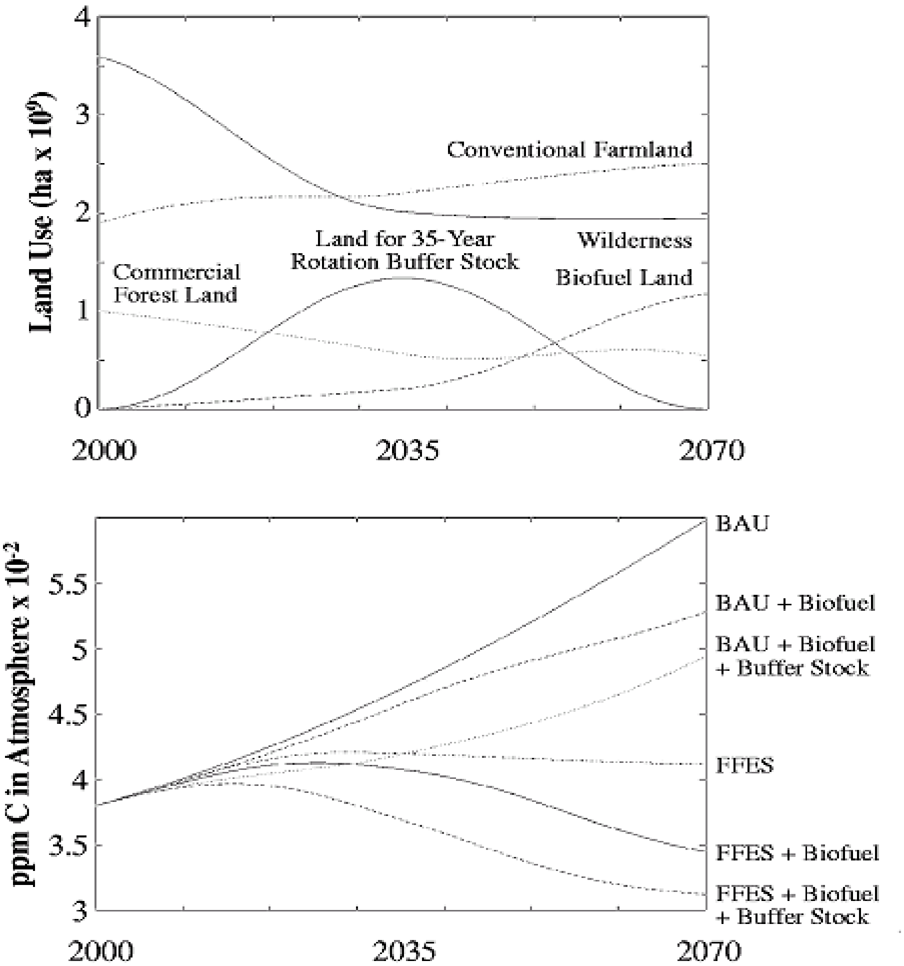

Figure 2: CO_2 mitigation with dynamic land-use policy (FLAMES model). Impact on GHG levels over 70 years comparing two reference scenarios [business-as-usual (BAU) and fossil-free energy scenario (FFES)] with two land-use scenarios (enhanced biofuel and enhanced biofuel plus "buffer stock"). Source: Read (1999).

This shows that, *without BECS*, the combined stock and flow effects of a mixed policy of large scale long rotations added to the growing use of short rotation based bioenergy can stabilize CO_2 levels for a few decades even with business-as-usual fossil fuel consumption. Combined with a vigorous energy efficiency and renewable energy program such as the Greenpeace-Tellus fossil free energy strategy, CO_2 levels can be reduced towards 350 ppm. It should be noted that the land allocations illustrated — chosen to illustrate the stock effect — are not optimized, and are likely excessive as regards the long rotation; a more likely program would involve more land allocated to short rotation and much less to long rotation.

2.2.2 Bioenergy utilization with CO_2 capture and sequestration (BECS)

Generally, the CO_2 removal by scrubbing and the CO_2 recovery from flue gas is referred to as "add-on" environmental strategies. After recovery of CO_2 from the energy system it must be disposed of, stored, or otherwise used. For example, for enhanced oil recovery, CO_2 is injected in oil fields (originally to improve the oil recovery rate).

2.2.2.1 Carbon capture

Much recent attention has been given to technologies that could prevent CO_2 from fossil-fuel combustion entering the atmosphere. The same basic CO_2 capture and sequestration (BECS) technologies can be applied in connection with the utilization of biofuels (*Figure 3*). A comparison between the two alternatives shows that bioenergy systems with BECS have a clear environmental advantage. Even with very efficient CO_2 removal in fossil fuel-based systems, parasitic energy consumption caused by additional process steps needed for BECS makes it impossible to achieve CO_2-neutral energy utilization with such systems. Möllersten and Yan (2001) have shown on the other hand, considering a whole process chain of fuel upgrading, CO_2 removal, compression, transportation, and injection at the final storage site, that BECS in biofuel-based energy systems enables energy utilization with a clear negative CO_2 balance. Hence, such energy systems would lead to net reductions of CO_2 emissions.

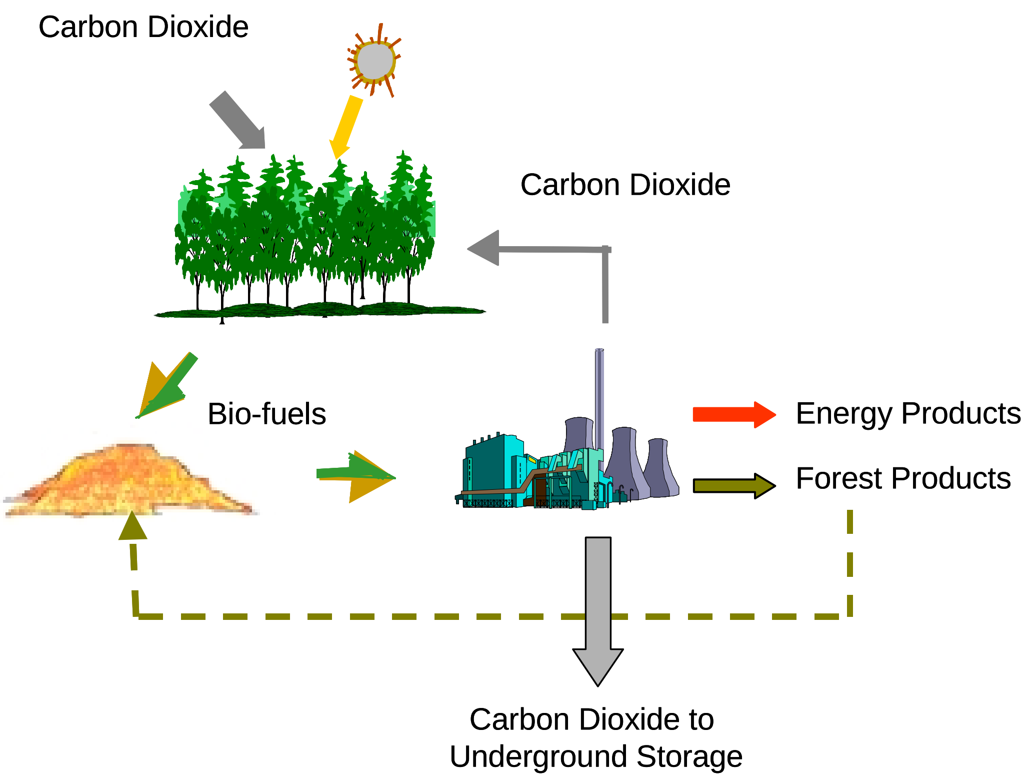

Figure 3: The carbon cycle of bioenergy with carbon capture and sequestration.

