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REPORT OF THE STAP BRAINSTORMING SESSION ON CARBON SEQUESTRATION

[PREPARED BY THE SCIENTIFIC AND TECHNICAL ADVISORY PANEL (STAP)]

Report of the STAP Brainstorming Session on Carbon Sequestration

Washington, D.C.
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Prepared by
The Scientific and Technical Advisory Panel (STAP)
Of the Global Environment Facility (GEF)

STAP Secretariat

United Nations Environment Programme

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PREFACE

It is a pleasure to present the report of *The STAP Brainstorming Session on Carbon Sequestration*. The Brainstorming Session was held on June 16, 1998 in Washington, D.C., U.S.A. It was attended by both outgoing and incoming STAP members, representatives of the GEF Implementing Agencies and two outside experts on Carbon Sequestration. This meeting was convened by the Scientific and Technical Advisory Panel (STAP) of the Global Environment Facility (GEF) to advise the GEF on scientific and technical issues relating to carbon sequestration, as the GEF explores the feasibility to launch a new operational program in this area.

The STAP report on *Brainstorming Session on Carbon Sequestration* provides much of the basis for the findings and recommendations relating to carbon management both by growing trees and by fuels decarbonization/Carbon Sequestration. On the basis of the findings of this brainstorming and additional analysis and consultations, STAP will finalize and submit for Council's consideration, further guidance on Carbon Sequestration.

This brainstorming session was written by the STAP Working Group on Climate and Energy under the chairmanship of Dr. Robert Williams. Members of the outgoing STAP as well as the incoming STAP participated in the brainstorm.

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Introduction

1. In conjunction with its Twelve Meeting, STAP convened a Brainstorming Session on Carbon Sequestration on 16 June 1998 in Washington, DC, to advise the GEF on scientific and technical issues relating to carbon sequestration, as the GEF considers whether to launch a new operational program in this area.

2. The Brainstorming Session dealt with two very different kinds of carbon sequestration, spending a half day on each. The morning session was devoted to the more familiar form of carbon sequestration: the growing of trees to extract CO_2 from the atmosphere via photosynthesis. The afternoon session dealt with the less familiar variant: decarbonization of carbonaceous fuels to produce hydrogen (H_2) plus sequestration in geological (underground) reservoirs of the CO_2 separated out during H_2 production.

3. The Brainstorming Session was Chaired by outgoing STAP member Robert Williams and attended by both outgoing and new incoming STAP members, representatives of the GEF implementing agencies, and two outside experts on carbon sequestration. A copy of the program schedule is attached as an appendix to this report.

4. Williams opened the Brainstorming Session with an overview presentation of the two kinds of carbon sequestration.[1] There were two subsequent presentations in the morning session: The first, by outgoing STAP member Jyoti Parikh, described how tree planting activities at the village scale might be shaped to provide significant benefits to the local population while providing the global benefit of carbon sequestration in the trees; Parikh's presentation was based largely on a detailed case study she had carried out on the growing of trees at the village scale in India (Parikh and Reddy, 1997a). The second, by Dr. Greg Marland (Environmental Sciences Division of the Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA) summarized the results of a detailed modeling exercise comparing the relative impacts on the atmosphere of the growing of biomass for carbon sequestration and the growing of biomass as a fossil fuel substitute (Marland and Schlamadinger, 1997). There were also two presentations in the afternoon session. The first, by Dr. Werner Soyez (Product Technical Manager, Hydro Agri Europe, Brussels, Belgium) described a tentative proposal by Norsk Hydro to build a large combined cycle power plant that would burn a hydrogen-rich gas derived from natural gas in a facility integrated with the power plant and use the CO_2 generated as a byproduct of the produced hydrogen for enhanced oil recovery.[2] The second, by Williams, described how hydrogen production from coal and coal bed methane could be coupled to the recovery of methane from deep beds of unminable coal, with sequestering of the separated CO_2 in the coal bed (Williams, 1998c).

[1] The material presented by Williams relating to carbon sequestration via tree growing was drawn largely from Hall, Mynick, and Williams (1991a; 1991b). The material presented by Williams relating to fuels decarbonization and CO_2 sequestration was drawn largely from Williams (1998a; 1998b) and Socolow (1997).

[2] A Norsk Hydro press release relating to the proposed power plant ("Norsk Hydro announces new hydrogen-fueled power plant," 23 April 1998) can be found on the World Wide Web at http://www.hydro.com

5. What follows immediately are sections with the STAP findings and recommendations relating to carbon management both by growing trees and by fuels decarbonization/CO_2 sequestration. These summary sections are followed by detailed discussions of the major issues in each of these areas.

6. This report is a joint product of the outgoing and the incoming STAP members.

STAP Findings and Recommendations: Carbon Management by Growing Biomass

Findings

7. Often the biomass grown on a fixed amount of land will serve multiple purposes simultaneously. The impact on the carbon cycle will depend in complex ways on the species selected and their growth rates, the prospective uses of the biomass, the time horizon of interest, and the prior use of the site. Complex models are needed to understand better the carbon balances of such systems as a basis for making definitive judgments about alternative strategies. Moreover, decisions relating to specific proposed projects depend on considerations of a wide range of local costs and benefits as well as carbon cycle costs and benefits.

8. Despite such inherent complexities and uncertainties, some general conclusions can be drawn on the basis of present knowledge.

9. With regard to sequestration, consideration should be given to both "grow-and-store" and "perpetual-rotation" approaches. The former can often provide some local public benefits other than the global benefit of carbon sequestration (e.g., watershed protection, maintenance of biodiversity, creation of wildlife sanctuaries), but it can offer few private benefits (except possibly enhanced tourism). Widespread public acceptance of tree-growing strategies will probably require that a significant part of the overall sequestration effort be devoted to perpetual-rotation as well as grow-and-store strategies.

10. With the perpetual-rotation approach to sequestration, sales of products created from the harvested biomass can provide significant local benefits from their sales in the market and their utility in serving local needs, though at the expense of reduced global sequestration benefits compared to the grow and store approach. The global potential for sequestering carbon in long-lived forest products so produced (in addition to what is sequestered in the inventory of the plantations averaged over the entire planting/growth/harvesting cycle) will tend to be very modest.

11. Large potential local benefits can be achieved with perpetual-rotation biomass growth strategies without diminishing and often greatly enhancing climate change benefits if the produced biomass can be sold profitably in energy markets. Use of biomass for energy would tend to be favored from both local and global perspectives over sequestration strategies (both grow-and-store and perpetual-rotation variants): (*i*) when the energy alternatives are based on coal and if advanced modern biomass energy conversion technologies are available; (*ii*) in areas where climatic and soil conditions are such as to make feasible high biomass yields; and (*iii*) where a long-term perspective is taken in considering climate change benefits.

12. Growing biomass to sequester carbon (either a grow-and-store or a perpetual-rotation variant) will be preferred over growing biomass for energy in areas where: (*i*) the high yields needed for profitable bioenergy applications are unachievable; (*ii*) harvesting costs are too high to make bioenergy strategies

attractive (*e.g., on steep hills*); (*iii*) sites are remote from potential biomass energy markets; or (*iv*) conserved forests are deemed desirable for economic reasons, for preservation of wildlife sanctuaries, for biological diversity maintenance, for watershed preservation, and/or for other environmental reasons.

Recommendations

13. STAP makes the following recommendations to the GEF regarding a possible new operational program relating to carbon management by growing biomass:

- GEF-supported projects involving the growing of biomass for carbon management should be designed to choose the optimal uses of the produced biomass (in the form of products that can be created from harvesting the biomass as well as from carbon sequestration), taking into account not only the net impacts on the carbon cycle over time but also costs and benefits relating to local development goals.

- GEF-supported projects that involve intensive management of biomass production largely for energy purposes should be focused primarily on degraded lands that can be restored to productive use to levels such that growing of biomass for energy purposes could be profitable, once the biomass production activity is launched in the market.

- GEF-supported projects that involve primarily an emphasis on carbon sequestration should be focused largely on areas where: (*i*) the high yields needed for profitable bioenergy applications are unachievable, (*ii*) harvesting costs are too high to make bioenergy strategies attractive (*e.g., on steep hills*), (*iii*) sites are remote from potential biomass energy markets, or (*iv*) conserved forest reserves are deemed desirable for economic or environmental reasons.

- The GEF should encourage the development and commercialization of small-scale (25 to 500 kW) high-efficiency biomass electric conversion technologies that would make it possible for biomass to compete with coal, thereby promoting rural industrialization,

- The GEF should encourage agroforestry strategies that make it feasible for small land holders to co-produce trees for energy purposes along with food crops.

In addition to the above, the GEF should consider supporting *targeted research* in the following areas:

- The GEF should help support the development and validation of carbon management models for biomass production and use, with an emphasis on applications to degraded lands on a region-by-region basis. Such models should be capable of taking into account a wide range of societal goals for the growing of biomass on such lands, including local development, maintenance of biological diversity, and local environmental protection, as well as carbon emissions reduction goals. Variants of these models that incorporate economic costs and benefits (including various external costs and benefits) should also be developed.

- The GEF should help initiate efforts to develop inventories of degraded lands suitable for restoration to much more productive uses, including the production for biomass for both carbon sequestration and energy and other applications of biomass in conjunction with perpetual-rotation management strategies for biomass. These inventories should include characterization of the present uses of theses lands.

- The GEF should help support research aimed at identifying and articulating the most effective strategies for restoring degraded lands to productive uses, on a region-by-region basis.

- The GEF should help support collaborative research involving ecologists as well as agriculture/forest technology specialists to develop environmentally sound and sustainable biomass production strategies, including polycultural production strategies.

- The GEF should help support the development of environmental guidelines for biomass energy production.

STAP Findings and Recommendations: Carbon Management by Fuels Decarbonization/CO_2 Sequestration

Findings

- While carbon management via the sequestration of carbon in trees must be regarded as limited stop-gap measure (with a global sequestration capacity ~ 70 GtC) that buys time until renewable energy and other non-carbon-based systems can come into wide use, the fuels decarbonization/CO_2 sequestration approach might enable fossil fuels to continue to play major roles in the global energy economy for centuries, even in a severely greenhouse emissions-constrained world.

- Key to such a future for fossil fuels is successful commercialization of energy conversion technologies that put a high market value on hydrogen (H_2) as an energy carrier because: (*i*) the least costly ways to make H_2 are from fossil fuels—for which the production technology is well established in the market, serving today mainly chemical industrial applications, (*ii*) when H_2 is produced from fossil fuels a stream of relatively pure CO_2 can be produced as a byproduct, (*iii*) this CO_2 can be stored in deep geological reservoirs (e.g., depleted oil and gas fields, deep saline aquifers, or deep coal beds) at low incremental cost, (*iv*) although there are still many uncertainties that must be resolved, there is growing confidence in the scientific community that it may be feasible to store in such geological reservoirs a significant fraction of the next several centuries of global CO_2 production from human activities might be feasible.

- The fuel cell is a technology which, if successfully commercialized, would put a high market value on H_2 and create a market demand for H_2, because this fuel cell "prefers" to be fueled by H_2. Recent advances indicate that fuel cells can begin to make significant contributions to energy needs in both transportation and stationary combined heat and power (CHP) markets during the first decade of the next century. Proton exchange membrane (PEM) fuel cells in particular are the focus of intensive developmental efforts for automotive applications in the industrialized countries on the part of all major auto-makers. This technology could also be used for bus, small (2- and 3-wheeled) vehicle, and locomotive applications, which are especially important in many developing countries. PEM fuel cells make it possible: (*i*) to provide transportation services at high energy efficiency with zero or near zero pollutant emissions, without the need for complicated end-of-pipe pollutant emission control technologies, and (*ii*) the opportunity to use a wide range of primary energy sources (e.g., natural gas, coal, biomass, municipal solid waste) other than petroleum to provide transportation services.

- Initial fuels decarbonization/CO_2 sequestration activities will probably be focussed mainly on those activities where CO_2 sequestration can be accomplished in conjunction with resource recovery—enhanced oil recovery (EOR) and coal-bed methane (CBM) recovery. The global potential for sequestration in conjunction with resource recovery is much smaller than the potential with aquifer disposal, but it is probably comparable to the potential for sequestration by growing trees.

- CO_2 injection for EOR is well-established commercial technology. The technology requires a low-cost source of CO_2. One way to provide the needed CO_2 in the near term is to generate it as a byproduct of the production of H_2 from natural gas, siting the H_2 production facility near the EOR site. Norsk-Hydro is planning to build such a H_2 plant coupled to a combined cycle power plant that would be fueled by the produced H_2. When credit is taken for the value of the CO_2 in EOR, the net cost of the produced electricity would often be comparable to that for a conventional natural gas combined cycle power plant, but the CO_2 emissions per kWh from power generation would be reduced by up to 90%.

- Coal-rich countries that also have substantial coal bed methane (CBM) resources could use coal bed methane as well as coal as a feedstock for H_2 production. H_2 derived from CBM would typically be less costly than H_2 derived from coal. Moreover, the CO_2 byproduct generated in making H_2 from coal and CBM could be injected into deep beds of unminable coal to stimulate CBM recovery while sequestering the injected CO_2 in the coal bed. Using CO_2 injection to stimulate CBM recovery is a new technology that is not yet fully commercial that warrants intensive development, since it holds forth the promise of being able to provide energy from coal in the form of H_2 with low lifecycle CO_2 emissions.

- The production of H_2 from coal plus CBM with sequestering of the separated CO_2 need not await the commercialization of fuel cells, because in the near term this strategy could be used to provide H_2 for ammonia production to serve fertilizer market needs. In those countries that currently make ammonia from coal using modern coal gasification technology (e.g., China) this strategy would probably lead to lower ammonia production costs while simultaneously reducing substantially the CO_2 emissions.

- Coal-rich countries that have are not well endowed with petroleum resources and that do not yet have in place extensive hydrocarbon fuel infrastructures for transportation (e.g., China) have the opportunity to "leapfrog" directly to H_2 fuel cell technology for transportation, obviating the need for the costly HC-fueled fuel cell transition technology that is being considered for launching fuel cells in transportation markets in some industrialized countries..

Recommendations

- If the GEF decides to establish a new operational program relating to carbon sequestration, the program should include fuels decarbonization/CO_2 sequestration strategies as well as biomass-growing strategies. Such and operational program should both help commercialize key technologies (including enabling technologies) and provide targeted research support.

- The GEF should help accelerate the commercialization of H_2 fuel cells and enabling technologies (e.g., H_2 storage technologies) for transportation and combined heat and power (CHP) markets in developing countries, by supporting demonstration projects and strategies for "buying down" the prices of demonstrated technologies to market-clearing levels. Demonstration projects should focus on applications that are especially relevant to developing countries (e.g., buses, 2- and 3-wheeled vehicles, and locomotives, in the transport sector).

- The GEF should help accelerate the commercialization of innovative technologies for producing H_2 from carbonaceous feedstock in conjunction with sequestration of the separated CO_2, giving priority to those countries where a hydrocarbon-based fuel infrastructure for transportation is not yet in place.

- The GEF should help support near-term projects for EOR using CO_2 injection, to clarify the economics in developing country situations where this commercial technology is unfamiliar.

- The GEF should help support demonstration projects for coal bed methane recovery based on injecting CO_2 into deep coal beds.

In addition to the above, the GEF should consider supporting *targeted research* in the following areas:

- The GEF should help support targeted research aimed at assessing the CO_2 sequestration capacity in geological reservoirs (depleted oil and gas fields, deep saline aquifers, deep coal beds) on a region-by-region basis in developing countries, including cost, safety and security aspects of such storage.

- The GEF should help support targeted research aimed at developing learning/experience curves for PEM fuel cells and the costs of buying down the prices of PEM fuel cell systems for both transportation and CHP market applications.

- The GEF should support detailed studies of alternative H_2 production/use systems at local/regional levels based on real-world data, including such systems studies for innovative configurations such as H_2 use and production from coal plus coal bed methane in conjunction with the use of the separated CO_2 for coal bed methane recovery.

Major Issues: Carbon Management by Growing Biomass

14. The carbon management by growing biomass analysis begins with a literature review relating to carbon sequestration, followed by a section providing a rationale for the scientific and technical focus chosen by STAP for the Brainstorming Session, followed by a discussion of the relative merits of growing biomass for sequestration vs. growing biomass as a fossil fuel substitute.

Background on Growing Biomass to Sequester Carbon

15. The growing of biomass extracts CO_2 from the atmosphere and thereby provides the opportunity to sequester carbon in the biomass as long as the biomass is not harvested or if harvested is stored in long-lived industrial products. This prospect provides the basis for carbon management strategies in

which CO_2 emissions from fossil fuel burning in one part of the world might be offset by carbon sequestration realized by growing trees in another part of the world.

16. The idea of sequestering carbon by growing trees has attracted considerable interest in the climate change policy community since physicist Freeman Dyson first proposed the idea more than 20 years ago (Dyson, 1997). Dyson argued that since it would probably require at least 50 years for the world to make a transition from a primary dependence on fossil fuels to a primary dependence of the global energy system on non-carbon-based (e.g., renewable) energy sources, consideration should be given to the growing of trees as carbon sinks to "buy time" for the development and commercialization of such alternative energy sources. In his classic paper he carried out a "back-of-an envelope" calculation suggesting that a crash tree-growing program that would remove 4.5 billion tonnes of carbon from the atmosphere each year would cost about $630 billion (1997$) for establishing tree plantations on 700 million hectares (@ $900/hectare) plus annual fertilizer costs amounting to $31 billion (1997$). The present value of the cost of such a program (assuming a 12% discount rate) amounts to $730 billion and the cost per tonne of carbon sequestered would be an extraordinarily low $3 per tonne of carbon sequestered (assuming that trees grow at a constant rate for 50 years until they reach maturity and that fertilizer is applied at a constant rate during this period). Many papers have been written on the sequestration option since Dyson's pioneering analysis, and all have affirmed his general findings. And a number of pilot projects exploring the practical feasibility of sequestering carbon by planting trees have been carried out as Activities Implemented Jointly under the Framework Convention on Climate Change.