The capture of CO_2 from mobile or small stationary sources is probably not viable for technical and economic reasons. It is, therefore, biofuels used in industrial-sized energy production units that could be used for combining bioenergy with BECS. The biofuels can be divided, according to their origin, into industrial residues, raw materials extracted from forests or produced in the agricultural sector, and recycled biomass from wastes. Today, a large share of large-scale use of biofuels occurs in the industrial sector, mainly in the forest products industry. In some countries (e.g., Sweden and Finland) large district heating plants are fired with biofuels. Meanwhile, electric utility use of biofuels remains rather low. Yan *et al*. (1997) discuss the main challenges to development of technically and economically competitive systems for biomass power generation. Future biomass-based power generation technologies have to be designed to provide superior environmental protection at lower cost by combining sophisticated biomass preparation, combustion and conversion processes with exhaust gas cleanup. These systems include fluidized-bed combustion, biomass-integrated gasification systems, biomass externally fired gas turbines, and, in the long term, fuel cell hybrids. Biomass co-firing with coal may provide a cost-effective, near-term opportunity for biomass power generation.

Biofuel-based energy production units with CO_2 removal can be divided into three main process groups (*Figure 4*). Process group 1 covers processes where the fuel is gasified and CO_2 is removed from the fuel gas before it is combusted or converted to refined biofuels such as, for example, methanol or Fischer Tropsch liquids for substituting gasoline, avgas and diesel. In such systems, one can opt to increase the CO_2 production and improve fuel quality through introducing a water-gas shift reaction before CO_2 removal, whereby carbon monoxide is reacted with water to form CO_2, and the final product (apart from CO_2) is hydrogen. For power generation, further development of advanced systems and technologies that can use hydrogen-rich fuels is required. Process group 2 is based on the combustion of the fuel in oxygen instead of air, using recirculated CO_2 to moderate the combustion temperature. This process results in a very high CO_2 concentration in the flue gases, and any further processing of the flue gases is governed by CO_2 purity requirements rather than CO_2 removal. The technology has not been extensively demonstrated and should be regarded as long term. Process group 3, where the most technically mature solutions are found, covers end-of-pipe solutions in energy production units, where CO_2 is removed from the flue gases.

Absorption is the most commonly used technology used for removing CO_2 from gas streams, whereby chemical or physical solvents are used to scrub the gases and collect the CO_2. Chemical absorption is a proven end-of-pipe method for removing CO_2 from flue gases. When a gas is at high pressure, such as fuel gas in some integrated gasification combined cycles, physical absorption is more suitable and relatively little extra energy is then required. The energy demand of absorption is mainly due to heat consumption for regeneration of solvent (chemical absorption) or compression and pumping of solvent (physical absorption). Gas separation membranes is another promising technology for CO_2 removal from gas streams, which can lead to energy and cost savings. However, much further development is necessary before it could be used in large-scale applications. Although there are commercially available technologies for CO_2 removal, the efficiency and economic performance of bioenergy with CO_2 removal can be improved through improved process configurations and the development of new technologies.

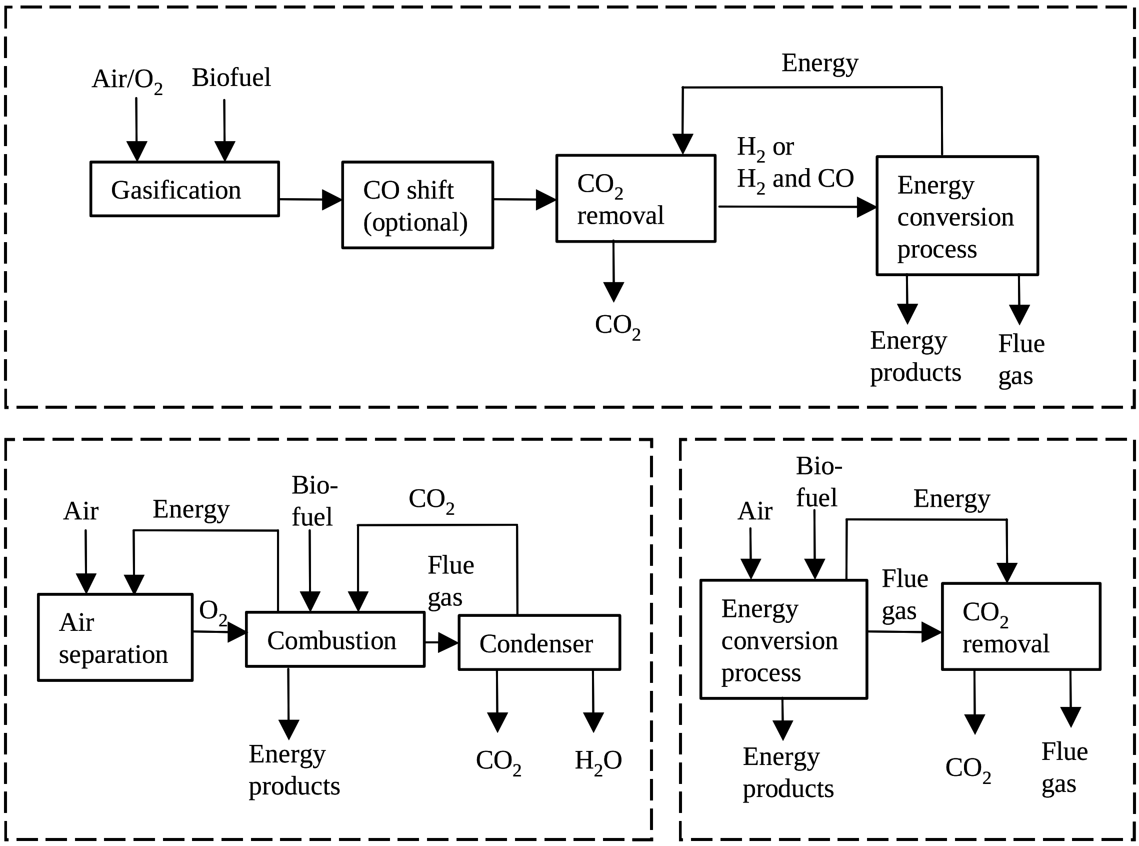

Figure 4: Process groups for bioenergy CO_2 removal before (top), during (bottom left) and after (bottom right) the energy conversion step.