17. However, many of the more recent studies have deemphasized the "plant-and-store" approach described by Dyson (in which trees are not harvested after they reach maturity) in favor a "perpetual-rotation" approach in which the trees are harvested at maturity and used for a variety of purposes and the plantation lands are subsequently replanted in an indefinite plant/grow/harvest/replant cycle, because of the importance of benefits other than carbon sequestration from tree planting efforts (Sathaye et al., 1995). Although the plant-and-store approach can provide besides carbon sequestration benefits a variety of other public benefits such as watershed protection (water supply and soil stabilization), maintenance of biodiversity, creation of wildlife sanctuaries, it offers few private benefits (except possibly enhanced tourism). Widespread public acceptance of tree-growing strategies will probably require that a significant part of the overall sequestration effort be devoted to perpetual-rotation strategies, in which the local populations can earn income from the sale of timber, pulpwood, fuelwood, etc., products generated from the harvested biomass and can often use many of these products in serving local needs (Parikh and Reddy, 1997a; Sathaye et al., 1995; Wangwacharakul and Bowonwiwat, 1995; Xu, 1995). With the perpetual- rotation approach the sequestration potential per hectare [essentially the average carbon stored in the standing biomass and soil over a rotation cycle plus the carbon stored in post-harvest products (Sathaye et al., 1995)] is much less than for the plant-and-store approach in which carbon sequestration levels per hectare can sometimes exceed 200 tonnes C [see, for example, Maclaren (1996)],[3] but by taking into account perpetual-rotation opportunities

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[3] Consider, for example, that with the grow-and-store approach the carbon sequestration in the standing biomass per hectare (neglecting sequestration in the litterfall and soil) is $C_{SM}*T_M$, where C_{SM} is the average annual rate of growth (tonnes C in the standing biomass per hectare per year) until forest maturity T_M years after planting. In contrast, with the perpetual-rotation approach the carbon sequestration in the standing biomass per hectare (neglecting sequestration in the litterfall and soil) is $C_{SR}*T_R/2$ + the carbon stored in wood products after harvest,

sequestration projects can probably be carried out on far more land than would otherwise be practically feasible. Moreover, the potential for net low-cost carbon sequestration can still be significant with the perpetual-rotation approach. For example, a recent very detailed study (Xu, 1995) indicates that sequestration carried out in China using the sustainable rotation approach on 130 million hectares of land[4] under the control of the Chinese Ministry of Forestry that is available for afforestation plus 70 million hectares of dry croplands under control of the Ministry of Agriculture that is suitable for agroforestry development could sequester 9.7 billion tonnes of carbon (49 tonnes C per hectare) for an initial cost (exclusive of benefits from the sales of harvested products) of $19.3 billion ($2 per tonne of C). This sequestration potential is equivalent to 11 years of China's total CO_2-equivalent GHG emissions at the 1995 emission rate. Moreover, when account is taken of the income from harvest sales, some 8.1 billion tonnes in this total is available at negative net cost, and the rest is available at a net cost of only $820 million ($0.5 per tonne of C) (Xu, 1995).

18. Consideration of local benefits and the importance of minimizing opportunity costs that could be significant if trees were planted on prime agricultural lands has also led to emphasis in recent studies on carbon sequestration projects that might be carried out on degraded lands (Parikh and Reddy, 1997b; Ravindrath and Somashekhar, 1995; Xu, 1995; Ismail, 1995), which could simultaneously generate local benefits by providing watershed protection, maintaining biodiversity, providing biomass products to serve local needs, and generating rural employment.

19. Vast degraded land areas suitable for carbon sequestration are a common feature of the landscape in many countries; in many instances these lands were forested until recently, and they retain adequate soil fertility to support biomass growth (Sathaye et al., 1995). In India, for example, some 53 million hectares of degraded non-crop and non-forest land (16% of the total land area of India) is potentially available for reforestration projects (Gautam, 1997; Ravindranath and Somashekhar, 1995). For tropical regions Grainger (1988, 1990) has estimated that there are 2100 million hectares of degraded lands, of which 30% is theoretically suitable for reforestation. Another estimate is that 950 million hectares may be technically available for revegetation (Dixon et al., 1994). Moreover, Trexler et al. (1989) estimate that it is typically socio-economically feasible to utilize about 70% of technically available land.

Focus of the Brainstorming Session in Dealing with Scientific and Technical Issues

20. There are many scientific and technical issues associated with the growing of trees for carbon sequestration—both tactical and strategic issues. Measurement is one important tactical issue that would have major public policy significance if Joint Implementation (JI) were to become an agreed upon policy under the Framework Convention on Climate Change (FCCC). The process of measuring carbon accumulation in trees and soils as a result of sequestration efforts is a difficult and nontrivial exercise that warrants careful scrutiny. However, it is not an issue for which GEF should have to assume major responsibilities, because other public agencies are likely to be heavily involved in dealing with measurement challenges, because measurement has emerged as an important tactical issue in

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where C_{SR} is the average annual rate of growth (tonnes C in the standing biomass per hectare per year) during the rotation period of T_R years, planting to harvest.

[4] This is in addition to the 125 million hectares in forests (13% of China's land area) in 1988.

conjunction with near-term efforts on the part of Annex I parties to the FCCC in meeting their obligations for reducing greenhouse gas (GHG) emissions under the Kyoto Protocol.[5]

21. Instead of addressing such tactical issues the STAP Brainstorming Session was focused on providing GEF strategic advice on how to think about the growing on degraded lands of trees for carbon sequestration vs. the growing of trees or other forms of biomass as a fossil fuel substitute.

22. When biomass is burned for energy as a fossil fuel substitute, the CO_2 extracted from the atmosphere during photosynthesis is released, so that there is zero net impact on the atmosphere, except for the CO_2 emissions associated with the fossil fuel energy required for biomass production, transport, and conversion into useful energy. [With modern biomass plantation technology, such lifecycle emissions, represent a small fraction of the carbon content of the biomass (IPCC, 1996).]

23. Emphasis in the STAP analysis is given to alternative strategies for growing biomass on degraded lands. One reason for this choice is to minimize opportunity costs (see previous section). Also, in growing biomass for sequestration purposes there are generally no potential carbon sequestration benefits when old-growth forests are replaced by young forests (Harmon et al., 1990). Replacing natural forests with managed plantations grown for energy purpose can lead to net carbon benefits only if the managed plantations have very high yields and the produced biomass is used efficiently. Even in such cases, considerations other than impacts on the carbon cycle will often be decisive in deciding the desirability of such an option. Especially important are local development impacts, conflicts with the goal of maintaining biological diversity, environmental impacts associated with use of chemicals in biomass production, and soil erosion associated with biomass harvesting.

24. Moreover, for the reasons articulated in the previous section, carbon sequestration programs for degraded lands should include projects that are based on the perpetual-rotation approach. Under this approach, consideration should be given to the impact on the atmosphere of the harvested products. The two major options for generating post-harvest atmospheric carbon benefits are long-lived wood products and use of the harvested biomass for energy as a fossil fuel substitute. A comparison of sequestration and fossil fuel substitution options is desirable because the growing of biomass for either sequestration or fossil fuel substitution is a very land-intensive process, and land is a scarce resource, the use of which should be efficient with due consideration of the interests of all stakeholders involved. It is thus desirable to ask if land resources are being allocated among these options in an optimal fashion in addressing the climate change challenge while simultaneously addressing local needs.

25. Long-lived wood products can provide significant local benefits as a result of the high prices such products command in the market, but the potential for global carbon sequestration benefits is relatively limited because the market for long-lived forest products is modest. For example, in 1991-93 the global consumption of sawnwood and wood panels from timber accounted for less than 1/5 of total

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[5] Article 3 of this Protocol sets forth the quantitative emission limitation and reduction objectives (QELROS) for Annex 1 countries for the period to 2008-2012. Paragraph 3 under Article 3 has established that net changes in GHG emissions from sources and removals by sinks shall be used by Annex I Parties to meet their QELROS commitments. It defines removals by sinks as those "resulting from direct human-induced land use change and forestry activities, limited to afforestation, reforestation and deforestation since 1990." It also defines net changes as "verifiable changes in stocks in each commitment period." (The word of greatest scientific and tactical relevance here is *verifiable*, which reflects the inherent measurement difficulties.)

global roundwood production—some 442 million cubic meters per year for sawnwood and 129 million cubic meters per year for wood panels (World Resources Institute, 1996), with a total carbon content of just 0.12 GtC per year, which is small in relation to the CO_2 emission rate from fossil fuels. In contrast, suppose that biomass grown on 500 million hectares of degraded land worldwide at an average yield of 10 tonnes per hectare per year is harvested and substituted for coal, with both coal and biomass used at the same efficiency; this substitution would avoid the emissions of 2.4 GtC per year from coal.[6]

26. This large disparity in potential post-harvest atmospheric carbon benefits underscores the importance of understanding the relative merits of sequestration versus fossil fuel substitution strategies for biomass use. Moreover, because sequestration strategies typically involve multi-decadal projects, an assessment of these alternatives should take into account not only biomass energy technologies that are commercially available but also technologies that can be developed and commercialized in the near-term future—an especially important consideration in light of the fact that commercially available biomass energy technologies are quite inefficient and the good prospects that a range of modern, energy-efficient biomass energy conversion technologies can be brought to market over the next decade (IPCC, 1996; Reddy et al., 1997, PCAST Energy R&D Panel, 1997).

Sequestration vs.Fossil Fuel Substitution

27. The relative carbon management implications of growing biomass for sequestration vs. growing biomass as a substitute for fossil fuels can be compared on a per tonne of biomass grown basis, on a per hectare basis, and on a temporal duration basis. The discussion that follows in this section is based largely on the principles set forth in Hall, Mynick, and Williams (1991a; 1991b) and various modeling exercises that reflect these principles, as set forth in Marland and Schlamadinger (1997).

28. *Relative C benefits per tonne of grown biomass.* When biomass is substituted for a fossil fuel as an energy source, the impact on the atmosphere[7] depends on both the carbon content of the fossil fuel[8] and the relative efficiencies of energy conversion. With current technologies, biomass tends to be used less efficiently than coal; in power generation, for example, current biomass power plants are about 20% efficient, compared to about 35% for coal. In this case growing a tonne of biomass for sequestration (grow-and-store approach) reduces net atmospheric CO_2 emissions 1.8 times as much as using the biomass as a coal substitute (neglecting the sequestration benefit associated with the average amount of biomass stored in the plantation inventory over the entire plant/grow/harvest cycle for the fossil fuel

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6 Assuming a biomass energy content of 20 GJ per tonne (HHV basis) and a coal emission rate of 0.025 tC per GJ.

7 In general the fossil fuel carbon displaced (in tonnes) by growing 1 tonne of biomass to substitute for fossil fuel = $(\eta_B/\eta_F)*HHV_B*CER_F$, where η_B = the efficiency of biomass energy conversion, η_F = the efficiency of fossil energy conversion, HHV_B = the higher heating value of biomass (GJ/tonne), and CER_F = the CO_2 emission rate for the fossil fuel (in tC/GJ, higher heating value basis). It is assumed here that HHV_B = 20 GJ per dry tonne, a typical value for woody biomass.

8 For example, the carbon contents of a typical coal, LPG, and natural gas, are 0.0245, 0.165, and 0.141 tonnes C/GJ, respectively, on a higher heating value basis.

substitution option).[9] The advantage of sequestration over fossil fuel substitution per tonne of biomass grown is even greater when biomass is substituting for less carbon-intensive fossil fuels that are also converted to useful energy at higher efficiency. For example, when one tonne of biomass is substituted for LPG in cooking or for natural gas in power generation, the atmospheric CO_2 emissions avoided are only 1/5 as large as amount of CO_2 removed from the atmosphere when the biomass is grown for sequestration.[10]

29. At present biomass energy conversion efficiencies are typically lower than for fossil fuel technologies. However, current biomass technologies used in combined heat and power (CHP) applications can often be more efficient than fossil energy systems that produce electricity and heat in separate facilities. The much smaller scales of the biomass energy systems that can often be sited near heat users facilitate the CHP option.

30. With future biomass energy conversion technologies, the efficiency gap between biomass and coal can be largely eliminated, [11] and the efficiency gap between biomass and other fossil fuels can be narrowed. With equal energy conversion efficiencies, the growing a tonne of biomass as a coal substitute has the same impact on the atmosphere as the growing of a tonne of biomass for sequestration purposes,

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[9] Growing 1 tonne of biomass for sequestration purposes extracts approximately 0.5 tonnes of carbon from the atmosphere.

[10] Here it is assumed that in cooking applications, biomass stoves are 15% efficient, compared to 50% for LPG, and that in power generation applications, biomass power plants are 20% efficient, compared to 53% for state-of-the-art gas turbine/steam turbine combined cycles (see Table 1).

[11] Consider first, as an example, power generation via integrated gasification combined cycle (IGCC) technologies. Coal IGCC technology is commercially available, and several biomass IGCC demonstration projects are moving ahead in various parts of the world—one of which is demonstration project in the northeast of Brazil that is being supported by the Global Environment Facility. If sulfur and moisture contents of biomass and coal were the same, the conversion efficiencies would be about the same for biomass and coal power plants of the same capacity. The very low sulfur contents of most biomass feedstocks gives an energy efficiency advantage to biomass relative to coal, because of the energy efficiency penalties associated with sulfur removal. But there can be significant energy efficiency penalties if some of the biomass must be burned to dry the feedstock, which is typically 50% moisture at the time of harvest for woody biomass. However, if the biomass is dried in the field to 30% moisture (as is often feasible), all the heat needed for biomass drying can be provided by waste heat, so that the energy conversion penalty associated with biomass drying is negligible (Hughes and Larson, 1998). There can also be scale-related energy efficiency penalties for biomass plants that tend to be smaller than coal plants. However, at the optimum scales (~ 150 MW_e) for biomass IGCC plants, capacities are sufficiently large that scale-related efficiency penalties are very small (Larson and Marrison, 1997). Moreover, the next generation of biomass power-generating technologies (gasification/solid oxide fuel cell/gas turbine hybrid cycles), which might become commercially available in the 2005-2010 time frame, will make it possible to achieve cost-effectively high efficiencies (40-45%, HHV basis) at power plant scales of just hundreds of kilowatts (Kartha et al., 1997).

Secondly, consider synthetic fuels such as hydrogen (the preferred fuel for low-temperature fuel cell, such as those that might be used one day in fuel cell vehicles)that might be derived from both coal and biomass via gasification processes that produce synthesis gas. Making synthesis gas from coal requires oxygen-blown gasifiers, for which the energy penalties associated with the production of oxygen are significant; but synthesis gas can be made from biomass via gasification in steam using indirectly heated gasifiers, because biomass is much more reactive than coal. As a result the efficiency of a relatively small-scale biomass-to-hydrogen plant would be about the same as a much larger coal-to-hydrogen plant (Williams et al., 1995).

neglecting the sequestration benefit associated with the average amount of biomass stored in the plantation inventory over the entire plant/grow/harvest cycle for the fossil fuel substitution option. (If this sequestration benefit is taken into account, the reduction in atmospheric CO_2 would be greater for the coal substitution option when efficiencies are equal.)

31. *Relative C benefits per hectare of biomass plantations.* Species choice is another key parameter that should be considered in comparing biomass for fossil energy substitution with biomass for sequestration purposes.

32. If biomass is grown with the primary purpose of sequestering carbon (grow-and-store approach), species will be chosen so as to maximize the total amount of carbon that can be sequestered on a hectare of land (C per hectare); typically this algorithm implies the choice of a slow-growing species with a long maturation period. But if instead biomass is grown primarily as a fossil fuel substitute, fast-growing species (species with high growth rates, measured in tonnes of biomass per hectare per year), which will typically lead to a several-fold net greater carbon benefit per hectare per year.

33. Moreover, the sequestering option usually involves the growing of trees, whereas the fossil fuel substitution option can involve the growing of perennial grasses or annual energy crops as well as trees. High yields can be realized with suitable perennial grasses and annual energy crops, even though their sequestration potential tends to be much less than for trees. This possibility makes it possible to get significant climate-change benefits from biomass even in areas that are not well-suited for the growing of trees.

34. *Relative C benefits over time.* Sequestration strategies that do not involve harvesting biomass (grow-and-store approach) are constrained by the cessation of net CO_2 extraction from the atmosphere by the forest considered as a system, when the forest reaches maturity. Sequestration strategies that involve harvesting biomass (perpetual-rotation approach) are also limited to a maximum sequestration capacity equal to about half the sequestration capacity with the grow-and-store approach (see footnote 3). In contrast, the growing of biomass for energy in perpetual rotation as a fossil fuel substitute could be continued indefinitely, with continually increasing atmospheric carbon benefits.