The major challenge for CO_2-capture technology is to reduce the overall costs by lowering both energy penalties and capital requirements, in particular those for energy. As far as economic assessment of bioenergy with CO_2 removal is concerned, very little has been done so far. However, studies on fossil-based systems can give some guidance. A number of comparative studies of CO_2 avoidance costs ($/t$CO_2$) in fossil-based systems with carbon removal and sequestration show rather uniform results (IEA, 1994; Göttlicher and Pruschek, 1997; Herzog, 1999). For coal-based technologies, integrated gasifier combined cycles with CO shift and CO_2 removal from the fuel gas show lower costs than conventional coal-fired steam cycles with CO_2 removal from flue gases. Natural gas-fired combined cycles with CO_2 removal from flue gases show higher avoidance costs than both of these alternatives. If the coal in the coal-based alternatives were to be replaced with biofuels, the additional cost for CO_2 removal would most likely be similar. It can be concluded that, due to the low additional cost for CO_2 removal, in the short term, bioenergy with end-of-pipe scrubbing technology might turn out to be a cost-effective mitigation option. Co-firing of biomass with coal would probably be a quick path for large-scale phasing in BECS. Further technical development of biomass-integrated gasification systems is needed to take advantage of the lower additional cost for CO_2 removal in such systems. For several reasons, gasification of black liquor in chemical pulp mills is an interesting candidate. The combustion of black liquor in pulp mills gives rise to the large single-source emissions of CO_2 that are a prerequisite for cost-effective BECS. Furthermore, there are strong incentives for the development of black liquor gasification since it is driven by product-, process-, and energy-related causes. Other biomass-integrated gasification systems that are particularly interesting are systems for the production of gas or liquid fuels, e.g., biomass-based methanol and Fischer-Tropsch liquids, where suggested process designs include CO_2 removal from the gasified biomass for reasons related to process economy and efficiency.

2.2.2.2 *CO_2 sequestration technologies*

Traditionally, CO_2 from the consumption of carbon-based fuels has been disposed by dilution in air rather than returning the carbon to the earth's crust. There are technologies developed that sequester CO_2 in some form for long periods of time by disposal in a form that separates the fossil carbon from the atmosphere. Much further work is required to investigate the collection and disposal of CO_2. It appears that the issues surrounding the permanence and safety of proposed sequestration alternatives are more difficult to solve than anticipated both from a technological and economic point of view.

The most widely discussed options for sequestration of separated $CO_{2,}$ include injection into deep geological formations and disposal in the deep oceans (Royal Commission, 2000). Deep underground disposal is regarded as the most mature storage option today (Lindeberg, 1999). The advantage with underground disposal compared with other storage options is that it gives minimum interference with other ecological systems and can provide storage for very long periods of time. There are four main geological settings appropriate for deep storage: oil and gas fields, deep rocks containing saline waters, and unmineable coal formations.

Enhanced oil recovery through the disposal of CO_2 in oil fields is the largest current industrial use for carbon dioxide (Royal Commission, 2000) and is more economically viable than most other sequestration options. Fossil gas fields allow almost all of the space previously vacated by methane to be occupied by CO_2 before the natural field pressure is reached, ensuring long-term integrity of the storage. Deep reservoirs of saline groundwater with traps inhibiting the escape of injected CO_2 are much more common than oil or gas fields. Nearly one million tonnes of carbon dioxide a year are separated from CO_2-rich natural gas and injected into the Utsira formation in the North Sea, as part of a three-year monitoring and verification project (Kaarstad, 2000). The capacity of suitable geological formations, consisting mainly of saline aquifers, is sufficiently large that a significant fraction of the carbon dioxide produced globally by burning fossil fuels could be contained for decades to come (Royal Commission, 2000). The injection of CO_2 into deep unmineable coal formations, which more than doubles methane recovery, requires more research before the potential of this alternative can be evaluated (Royal Commission, 2000).

Among potential environmental impacts associated with underground disposal are stimulated seismic activity and the escape of CO_2 to the surface. International monitoring of current disposal projects will help to evaluate whether underground storage is a safe mitigation option (Royal Commission, 2000). Disposal of CO_2 in deep oceans has been suggested (Marchetti, 1989), but there are considerable uncertainties regarding potential environmental damage, especially the effects on marine life due to increased acidity and regarding the long-term isolation of the CO_2 (Falkowski *et al.*, 2000). CO_2 disposed into seawater at a depth of 3000 meters might be returned to the atmosphere within 250 to 550 years (Royal Commission, 2000).

Original natural gas reserves alone correspond to a potential storage capacity of about 150 GtC. With the extraction of higher gas categories, this storage capacity may be larger than 250 GtC. IPCC (1996) estimated the potential storage capacity of depleted oil and gas fields alone to be as high as 500 GtC. Deep subterranean sandstone aquifers have a long-term CO_2 storage capacity of about 90 GtC. CO_2 is also stored in chemical feedstocks and basic materials, e.g., CO_2 is used in the synthesis of urea (>10 MtC yr^{-1}). Perhaps a promising new method is the hydrocarb process (Yamada *et al.*, 1992), originally developed by M. Steinberg, to produce methanol and carbon from biomass and fossil fuel with subsequent storage of very large volumes of carbon in elemental form. A more recent method developed by Steinberg (1996) is the Carnol system, which consists of methanol production by CO_2 recovered from coal-fired power plants and natural gas and the use of methanol as an alternative automotive fuel. By far the largest reservoir for carbon disposal, in the form of solid CO_2 ice, is the deep ocean, which currently stores about 36,000 GtC. The global carbon cycle involves an annual exchange of about 200 GtC between the oceans, the atmosphere, and the biosphere, compared to about 6 GtC emissions from fossil fuel production and use.

Table 2 presents an overview of storage potentials as discussed in the literature. These storage potentials also include aquifers and ocean disposal that was not discussed above. Further discussion on the economics and environmental aspects of these storage reservoirs can be found in Hendricks and Turkenburg (2001) and IPCC (2001). However, it should be noted that, until environmental and safety issues related to deep ocean disposal have been adequately addressed, total permanent storage capacity is limited. It is not capable of containing continued CO_2 disposals from unconstrained business-as-usual exploitation of fossil fuels in addition to the disposals from BECS technology that could result should the ‘real option’ require to be exercised in the face of revelation of a low threshold for dangerous self-reinforcing climate change process. Thus, an effective risk management strategy requires both precautionary reductions of fossil fuel utilization and precautionary pro-active land use change.

Table 2: Low and high estimated potential of CO_2 utilization and storage options. Sources: Turkenburg (1997), IPCC (2001c).

Utilization[a]	0.2	1	GtC/yr
Exhausted gas wells	90	400	GtC
Oil wells	40	100	GtC
Unmineable coal measures		40	GtC
Saline aquifers	90	>1000	GtC
Ocean disposal	400	>1200	GtC

[a] Mainly for the use of enhanced oil recovery. Minor contribution for the production of chemicals.

2.2.3 Sustainability and bioenergy

The combination of impacts of climate change with the production of energy crops in simple ecosystems might bear risks in itself. The extent to which species populations can adapt and ecosystems can shift, disintegrate, or reorganize has implications for humans at cultural, economical, and ecological levels (Peterson *et al*., 1997). Particular species and ecosystems hold cultural value for different societies (Colding and Folke, 1997). Many species and ecological services are economically valuable. The spread of many diseases is mediated by specific species and ecological processes. Climate change will disrupt these and other relationships in uncertain ways that will benefit some, but will probably harm many.