Other Considerations Relating To The Growing of Biomass as a Fossil Fuel Substitute

35. Emerging energy-efficient biomass conversion technologies offer the potential that biomass will be able to compete with coal in many situations [see Larson and Williams (1996) and Kartha *et al*. (1997) for power generation options and Williams et al. (1995) for synfuel options.] Energy-efficient biomass conversion technologies that can compete with coal would make possible high biomass feedstock prices that will make the intensive management of biomass energy crops profitable for farmers. In addition, the commercial availability of small-scale biomass power technologies that can compete with coal would promote rural industrialization (*and thus rural job generation*) by making low-cost electricity available in rural areas (Reddy *et al*., 1997).

36. Moreover, recent favorable experience with the growing of trees for commercial applications on small land plots in agroforestry configurations indicates that large-scale plantations are not necessary to make bioenergy strategies economically interesting, and that small farmers could benefit from these innovations in biomass energy conversion technology (Larson et al., 1994).

37. At present, intensively managed biomass crops are mainly monocultures, largely because the markets being served require very specific products (e.g., a food product or pulp/paper). The embryonic activity of growing biomass for energy purposes is also focused today on monocultures largely because the production technology is adapted from agricultural or forest product technology that is monoculture based. If biomass is grown for energy purposes based on thermochemical conversion processes (which are likely to dominate at least most biomass electricity markets), monocultural production strategies are not necessary, although biomass production management might well be more complicated with mixed species. If polycultural strategies offer significant prospective environmental or economic benefits (e.g., reduced risk of catastrophic crop loss from disease) and if they could be readily managed, their development should be considered.

Major Issues: Carbon Management by Fuels Decarbonization/CO_2 Sequestration

38. The analysis of carbon sequestration via fossil fuel decarbonization with sequestration of the separated CO_2 begins with a literature review, followed by a section providing a rationale for the scientific and technical focus chosen by STAP for the Brainstorming Session, followed by a discussion of the prospects for CO_2 sequestration associated with both enhanced oil recovery and enhanced coal bed methane recovery, and by STAP findings and recommendations.

Background on Fuels Decarbonization/CO_2 Sequestration

39. Growing trees to extract CO_2 from the atmosphere is not the only way to reduce the buildup of CO_2 in the atmosphere from the combustion of fossil fuels. Another approach is to recover energy from fossil fuels while preventing the release of CO_2 to the atmosphere by means of appropriate long-term storage.

40. The discussion of this approach to carbon sequestration begins with a review of the history of the concept. This is followed by a discussion of how widespread adoption of the fuel decarbonization/CO_2 sequestration strategy could be facilitated by the development of fuel cells, which would put a high market value on hydrogen (fully decarbonized fuel), a review of H_2 production technologies, a section discussing the importance of finding ways to give CO_2 a high value as a near-term strategy for expanding H_2 production while awaiting the commercial arrival of fuel cell technologies, and finally a review of the prospects for CO_2 sequestration.

41. The initial version of the fossil fuel decarbonization/CO_2 sequestration concept, advanced by Marchetti (1997), was to recover CO_2 from the stack gases of fossil fuel power plants, compress it, and pipe it to the deep ocean for disposal.

42. This “flue gas decarbonization” approach to carbon sequestration is technically feasible but costly, largely because of the expenses associated with separation of the CO_2 from flue gases (in which the concentration of CO_2 is only 8-15 percent); once the CO_2 is separated out, the incremental cost of isolating the recovered CO_2 from the atmosphere can often be relatively modest (Engelenburg and Blok, 1993; Hendriks, 1994).

43. A much more promising approach is "fuel gas decarbonization," which involves the production of hydrogen or a hydrogen-rich fuel from a carbon-rich fuel, in the process of which a stream of essentially pure CO_2 is separated out as a byproduct. Pioneering work on fuel gas decarbonization has been carried out at the University of Utrecht (Blok et al., 1989; Hendriks, 1994) and at Shell in The

Hague (Burgt et al., 1992) in conjunction with the production of electricity via coal IGCC power plants. The energy and cost penalties for fuel decarbonization and sequestration of the separated CO_2 with this approach are far less than for various flue gas decarbonization schemes. However, the electricity produced this way would nevertheless be about 30-50 percent more costly than with a conventional coal IGCC power plant (Hendriks, 1994; Socolow, 1997), simply because there are no direct economic benefits (only environmental benefits) arising from fuel gas decarbonization.

44. *Giving hydrogen a high market value*. One way to compensate for the cost penalty associated with CO_2 separation and sequestration is to find technologies that give hydrogen a high market value. The fuel cell is a device that converts the chemical energy of fuel directly into electricity without first burning the fuel to produce heat (Kartha and Grimes, 1994). Electricity is produced at high efficiency with little or no pollutant emissions—without the need for end-of-pipe emission control technologies. All practical fuel cells are fueled by H_2.

45. How soon will fuel cells begin to make substantial inroads into energy markets? At present only the phosphoric acid fuel cell is being marketed commercially—largely for stationary CHP markets in commercial and residential apartment buildings. Power densities achievable with this technology are too low for it to be used in cars, and high costs might limit its overall market potential.

46. The technology currently getting the most attention is the proton exchange membrane (PEM) fuel cell, which operates at a low temperature (~ 80 ^oC) and offers both a high power density (suitable for use in cars) and a prospective cost in mass production that might enable the PEM fuel cell electric vehicle (FCEV) to compete with the internal combustion engine vehicle (ICEV) in automotive applications. Over the next two or three years this technology is expected to be commercially available for both transit bus and buildings CHP applications.

47. Activities relating to PEM FCEV development are expanding rapidly (see Box); most major auto manufacturers are developing fuel cell cars. Costs are currently high, and many engineering challenges remain to be resolved before the realization of cost targets that would enable FCEVs to compete with ICEVs, but many companies are evolving strategies to reach such goals. Current costs are not associated with *intrinsically* high costs for materials or manufacturing techniques; rather they are high largely because most fuel cells purchased today are constructed, almost by hand, as "one-off" demonstrators. For successful demonstrations, developers have relied on tried-and-true designs and materials. Now that the PEM fuel cell is technically proven, there is considerable ongoing activity to push the envelope in improving performance and reducing materials costs. Moreover, manufacturing fuel cells in the high volumes associated with automotive applications is expected to drive costs down several-fold.

48. The fuel delivered to the fuel cell can be either H_2 or an energy carrier such as a hydrocarbon or alcohol fuel that is processed at the point of use into a H_2-rich gas that the fuel cell can use. Because a H_2 infrastructure does not yet exist, PEM fuel cells will probably be introduced using conventional hydrocarbon fuels or other easily transportable and storable liquid fuels that are converted into a H_2-rich gas at the point of use. For example, most car manufacturers engaged in the development of fuel cells for cars are developing onboard fuel processors for use with either gasoline or methanol; and PEM fuel cell systems being developed for CHP markets are being designed for use with natural gas fuel processors. For fuel cell vehicle applications these are likely to be only transitional strategies, however, because the direct H_2 FCEV will probably be preferable to any liquid fueled FCEV with an onboard fuel processor—because of the higher first cost, higher maintenance cost, and lower fuel economy of such vehicles compared to the H_2 FCEV (Ogden et al., 1997). The expected lower costs for H_2 FCEVs would lead to an internally generated automotive market pressure to shift to H_2, as soon as a H_2 infrastructure can be put into place. (It remains to be shown whether the same kind of market dynamic is to be expected for CHP applications of PEM fuel cells.)

49. *Hydrogen production technologies.* Although H_2 is not used as an energy carrier, it is a common chemical feedstock, used mainly in the chemical industry (mostly for making ammonia) and in petroleum refining; about 1% of U.S. primary energy is converted to H_2 for such applications; there are about 1200 km of H_2 pipelines in the world—mainly in the United State, Germany, the Netherlands, and Great Britain. The technology for H_2 manufacture is well-established. The dominant commercial technology is via steam reforming of natural gas; H_2 can also be made via gasification of coal or any other carbonaceous feedstock (Williams et al., 1995) or via electrolysis of water using renewable or other power sources. Until fossil fuel prices are much higher than at present, electrolytic H_2 will be much more costly than fossil fuel-derived H_2 (Williams, 1998a), except where low-cost off-peak hydroelectric power is available—supplies of which are very limited.

Box: Progress in Developing Motor Vehicles Powered by PEM Fuel Cells

1993	Clinton Administration announces Partnership for a New Generation of Vehicles (PNGV) with U.S. auto-makers, aimed at introducing by 2004 production-ready prototypes of "cars of the future" that will be three times as fuel efficient as today's cars but will maintain size and performance and cost no more to own and drive
1993	Ballard Power Systems of Vancouver (Canada) introduces proof-of-concept H_2 PEM fuel cell bus (with compressed H_2 storage)
1995	Daimler-Benz introduces NECAR I, a H_2 PEM fuel cell test van (with Ballard fuel cell, compressed H_2 storage)
1995	Ballard demonstrates H_2 PEM fuel cell bus suitable for commercial use (with compressed H_2 storage)
1995	Mazda demonstrates a H_2 PEM fuel cell golf cart (with compressed H_2 storage)
1996	Daimler-Benz introduces NEC AR II, a prototype passenger van equipped with a compact H_2–powered fuel cell system developed jointly with Ballard (with compressed H_2 storage)
1996	Toyota introduces prototype PEM H_2 fuel cell car (with metal hydride storage)
1996-97	Ballard sells several H_2 PEM fuel cell buses to cities of Chicago and Vancouver
1997	Ballard and Daimler-Benz form joint venture with $320 million planned investment to develop PEM fuel cell cars, with commercialization targeted for 2005 timeframe
1997	Daimler-Benz introduces NECAR III, a prototype small fuel cell passenger car [with onboard methanol (MeOH) reformer]
1997	Toyota introduces prototype fuel cell passenger car (with onboard MeOH reformer)
1997	Ford joins Daimler-Benz & Ballard in joint venture to commercialize fuel cell cars, bringing planned pooled investment total to $420 million; fuel cell power trains for cars targeted for commercialization in 2004
1998	GM announces it will develop production-ready prototype fuel cell cars by 2004
1998	Chrysler announces it will develop production-ready prototype fuel cell cars by 2004 (with onboard gasoline partial oxidation systems)
1998	Mobil Corporation and Ford Motor Company form a strategic alliance to develop a hydrocarbon fuel processor for use in fuel cell vehicles
1998	Mazda joins automotive fuel cell alliance with Ballard, Daimler-Benz, and Ford

50. When H_2 is made from a carbonaceous feedstock, an intermediate product is a gaseous mixture consisting mainly of CO_2 and H_2, from which the H_2 must be separated by a chemical or physical process. Relatively minor process changes can be made to recover the CO_2 as a relatively pure stream instead of venting it to the atmosphere. The recovered CO_2 can then be compressed and transported by pipeline as a dense supercritical fluid to where it can be stored in isolation from the atmosphere. If the H_2 is produced in a large, centralized production facility, the cost of separating and sequestering the CO_2 would be significantly less than the cost penalty associated with CO_2 recovery and sequestration for a natural gas or coal electric plant (Kaarstad and Audus, 1997).

51. *Giving CO_2 a high market value.* If, as the above analysis suggests, there are good prospects that H_2 could become a major energy carrier in serving fuel cell markets in the longer term, a major challenge will be to find ways begin a transition to begin a transition to H_2 now, so that the H_2 infrastructure developmental challenges will not be so formidable as they appear to be today. One way to begin a transition to hydrogen is to find early markets that put a high value on the CO_2 generated as a byproduct of H_2 production—a strategy explored in the STAP brainstorming session on fuels decarbonization and CO_2 sequestration. Specifically, the brainstorming session focussed on use of CO_2 for enhanced oil recovery and for enhanced coal bed methane recovery in conjunction with sequestration of the injected CO_2 in the oil field and coal bed. These activities can be helpful both in expanding H_2 production in the near term, before low-temperature fuel cells are launched in the market, and they can provide valuable initial experience with CO_2 sequestration that can pave the way for using fossil fuels at large scales with low emissions of CO_2 (Williams, 1998a). Before discussing the specifics of these technologies, however, the prospects for CO_2 sequestration with these technologies should be placed in the context of the general prospects for CO_2 sequestration.

52. *The prospects for CO_2 sequestration*. Although disposal in the deep oceans has been the most-discussed option for CO_2 disposal, much more research is needed to better understand the security of various ocean disposal schemes and their environmental impacts (Turkenburg, 1992). In recent years increasing attention has been given to geological (underground) storage of CO_2: in depleted oil and natural gas fields (including storage in conjunction with enhanced oil and gas recovery), in deep coal beds [in conjunction with coal bed methane (CBM) recovery], and in deep saline aquifers.

53. Sequestration in depleted oil and gas fields is generally thought to be a secure option if the original reservoir pressure is not exceeded. One estimate of the prospective sequestering capacity of oil and gas reservoirs associated with past production plus proven reserves plus estimated undiscovered conventional resources (most of which will be used up during the next century) is about 100 GtC for oil fields and about 400 GtC for natural gas fields (Hendriks, 1994); other estimates of the oil and gas field sequestering capacity are as low as 40 GtC for depleted oil fields plus 20 GtC associated with enhanced oil recovery (EOR) plus 90 GtC for depleted natural gas fields (IPCC, 1996).

54. There is a considerable range of uncertainty in the global sequestering capacity of depleted oil and gas fields and the security of such sequestration. More research and field testing are needed to refine sequestering capacity estimates, because reservoir properties vary greatly in their suitability for storage, and because the recovery of oil and gas from these reservoirs may have altered the formations and affected reservoir integrity. Much of the prospective sequestering capacity will not be available until these fields are nearly depleted of oil and gas.

55. CO_2 injection for EOR is established technology. When CO_2 is injected into an oil reservoir it is above its critical point and has a density between ½ and ¾ of the density of water. The CO_2 is miscible with the lighter fractions of the oil and the oil/CO_2 mixture is less dense and less viscous than the original oil, which facilitates oil recovery.

56. Worldwide CO_2 injection is used for EOR in over 70 oil fields, mostly in the United States, where CO_2 flooding accounts for about 2% of production. There, between 2% and 10% of the remaining 300 billion barrels of oil resources that cannot be recovered by water flooding or primary oil production techniques are prospectively recoverable via EOR (Blunt et al., 1993). Although EOR is not carried out in the North Sea, the conditions for EOR are typically more favorable there than in the United States: the crudes are lighter, and the reservoirs have higher permeabilities and are more homogenous; as a result typically less CO_2 needs to be provided to extract a barrel of oil. For example, a detailed modeling of the Forties field in the North Sea indicates a CO_2 injection requirement (called "displacement efficiency" in Table 1) of 0.15 tonnes per barrel, compared to requirements of 0.2 to 0.6 tonnes per barrel in the United States (Fayers et al., 1981). At a recovery efficiency of 0.15 tonnes of CO_2 per barrel, the value of CO_2 for EOR when the oil price is $20 per barrel is more than $70 per tonne of CO_2 ($265 per tonne of carbon—see Table 1)—an extraordinarily high value [12] in relation to prospective CO_2 costs, even though it accounts for only about half of the oil price. Estimates of the EOR potential of the North Sea over the next decade or so range from 0.5 to 2.0 billion barrels (Blunt et al., 1993); for comparison, the total amount of oil produced by Norway and the United Kingdom in 1996 (mostly from North Sea fields) was 2.1 billion barrels.

57. The prospects for CO_2 sequestration in conjunction with CBM recovery arise as a result of the recent finding that methane can be recovered efficiently from deep coal beds by injecting CO_2 into the coal bed. Deep coals are both sources and sinks for methane. Methane is generated in coals during the coalification process. Coal beds can also trap methane in the pore spaces of the coal. (Coals are very porous solids, containing 20 to 200 m^2 of surface area in these pore spaces, per gram of coal.). Because CO_2 is typically twice as adsorbing on coal as is methane, injecting CO_2 into coal leads to the release of the methane, leaving the CO_2 behind in the coal. Of course, CO_2 sequestration in the coal bed would prevent subsequent mining of the coal. However, much of the world's coal resources are in beds of deep or otherwise unminable coal, for which coal mining is uneconomic; many such coal beds might prove to be attractive for CBM recovery and CO_2 sequestration. [For example, 90% of the nearly six trillion tonnes of U.S. coal resources deposited at depths less than 1800 m is unminable with current technology, either because the coal is too deep, the seams are too thin, or mining would be unsafe (Byrer and Guthrie, 1998).] If 1/3 of the estimated global CBM resources could be recovered by CO_2 injection, the global sequestering capacity would be 30 to 90 GtC. [13]

58. The potential for sequestration in conjunction with EOR and CBM recovery can be compared with the potential for carbon sequestration via the growing of trees. Nilsson and Schopfhauser (1995) have

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[12] When the oil price is $20 per barrel, the value V ($/t) of CO_2 as a function of the displacement efficiency (DE, in tonnes of CO_2 per barrel of oil) is given by [see Table 1 and Blunt et al. (1993)]
$V = 7.875 * DE^{-1.17}$, so that V = $72 per tonne of CO_2 when DE = 0.15 tonnes of CO_2 per barrel of oil.

[13] Global CBM resources are estimated to be 85 to 260 trillion Nm^3 (Rice et al., 1993). If all of these CBM resources could be recovered by CO_2 injection and if 2 CO_2 molecules were sequestered for each methane molecule recovered, the global sequestering capacity for CO_2 would be 170 to 520 trillion Nm^3 or 90 to 280 GtC.

estimated the global potential for carbon storage via sequestration to be about 70 GtC over a 60 year period on 345 million hectares of land. Thus the potential for sequestration via EOR plus CBM recovery is comparable to the potential for sequestration via growing trees.