Basic ecological services, such as carbon fixation, can be produced by simple ecosystems (Ewel *et al*., 1991); however, the elimination of more complex ecosystems may reduce the flexibility and range of ecological services generated globally. Simplification of ecological systems may also reduce their capacity to respond to novel conditions in the future as diversity is a fundamental principle of survival in nature and is also at the core of risk management. Although humans depend upon ecological products and services, there is little understanding of how these are produced, maintained, enhanced, or degraded (Daily, 1997). As bioenergy is (still) tied to land, the spatial component of biomass production and energy supply is very important, despite the increasing mobility of biomass. There is still an unresolved discussion on whether, from an ecological point of view, it is better to produce biomass intensively or extensively.

In Article 3.5, the UNFCCC recognizes the importance of merging economic efficiency with environmental and social integrity in one international system. Thereby, the UNFCCC also recognizes the importance of the third type of risk that was mentioned earlier — the risk from the interconnection of directly climate related risks with other risk factors than climate change. If bioenergy projects, including carbon separation and disposal, are well prepared chances are high that not only climate mitigation values, reducing global hazard of climate change, but also adaptation values, reducing vulnerability, can be produced. In addition, a number of other values for sustainable development in general are likely to be produced.

In the absence of governmental intervention, bioenergy will not be able to expand its market share in the near or medium future as energy investment decisions are based on strict cost minimization calculations given a particular demand pattern. Bioenergy will only be able to win the support of governments and ultimately of the mass of consumers if bioenergy can contribute to sustainable development in general. Only if the full social and environmental costs of energy producing technologies (from cradle to grave) are taken into account, will the long-term competitiveness of biomass increase and thereby the socioeconomic potential of bioenergy can be fully utilized.

In reviewing the discussion, it is important to note the significance of the assumptions made by various contributors. Drawing on experience from the past may provide poor guidance if the socioeconomic environment changes in ways that bear importantly on that experience. In particular, restraints on trade in food that derive from traditional concerns for food autonomy and the political influence of farming votes may weaken under European Union expansion and the World Trade Organization moves to liberalize trade in this sector. It has been remarked that if Zambia were farmed like the Netherlands it could feed all of Africa (Hall, 1998) — the problem is not shortage of land but lack of capital.

The lack of capital inputs that characterizes developing country agriculture and gives rise to the persistence of traditional, and in some cases unsustainable, land use practices may be eased by the prospect of profitable exports to developed countries. Also, in the nearer future, cash flows generated by the CDM of the Kyoto Protocol may serve a similar purpose in kick-starting more sustainable land use patterns (Read *et al*., 2001). Thus, treating competition for land as a zero sum game may lead to the neglect of opportunities for synergy between the expansion of bioenergy in developing countries and a shift to sustainable food production systems. Although the very large allocation of land to long rotations, noted previously in relation to the LULUCF discussion (IPCC, 2000b), may be sub-optimal as regards the split between long and short rotations, this does not mean that the total allocations of land envisaged are sub-optimal in relation to the sustainability of food production. Such very large allocations may be just what is needed to generate adequate funding for the transformation of agricultural practices in the early part of this century, that will enable the feeding of increased populations later on. And, as fully decarbonized energy technologies takes over later in the century, the need for land for bioenergy may reduce.

The literature on the bioenergy and sustainable development nexus is massive (see, e.g., Schlamadinger *et al*., 2001; FAO, 1997; 2000) and shall not be repeated here as we only want to add some points to this discussion. Despite the fact that there are large potentials for sustainable development, biomass production is not free of social and environmental costs. In the assessment of biomass projects, a number of synergies and potential trade-offs need to be considered. Miranda and Hale (2001) conclude, based on calculations of social costs of various energy production systems, that bioenergy may constitute a reasonable replacement for fossil fuel-based systems, but that environmental cost calculations are very site specific and that it is difficult to express all environmental impacts in monetary terms. Therefore, biomass projects must be appraised in the context of wider land management and industrial production systems that balance the local environmental, social, and economic impacts including food security; biodiversity; poverty, employment and equity; water production and flood control; soil degradation; and waste management and amenity values. There are still a number of issues to be solved to fully clarify the bioenergy and sustainable development nexus. In particular, the large-scale contributions of LULUCF activities to create a joint benefit of mitigation and adaptation to climate change are challenges that require strong institutional embedding, local participation, and development, transfer and adaptation of technology. Obersteiner *et al*. (2001) argue that certification procedures for sustainable forest management that are currently used for certifying timber products could help to solve some of the sustainability questions and site-specificity issues related to biomass production in combination with revenues from carbon markets. In a number of countries like Sweden green energy certificates are starting to win the hearts of consumers. These countries are just making their first experiences with auditing the production of green energy. Efforts to improve, be it national or international, should not miss the bandwagon of green energy auditing and certification as such audits are usually conducted under a wider sustainable development concept. These are far from perfect, but perhaps they are a good start.

Concluding, we would like to mention that although the calculations of potentials of sustainable bioenergy production and accessible storage for scrubbed carbon will still require additional work, the current estimates allow for the conclusion that a combined bioenergy/scrubbing technology could make net removal of carbon from the atmosphere feasible even under 'sustainablity' constraints. Thereby the use of bioenergy will enable a system of responsive carbon management and contribute substantially to climate risk management. If bioenergy projects are embedded in a wider sustainable development concept by including, for example, a certification scheme, strengthening of social, economic, and environmental values can be expected, which in turn could substantially reduce the full risk of climate change by reducing the vulnerability of social and ecological systems on local and global scales.

2.3 Scenario Calculations of BECS in Global Energy Models

2.3.1 MESSAGE-MACRO assessment

Present methodologies and technologies are sufficiently variable so that biomass-based synthetic fuels could easily substitute fossil feedstocks and energy carriers. The main reason why commercial bioenergy did not enter the energy market yet (with or without carbon scrubbing) is that bioenergy, at present, is not economically competitive compared to cheap fossil energy. This picture will most likely change and the dominance of fossil fuels is expected to diminish in the mid- to long-term future. This is particularly shown by the recent set of IPCC-SRES (Special Report in Emissions Scenarios) scenarios (IPCC, 2000a), where bioenergy gains significant importance across all scenarios including the so-called fossil fuel futures. The SRES report, which summarizes three years work of more than 50 scientists, suggests that global bioenergy consumption could increase from currently 46 EJ up to 250 EJ in 2050. The long-term estimates are even more optimistic ranging from 150 to 470 EJ in 2100.

The SRES report covers what is widely believed to be the full range of demographic, socioeconomic, and technological driving forces for future emissions of GHGs and other radiatively active gases, such as sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxides (NO_X), and describes a set of 40 resulting emissions scenarios for the 21st century. The scenarios are based on an extensive literature assessment, six alternative modeling approaches, and an "open process" that solicited worldwide participation and feedback.