59. The potential for CO_2 sequestration in deep saline aquifers is probably far greater than for all other underground reservoirs combined. Aquifers are much more widely available than oil or gas fields or CBM reservoirs; they underlie most sedimentary basins, which account for nearly half of the land area of the inhabited continents. However, without the benefit of credits for enhanced resource recovery, storage in aquifers will generally be somewhat more costly than for EOR or CBM recovery.

60. To achieve high storage densities, CO_2 should be stored at supercritical pressures (i.e., at pressures in excess of 74 bar). Since the normal hydrostatic geo-pressure gradient is about 100 bar per km, typically depths of about 800 m or more are desirable for sequestering CO_2 in aquifers. The aquifers at such depths are typically saline and not connected to the much shallower "sweet water" aquifers used by people.

61. If aquifer storage must be restricted to closed aquifers with structural traps, the potential global sequestering capacity is relatively modest—some 50 GtC (Hendriks, 1994), equivalent to less than 10 years of global CO_2 production from fossil fuel burning at the current rate. However, if structural traps are not required for secure storage, the storage capacity of aquifers might be huge – some 14,000 GtC (Hendriks, 1994), equivalent to more than 2,000 years of CO_2 emissions from fossil fuel burning at the current global rate. A growing body of knowledge indicates that many large horizontal open aquifers might provide secure storage if the CO_2 is injected far from the reservoir boundaries (Holloway, 1996). The notion that large horizontal aquifers can provide secure sequestration is a relatively new idea that has led to an increase in confidence that long-term sequestration of a significant fraction of the next several centuries of global CO_2 production from human activities might be feasible (Socolow, 1997).

Table 1. **Maximum Permissible Cost Of CO_2 For Enhanced Oil Recovery**[a,b] (*\$ per tonne of CO_2*)

Oil Price (*$ per barrel*)	10	20	30
Displacement Efficiency[c] (*tonnes CO_2 / barrel of oil*)			
0.16	30.6	66.5	102.6
0.32	12.7	30.7	51.6
0.53	5.5	16.3	27.0

[a] Source: (Blunt et al., 1993).

[b] For a 10% discount rate.

[c] 1 tonne of CO_2 = 18.9 Mscf.

62. Good estimates of the aquifer sequestration potential require considerable data gathering for and detailed modeling of specific aquifers. A recent major study carried out under the Joule II Non-Nuclear Energy Research Programme of the European Commission (Holloway, 1996) did a considerable amount of such modeling in an assessment of underground CO_2 storage reservoirs in Europe. This study estimated that the underground storage capacity accessible to the European Union plus Norway (mostly deep aquifers under the North Sea) would be adequate to store more than 200 GtC—storage capacity equivalent to 250 years of CO_2 emissions from all of OECD Europe at the current emission rate.

63. Experience with aquifer disposal will be provided by two projects involving injection into nearby aquifers of CO_2 separated from natural gas recovered from CO_2-rich gas reservoirs. One is a Statoil project begun in 1996 to recover 1 million tonnes of CO_2 per year from the Sleipner Vest offshore natural gas field in Norway (Kaarstad, 1992). The second, which will commence in about a decade, will involve the recovery of over 100 million tonnes per year (equivalent to about 0.5 percent of total global emissions from fossil fuel burning) from the Natuna natural gas field in the South China Sea (71% of the reservoir gas is CO_2) (IEA, 1996).

Focus of the Brainstorming Session in Dealing with Scientific and Technical Issues

64. Successful commercial development of fuel cells, especially low temperature fuel cells such as PEM fuel cells, could make feasible the widespread use of fossil fuels in a severely greenhouse-gas-emissions-constrained world, because these fuel cells put a high market value of H_2 and because H_2 derived from fossil fuels will be the least costly source of H_2, even if the separated CO_2 is sequestered, and the costs of sequestration are taken into account (Williams, 1998a; 1998b).

65. If H_2 fuel cells are to come into wide use, however, the challenge of providing the needed H_2 infrastructure to support fuel cells when they become commercially available must be addressed.

66. An important characteristic of systems that produce H_2 from fossil fuels will be low-cost byproduct CO_2. This fact suggests that a promising near-term strategy for partially addressing this "chicken-and-egg" problem that would also offer low-cost, near-term climate change mitigation benefits involves making H_2 from fossil fuels and using the low-cost byproduct CO_2 for enhanced resource recovery. The Brainstorming Session focused on two opportunities for enhanced resource recovery.

67. One, which is relevant for countries with oil and natural gas resources, involves making a H_2–rich gas from natural gas, using the byproduct separated CO_2 for EOR and CO_2 sequestration and burning the H_2-rich gas in a combined cycle power plant to make electricity.

68. The other, which is relevant to countries that are richly endowed with coal and CBM resources, involves making H_2 from coal for use in the ammonia industry, using the byproduct separated CO_2 for methane recovery from deep beds of unminable coal, and using the recovered CBM either for producing more H_2 for use in ammonia manufacture or for power generation in a combined cycle plant.

69. In April 1998 Norway's Norsk Hydro announced (see footnote 2)[14] tentative plans[15] to build two 700 MW_e combined cycle power plants at an estimated installed cost of $770 to $950 per kWe that would burn a H_2–rich gas derived from natural gas.[16] This system would consume 2 billion Nm^3 of natural gas per year, corresponding to an overall efficiency of converting natural gas into electricity of 44% (HHV basis) or 49% (LHV basis).[17] The Norsk Hydro announcement indicated that the CO_2 generated as a byproduct would probably be used for EOR in the Grane oil field offshore in the North Sea. For this system estimated CO_2 emissions would be reduced up to 90% per kWh compared to CO_2 emissions from a conventional natural gas combined cycle power plant.

70. STAP invited Dr. Werner Soyez (Product Technical Manager of Hydro Agri Europe in Brussels) to the Brainstorming Session to discuss these plans further, so that STAP could better advise the GEF about the technology involved. In his presentation at the Brainstorming Session Dr. Soyez provided further details regarding this project, including some mass balances relating to enhanced oil recovery that made it possible for STAP to carry out calculations relating to the proposed project.

71. After the Brainstorming Session the IEA Greenhouse Gas R&D Programme released a report prepared by Foster Wheeler (FW) that presented economic analyses for several alternative systems that are very similar to the system under consideration at Norsk Hydro. The FW results are presented in Table 2.

72. The H_2–burning system designed by FW[18] would have essentially the same performance as the proposed Norsk Hydro plant [an efficiency of 45% (HHV basis) or 49% (LHV), compared to 53% (HHV) or 59% (LHV) for a conventional natural gas combined cycle plant] and CO_2 emissions per kWh that are only 16% of those for the conventional combined cycle power plant. The installed capital costs for the FW-designed plants are in the range $710 to $970 per kW_e, very similar to the costs projected by Norsk Hydro. The cost of electricity for the H_2 combined cycle (including all the costs associated with producing H_2 and compressing the byproduct stream of relatively pure CO_2 to 90 bar)

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14 The Norsk Hydro announcement indicated an annual electricity production rate of 11 TWh per year for an installed cost of $1.07 billion to $1.33 billion. Here a 90% average capacity factor is assumed.

15 The final decision on the project will be made in March/April 1999.

16 The natural gas would first be reacted with steam in a "steam reformer" to produce a gaseous mixture consisting mainly of CO and H_2. This gaseous mixture would then be cooled and reacted with more steam in water gas shift reactors, in which the CO and steam react to form CO_2 and H_2. A solvent is then used to scrub most of the CO_2 from the gaseous mixture exiting the low temperature water gas shift reactor, and the H_2-rich product is delivered to the gas turbine combustor, where it is burned to provide electricity in a gas turbine/steam turbine power plant.

17 It is assumed that the natural gas is made up of 83.9% methane, 9.2% ethane, 3.3% propane, 1.4% butane, and 2.2% inerts.

18 Foster Wheeler considered several different schemes for H_2 production. The variant shown here is the one for which the estimated system cost is the least. It involves catalytic partial oxidation in air instead of steam reforming. As a result the gaseous mixture delivered to the gas turbine combustor (53% H_2 and 43% N_2) contains a considerable amount of nitrogen from the air used as an oxidant in the catalytic partial oxidation unit.

would be 2.7 to 3.4 cents per kWh, up 35-43% from the cost of electricity from a conventional combined cycle power plant.

73. This cost of electricity for the H_2 combined cycle plant, developed by FW and presented in Table 2, does not take into account credit for the value of the byproduct CO_2 in enhanced oil recovery, nor does it include costs for delivering the CO_2 to the EOR site. Here it is assumed that each of the proposed Norsk Hydro power plants is near the North Sea shore and that from each plant a 250-km CO_2 pipeline is installed (mostly offshore) to deliver the CO_2 to the EOR site. The cost of the pipeline brings the total cost of electricity, including the cost of this pipeline, to a level 44%-54% higher than for a conventional combined cycle (see Table 2)—again taking no credit for the value of the CO_2 in EOR.