The scenarios indicate that the future development of energy systems will play a central role in determining future emissions and suggests that technology is at least as important a driving force as demographic change and economic development, and that all of the driving forces influence not only CO_2 emissions but also the emissions of other GHGs. The scenarios illustrate that similar future GHG emissions can result from very different socioeconomic developments, and that similar developments in driving forces can nonetheless result in widely different future emissions. Thus, the SRES reveals many continuing uncertainties that climate research and policy analysis must take into account.

In particular, the report cautions against the use of single "best guess" or "business-as-usual" scenarios and instead recommends the use of multiple baselines to reflect uncertainty. It also puts technology policy in the forefront of possible response strategies in a warming world, although the uncertainties imply that traditional cost/benefit and cost minimization approaches are no longer appropriate. This is one of the reasons why SRES scenarios can be used to assess the role of energy technologies across alternative future developments. They were purposefully designed to cover a wide range of main driving forces including energy technologies.

The SRES writing team created four different narrative storylines and associated scenario families; each describes a different world evolving through the 21st century and each may lead to quite different GHG emissions trajectories. The storylines and scenario families are:

A1: This scenario family contains a future world of very rapid economic growth, global population that peaks mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system: fossil intensive (A1FI), non-fossil energy sources (A1T), and a balance across all sources (A1B).

A2: This scenario family contains a differentiated world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, resulting in continuously increasing population. Economic development is primarily regionally orientated and per capita economic growth and technological change more fragmented and slower than other storylines.

B1: This scenario family contains a convergent world with rapid change in economic structures towards a service and information economy, reductions in material intensity and introduction of clean technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improving equity, but without additional climate change policies. Consequently, all scenarios of the B1 family (B1, B1T, B1G) depict alternative directions of technological change striving toward the achievement of sustainable development paths (Riahi *et al.*, 2001).

B2: This scenario family contains a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than for A1 and B1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

The features summarized above were quantified using six different models, resulting in a number of alternative GHG profiles. In sum, 40 scenarios were quantified, and 35 included estimates for the full range of gases required for use by climate models. One representative of each scenario family was then selected to provide four "marker" scenarios (A1B, A2, B1 and B2).

In order to estimate the long-term potentials of carbon capture and sequestration from biomass technologies, we will confine our analysis to the four marker scenarios developed with the MESSAGE-MACRO modeling framework (Messner and Schrattenholzer, 2000) at IIASA, and refer to them henceforth as the four IIASA-SRES scenarios (Riahi and Roehrl, 2000). Quantitative results for the main scenario drivers: population and economic growth, and resulting primary energy use, carbon emissions and atmospheric carbon concentrations of the IIASA-SRES scenarios, are summarized in *Table 3*.

Table 3: The four SRES marker scenarios developed by the MESSAGE-MACRO modeling framework. The full SRES set consists of 40 scenarios developed with six different modeling frameworks. Source: Riahi and Roehrl (2000).

	Population (billion)		**Global Gross Domestic Product** (GDP) (trillion 1990 US$)		**Primary Energy**[a] (EJ)		**Cumulative CO_2 Emissions** (GtC)	**Atmospheric CO_2 Concentration** (ppmv)
	2050	**2100**	**2050**	**2100**	**2050**	**2100**	**1990–2100**	**2100**
A1B	8.7	7.1	187	550	1422	2681	1562	724
B1	8.7	7.1	136	328	837	755	842	486
B2	9.4	10.4	110	235	869	1357	1143	603
A2	11.3	15.1	82	243	1014	1921	1662	783

[a] Primary energy is calculated with the direct equivalent method.

All SRES scenarios (including the four IIASA-SRES variants) assume increasing affluence in the developing world and, hence, major shifts in the patterns of biomass use. At present, the majority of the bioenergy consumption is non-sustainable and comes from the direct use of non-commercial fuelwood in developing regions. In contrast, the future of bioenergy consumption is assumed to be based on highly efficient, large-scale energy plantations that supply sustainable amounts of biomass, which is converted into flexible and convenient energy forms for the consumer, such as electricity and synthetic gases or liquids.

For the assessment of carbon reduction potentials of biomass technologies in combination with carbon capture and sequestration, we perform an *ex post* analysis based on the biomass use in the four IIASA-SRES scenarios. In particular, we examine various energy-related sources of biomass deployment and conversion to identify the most promising options for biomass-based carbon sequestration. As a result, indicative ranges of cumulative carbon sequestration from biomass are presented. These estimates are then compared to the potentials of other principal mitigation measures based on the same set of scenarios analyzed by Riahi and Roehrl (2000).

Figure 5 shows the steadily increasing deployment of biomass for the world in the four IIASA-SRES scenarios. The scenario trajectories depict future developments in the absence of any climate change policies. The scenarios cover the full range of biomass use associated with baseline scenarios, consistent with the uncertainty range of all main driving forces for GHG emissions, such as technological, societal, economic, demographic, and institutional changes.

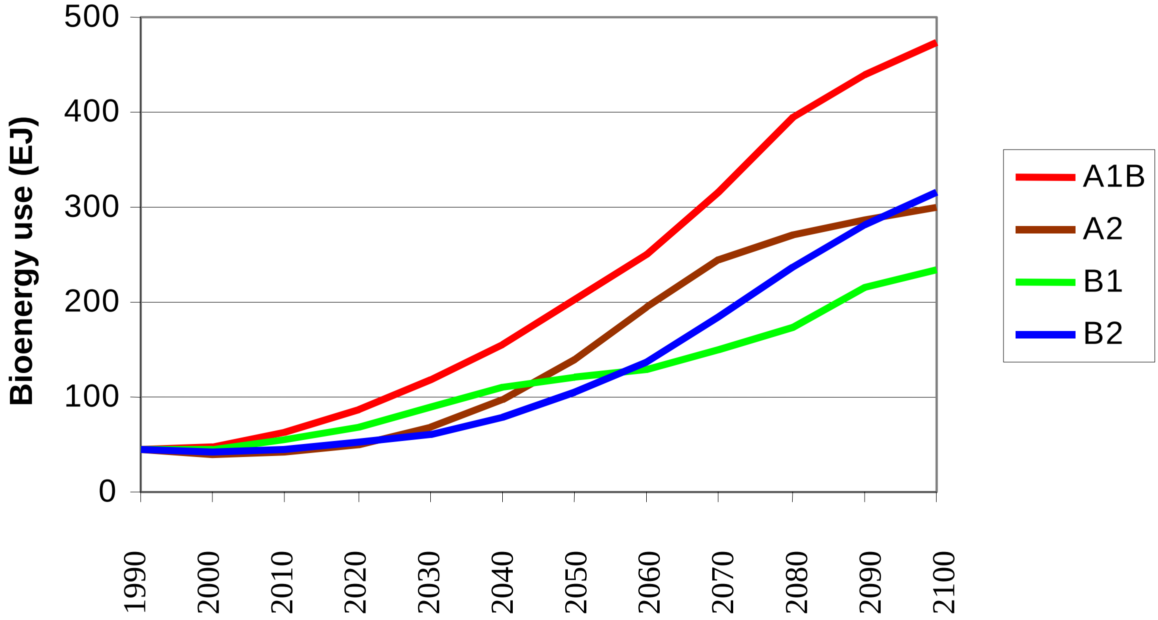

Figure 5: Global biomass use in the four IIASA-SRES marker scenarios developed with the MESSAGE-MACRO modeling framework. Source: Riahi and Roehrl (2000).

Assumptions of technological development, resource availability, and economic development strongly influence the future patterns of bioenergy consumption. The shaded areas in *Figure 6* illustrate the main sources of biomass-related CO_2 capture and sequestration in the global energy systems of the IIASA-SRES scenarios. In all scenarios, four principal contributors were identified by MESSAGE and MACRO as the most effective route:

- Carbon capture and sequestration in biomass-based power plants (particularly in combination with biomass gasification). We assumed that 90% of the carbon during centralized electricity generation may be removed and sequestered.
- Carbon capture and sequestration during ethanol (synthetic liquid) production from biomass. We assumed that the carbon capture potential from ethanol is limited to 50%, since ethanol is mainly used in the transportation sector, which does not allow for scrubbing of the remaining carbon in the transportation fuel.
- Carbon capture and sequestration during synthetic gases and hydrogen production from biomass. We assumed that 90% of the carbon during synthetic gases and hydrogen production may be removed and sequestered.

- Carbon capture and sequestration during heat production from biomass. We assumed that 90% of the carbon during centralized heat production may be removed and sequestered. The potential for carbon removal from heat production seems to be relatively limited compared to the other three major sources.

Note that the carbon sequestration potentials for non-commercial biomass and decentralized, spatially distributed, small-scale bioenergy facilities are assumed to be zero.

The contribution of the four main sources of carbon capture differs widely, depending on the baseline scenario that was explored. In the IIASA-SRES A2 and B2 scenarios, the major contributions to the CO_2 reduction come from ethanol production. The reasons for this are that both scenarios encounter a massive pressure on their oil resources particularly in the latter half of the century, which assists liquid substitutes such as ethanol from biomass to gain substantial shares in the transportation sector. The major theme of the A1B scenario is rapid growth of energy demand and capacity building in line with increasing affluence in the developing world. Combined with rapid improvements in technologies, this results in the massive introduction of renewables and, hence, biomass technologies into all energy sectors. Consequently, the potential of biomass-related carbon sequestration is highest in A1B, where carbon is mainly captured during ethanol and electricity generation. The B1 scenario describes a sustainable development of the future energy system. Thus, the B1 baseline emissions is lowest among all scenarios peaking at around 9 GtC in the early 40s, and decline later to less than 1990 emissions at the end of the century (see *Figure 6*). In B1, the major source of biomass-related carbon capture is the production of hydrogen. The sequestration potential itself is relatively small compared to, e.g., A1B, but due to the low baseline emissions, biomass-related capture and sequestration might eventually (by 2100) even lead to negative net emissions (see *Figure 6*).

Total cumulative sequestration potentials for biomass technologies are largest in A1B (450 GtC), followed by B1 (270 GtC), A2 (260 GtC), and B2 (240 GtC). The reader should note that the figures are based on the biomass deployment in baseline scenarios. In mitigation scenarios that aim to stabilize carbon concentrations (or emissions), the reduction potentials could be higher. This would particularly be the case if a carbon constraint were added to the fossil-intensive scenarios A2 and B2. Then, the elevated prices for fossil fuels would lead to additional structural shifts in favor of renewable sources increasing the contribution of biomass and, hence, the potentials for biomass-related sequestration.

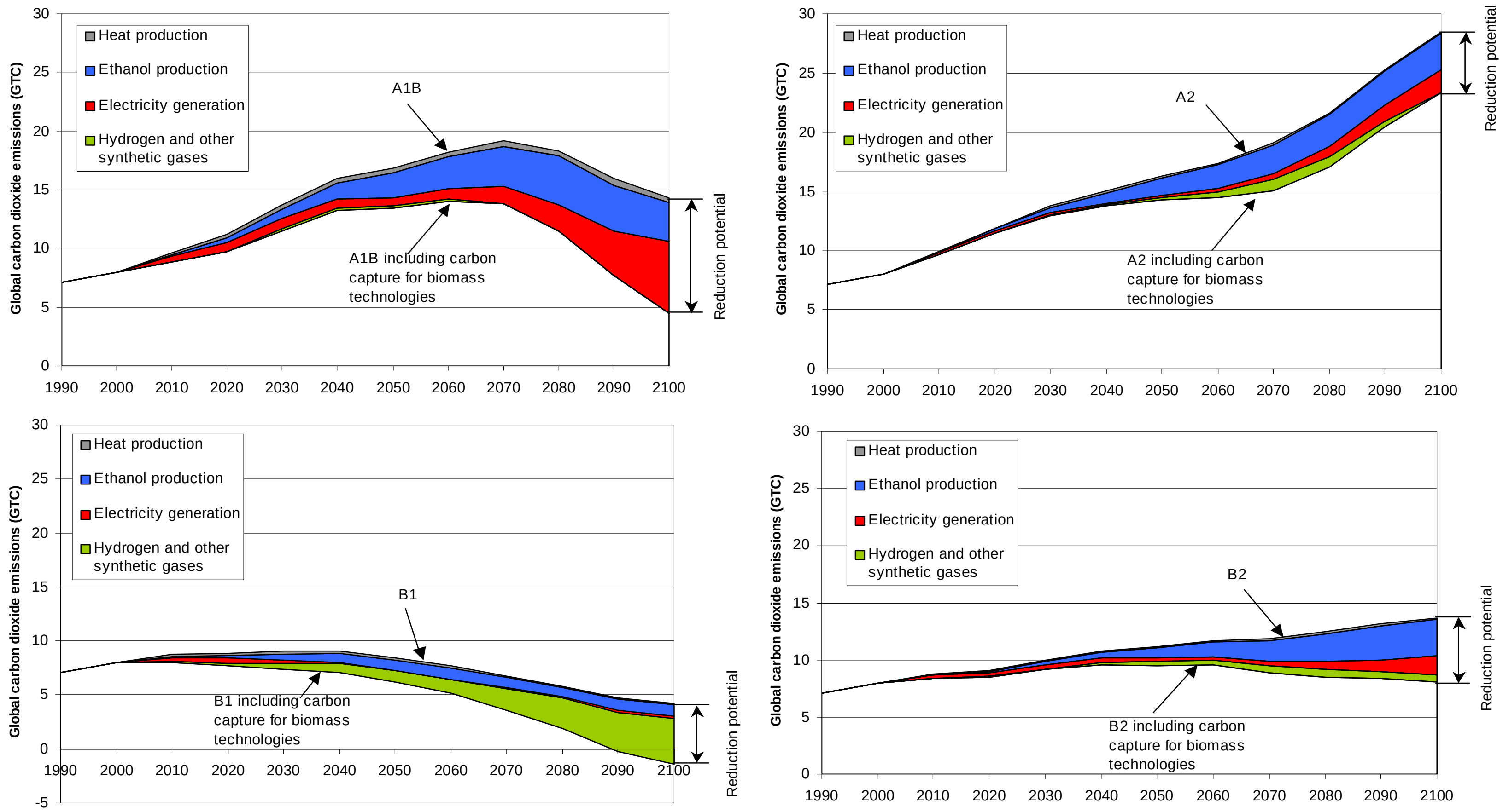

Figure 6: CO_2 emissions in the IIASA-SRES scenarios (A1B, A2, B2, and B1) and in the case of CO_2 capture and sequestration from biomass technologies. The shaded areas depict the four main sources of CO_2 sequestration during bioenergy production, compared to the respective IIASA-SRES baseline scenarios. The contribution of the four main sources of carbon capture differs widely, depending on the baseline scenario that was explored.

Table 4 compares the potentials of carbon capture and sequestration for biomass technologies with the potentials for other main mitigation measures in the energy sector (Riahi and Roehrl, 2000). Based on the same set of IIASA-SRES baseline scenarios, Riahi and Roehrl (2000) developed and analyzed a set CO_2 mitigation scenarios aiming at the stabilization of atmospheric carbon concentrations at various stabilization levels (from 450 to 750 ppmv). They concluded that out of all the available CO_2 emissions reduction measures, no single measure will be sufficient for the timely development, adoption, and diffusion of mitigation options sufficient to stabilize the atmospheric composition. Rather, a portfolio based on technological change, economic incentives, and institutional frameworks will be adopted. Riahi and Roehrl (2000) identified three major contributors to the emissions reduction of the CO_2 stabilization scenarios: carbon scrubbing and removal from fossil fuels, structural shifts in the energy structure away from carbon-intensive fuels (such as coal), and price induced demand reductions due to increased energy prices in the stabilization scenarios. The cumulative contribution (from 2000 to 2100) for each of these sources in the case of a 550 ppmv stabilization is compared to the potentials for biomass related carbon capture and sequestration in *Table 4*.

Table 4: Cumulative emissions reduction (GtC) between 2000 and 2100 for achieving a 550 ppmv stabilization target (Riahi and Roehrl, 2000) compared to the cumulative potentials for biomass-related carbon sequestration in the IIASA-SRES baseline scenarios.

	Demand reduction (550 ppmv)	**Carbon capture and sequestration from fossil fuels** (550 ppmv)	**Fuel switching** (550 ppmv)	**Potentials for carbon capture and sequestration during biofuels production**
A1B	58	296	199	450
B1[a]	n.a.	n.a.	n.a.	280
A2	111	243	316	260
B2	65	137	155	240

[a] Note that in the B1 baseline scenario the atmospheric carbon concentrations increase to about 490 ppmv by 2100 (see *Table 3*). Hence, there are no emissions reductions required to stabilize at 550 ppmv.

As shown in *Table 4*, the potentials for carbon capture and sequestration from biofuel technologies are large compared to other major sources for emissions reductions. This leads to two important methodological and policy conclusions. First, improved future models should include technologies for carbon capture and sequestration during biofuels production. Second, biomass and carbon capture technologies are obvious priority candidates for enhanced R&D efforts, with particular emphasis on their applicability for developing countries, which are expected to become the dominant source of energy-related CO_2 emissions and biomass-use in the long-term. Such a technology policy response appears especially meaningful for applying the precautionary principle under persistent and large uncertainties with respect to timing and magnitude of climate change and its impacts.

2.3.2 Azar and Lindgren (2001) assessment

The potential for carbon sequestration from biomass energy can be estimated in a back-of-an-envelope manner in the following way. Assume a technical potential for biomass energy by the year 2100 equal to 400 EJ/yr. This is a very large amount of biomass and would probably require a land area of plantations corresponding to as much as 1.5 Gha, or roughly the entire global crop land (this calculation assumes an average yield of 10 tons of dry matter/ha/yr which would lead to 300 EJ from plantations and 100 EJ/yr from byflows and residues in forestry and agriculture). A more plausible estimate, that take social and environmental constraints into account, would be 200 EJ/yr by the end of the century.

Four hundred EJ/yr corresponds to roughly 10 Gton C/yr. A large share of this biomass would most likely be used in applications where CO_2 sequestration is not possible. Thus, we assume here for simplicity, that half might be used in large-scale power or hydrogen production facilities. Thus, the sequestration potential might be 5 GtC/yr (but it could be higher if biomass use is concentrated to the above-mentioned plants). Assuming, for simplicity, that the use of this sequestration option grows linearly until 2100, we obtain a global sequestration potential over the next century equal to 250 Gton C, and half as much if a 200 EJ/yr biomass ceiling is assumed.

In *Figures 7* and *8*, we demonstrate scenarios developed by Azar and Lindgren (2001), in which an atmospheric CO_2 concentration target of 350 ppm is met. Here, the role of CO_2 sequestration in general is shown to be very important, but we also see that negative global CO_2 emissions are developed over time. The annual sequestration towards the end of the century becomes very large, since most of the biomass is used in power or hydrogen production facilities (because the possibility to sequester carbon becomes increasingly important).

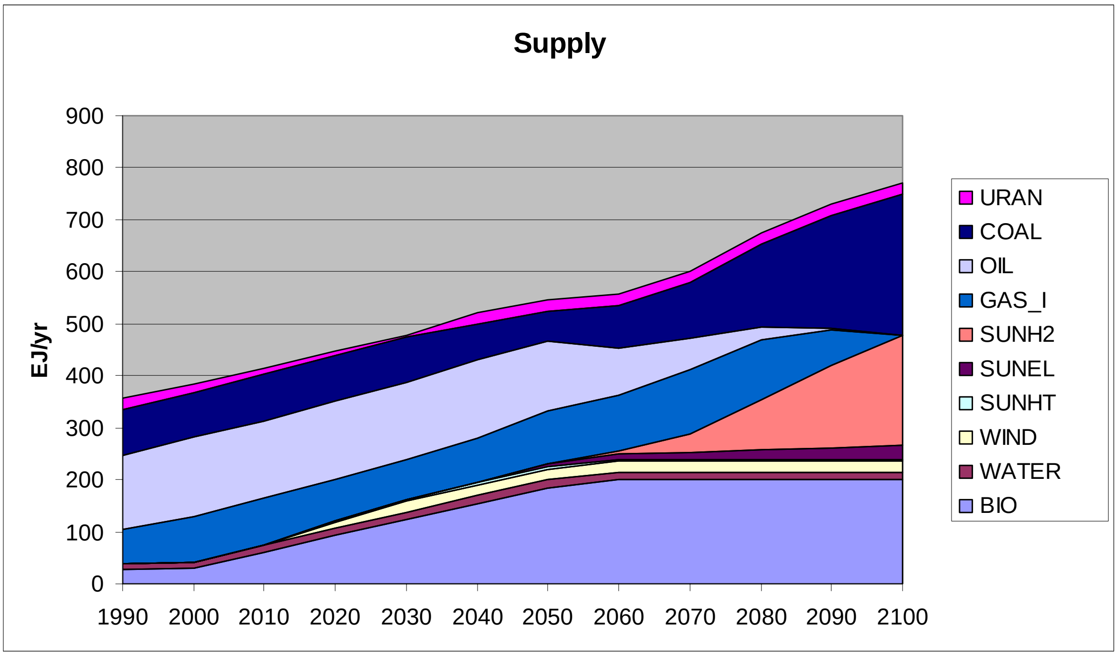

Figure 7: Global energy supply meeting an atmospheric stabilization target of 350 ppm (here modeled by allowing accumulated emissions of 350 Gton for the period 1990 to 2100). During the final decades of the century, carbon emissions are strongly negative (due to carbon sequestration from biomass energy, and the CO_2 concentration continues to drop after 2100). The biomass is initially used for heat and process heat production but, with increasing carbon taxes over time, an increasing share of the biomass is used in large scale facilities, for electricity and hydrogen production, where the CO_2 may be more easily sequestered. Source: Azar and Lindgren (2001).

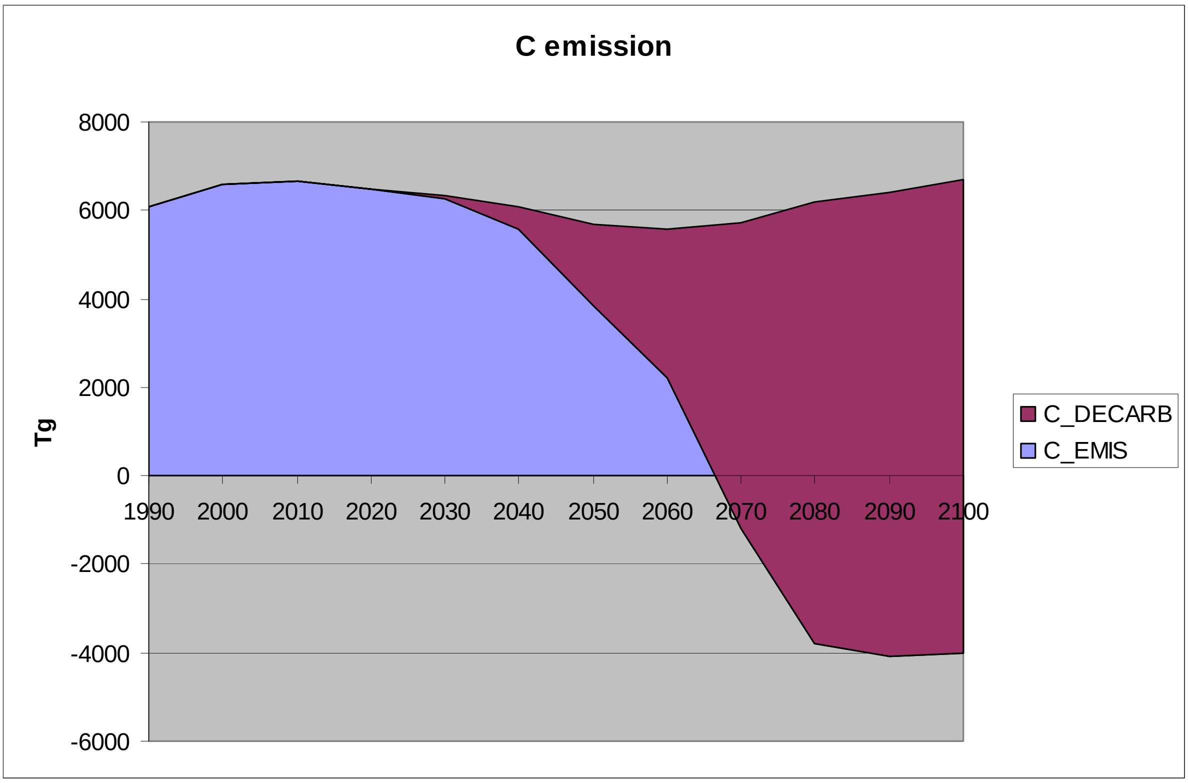

Figure 8: Emissions profile for the 350 ppm scenario. Since decarbonization from the use of biofuels is allowed, negative net C emissions may occur as the figure illustrates from 2070 and onwards. If the carbon abatement policy continues, atmospheric concentrations of CO_2 will continue to drop beyond 2100. Source: Azar and Lindgren (2001).

3 Conclusion

The purpose of this paper was to show that BECS could turn out to be an important 'real option' nested in a wider portfolio of climate mitigation technologies allowing for robust climate risk management. This is due to the fact that BECS allows for dynamic downward adjustment of atmospheric carbon concentrations in the atmosphere over long periods of time. We showed that negative emission scenarios should be added to the main attainability domain of the global energy system and thereby this technological possibility adds a new dimension to risk-hedging strategies under uncertain climate change. The main advantage of such a real option is that of flexibility in decision making allowing for increased learning and conditional risk taking. On the downside, we identified a number of possible environmental stresses that could occur from large scale use of BECS. Combined with a number of economic factors, the uncertainties on the competitiveness of BECS is still larger than that of conventional mitigation technologies, which has a negative impact on its competitiveness.

With respect to risk taking, BECS is essential for backstop risk mitigation and containment by lowering the long-term level of climate risk. However, at the same time, BECS might turn out to be a competitive mitigation technology that can be used as a compliance measure under climate mitigation regimes such as the Kyoto Protocol. Such early use would most likely only occur if this technology would be appraised under an uncertainty augmented investment calculus that takes the high option value of BECS into account. An early use of BECS serves two purposes in a system of joint production: it increases the preparedness for counteractions against self-reinforcing risk scenarios and, at the same time, might lead to more cost-efficient mitigation measures, consistent with real option theory, under a gradual climate change regime if sufficient learning can be accumulated. We have argued in this paper that the real option value has so far been ignored in emission scenario models and therefore underestimated the true competitiveness of BECS, which serve the dual purpose of hedging climate risks and supplying energy.

Risk reducing measures are dynamically not substitutes, but should rather act as complements and supplements to a baseline emission path. Negative emissions might most likely turn out to be an ineffective tool for risk containment, if accumulated fossil fuel emissions have *ex post* proved to be excessive. Risk management, under the climate change problematique, will only be effective if it is forward-looking and not employed on an ad-hoc basis. It is naïve to believe that mankind can, with this technological possibility at hand, now stay on the fossil fuel path until climate change became 'real' and then switch on the 'carbon scrubber' in order to quickly improve the climate again. Due to the long time lags between emissions and changes in climate pattern, climate risk management should be used to preclude excessive climate related catastrophes, way in advance, employing a precautionary mode of risk-reducing and risk-limiting actions. Ignoring climate risk management is dangerous and against the spirit of the UNFCCC Article 3.3. In this paper we have shown that if, however, the importance of climate risk is adequately understood and risk aversion is not infinite, BECS and other GHG removal technologies will always be essential in a wider portfolio of mitigation technologies managing for a robust and sustainable climate regime.

It is important to point out that there are still a number of issues open with respect to the environmental and social sustainability of large-scale global applications of BECS. In addition, the current state of technology is in its primordial stage and the current resource potentials are still rather limited. Given that land markets are rather sticky, large infrastructure investments are necessary and diffusion times will span several decades. As long as the high option value of BECS is not recognized, it will fail to be developed adequately as a competitive mitigation technology cluster. However, once it is allowed to learn — when there is a high value for emission reduction — it will learn at double speed due to its property of negative emissions. Furthermore, technological spillovers can be expected from the implementation of sequestration technologies for fossil fuels.

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