74. Allocating instead all the extra costs not to electricity but to the CO_2 delivered to the EOR site would lead to a delivered CO_2 cost of about $31 per tonne of CO_2 (see Table 2). This cost must be compared to the value of this CO_2 in EOR. According to the Norsk Hydro press release (see footnote 2) CO_2 would be injected into the Grane field at an average rate of 4 million tonnes per year. According to Dr. Soyez, the expected oil recovery over the first 10 years would average 10 million barrels per year, so that the CO_2 requirement (displacement efficiency in Table 1) would be 0.40 tonnes of CO_2 per barrel of oil. Assuming an oil price of $20 per barrel the CO_2 would be worth $23 per tonne, according to the model presented in Table 1. Taking credit for CO_2 at this value would bring the net electricity cost to 2.3 to 2.8 cents per kWh, some 11-14% above the cost of electricity from a conventional combined cycle power plant—which is indeed very close to the cost of electricity from the conventional natural gas combined cycle plant. In light of the prospect that the amount of CO_2 required to produce a barrel of oil via EOR in some North Sea oil fields can be as low as 0.15 tonnes per barrel (Fayers, 1981) and the much higher value of CO_2 for such fields (see Table 1), it is not unrealistic to expect that for some North Sea projects of this type the cost of electricity would be even less than for a conventional natural gas-fired combined cycle power plant.

75. The EOR technology and the H_2 production technology required for the Norsk Hydro proposed plant and the FW plant designs are commercially established technologies. According to the FW report, some developmental work is needed on the gas turbine to accommodate firing with hydrogen, but no technical breakthroughs are required.

Table 2. **Performance and Costs for Alternative Combined Cycle Power Plants** [a]				
	Conventional Gas Turbine/Steam Turbine Combined Cycle		H_2-Burning Combined Cycle Integrated with H_2 Production from Natural Gas Using Catalytic Partial Oxidation in Air	
	High Cost Estimate	Low Cost Estimate	High Cost Estimate	Low Cost Estimate
Installed Capacity (MW_e)	485	485	489	489
Installed Capital Cost ($/kW $_e$)	632	400	972	710
Efficiency, Natural Gas to Electricity (%, HHV basis)	53.2	53.2	44.9	44.9
CO_2 Emission Rate (gr CO_2/kWh)	350	350	57	57
CO_2 Disposal Rate (tonnes of $_{CO2}$/hour)	-	-	174.5	174.5
Busbar Cost (US cents/kWh)				
Capital	1.090	0.689	1.634	1.234
O&M	0.189	0.130	0.300	0.240
Fuel	1.209	1.209	1.432	1.432
Total	2.488	2.028	3.366	2.906
Cost Penalty for CO_2 Separation, cents/kWh	-	-	0.878	0.878
CO_2 Separation Cost Penalty, $/tonne of Separated $_{CO2}$	-	-	24.6	24.6
Extra Cost Penalty for Transporting CO_2 250 km, $/t [b]	-	-	6.3	6.3
Cost Penalty for Transporting CO_2 250 km, cents/kWh			0.224	0.224
Total Electricity Cost (incl. $_{CO2}$ Transport), cents/kWh	2.488	2.028	3.590	3.130
Total Cost for Separating and Transporting CO_2, $/t	-	-	30.9	30.9

[a] All but the estimate for the cost for transporting CO_2 100 km is from a report prepared by Foster Wheeler for the IEA Greenhouse Gas R&D Programme (Foster Wheeler, 1998). Costs presented here are for a 10% discount rate, a 25-year plant lifetime, a 90% capacity factor, and a natural gas price of $1.79/GJ on a higher heating value (HHV) basis. Costs and energy penalties associated with CO_2 disposal in this study include those for compressing the CO_2 to 90 bar for pipeline transmission.

[b] From Skovholt (1993), the diameter D (in inches) f or an offshore pipeline for CO_2 transport as a function of flow rate F (in million tonnes per year) is given by $D = 8.167*F^{0.382}$ = 10.6 inches for a power plant generating 5.5 TWh/y of electricity from natural gas-derived H_2 (the capacity of each of the two plants under consideration by Norsk Hydro), for each of which the annual flow rate is 2 million tonnes per year. Also from Skovholt (1993) he delivery cost C (in $/t) for a 250-km offshore pipeline as a function of pipe diameter D (in inches) is $C = 197.8*D^{-1.457}$ = $6.3/tonne for D = 10.6 inches.

H_2 Production from Coal and CBM, Using Byproduct CO_2 for Enhanced Methane Recovery and Sequestering the CO_2 in the Coal Bed

76. In the final presentation at the workshop Williams discussed how countries rich in coal and coal-bed methane (CBM) resources that now make H_2 from coal could use the low-cost byproduct CO_2 to stimulate the production of methane from deep beds of unminable coal while leaving the CO_2 sequestered in the coal bed. He illustrated the prospects for this strategy by showing how it might be developed in China.

77. China is well-positioned to launch an industry that produces CBM via CO_2 injection. It has large CBM resources and produces large quantities of low-cost CO_2 as a byproduct of making H_2 from coal as an intermediate product in ammonia (NH_3) manufacture. Because of the scarcity of its resources of conventional natural gas (the feedstock from which most of the world's NH_3 supplies are derived), most of the NH_3 China produces is derived from coal. Moreover, China is building up a capacity to make fertilizer from coal using modern gasification technology. China has in operation, under construction, or on order, 25-30 modern, oxygen-blown gasifiers; many are for gasifying coal and nearly all are for chemical process applications—mostly for NH_3 production. Chinese interest in such technology arises because nitrogen fertilizer demand is growing and much of the existing coal-based NH_3 production involves small, inefficient, and polluting plants, many of which are likely to be replaced with larger, cleaner, and more cost-competitive plants. The modern coal gasification technology now being introduced could be used to make H_2 for fuel cell applications when fuel cells are established in China's markets.

78. When NH_3 is produced from coal, the byproduct CO_2 generation rate is about one kmol of CO_2 per kmol of NH_3. The CO_2 potentially available for CBM recovery depends on the fertilizer produced. If the desired product is ammonium nitrate (NH_4NO_3), all the CO_2 is available. If instead the product is urea (NH_2CONH_2), about half the CO_2 is needed for urea manufacture. In either case excess CO_2 could be used for stimulating CH_4 recovery from deep beds of unminable coal, if such beds were located nearby. China should consider locating near prospective CBM recovery sites new plants for making NH_3 from coal and using the low-cost byproduct CO_2 for stimulating the production of CBM.

79. Williams presented the results of modeling CBM recovery and use in conjunction with NH_3 manufacture from coal (Williams, 1998c). For this modeling exercise it was assumed that NH_3 plants are located near sites with deep unminable coal deposits containing CBM, so that byproduct CO_2 can be used for stimulating CBM recovery, with sequestering of the injected CO_2 in the coal bed. Two alternative CBM uses were considered: (i) Case I: CBM is used to produce additional H_2 (thereby providing more excess CO_2 for use in stimulating more CBM recovery) and thus more NH_3; (ii) Case II: CBM is used to produce electricity in a gas turbine/steam turbine combined cycle power plant

80. He showed that when the CBM is used to make extra H_2: (*i*) the coal/CBM system would generate 1.2 to 1.8 times as much H_2 from a tonne of coal as a system for making H_2 from coal only (with modern coal gasifiers), (*ii*) the extra H_2 produced from the recovered CBM would cost 2/3 to 4/5 as much as H_2 from coal, and (*iii*) the CO_2 emissions from the system producing H_2 from coal plus CBM would be 1/6 to ½ of those for making H_2 from coal only, with venting of the excess CO_2. Alternatively, if the CBM is used to make electricity, the electricity would probably be less costly than electricity produced from coal in a pulverized coal plant with flue gas desulfurization, and the lifecycle CO_2 emissions for

the system of producing H_2 from coal plus electricity from CBM would be ¼ to ½ of the emissions from a system based on coal only that produces the same quantities of H_2 and electricity.

81. Williams concluded his presentation by showing such technology, introduced in the near term to produce NH_3 for fertilizer applications, might subsequently be used to support a H_2 fuel cell-based transportation system. For passenger transportation, such a system could be made up of some mix of buses, small (2- and 3-wheeled) vehicles, and cars powered by H_2 fuel cells. Such a system would be characterized by zero local air pollutant emissions and very low lifecycle emissions. Moreover, although the cost per GJ of the H_2 delivered to the consumer would be perhaps twice the cost of gasoline per GJ, the cost per km of travel would typically be no more than for a gasoline-powered internal combustion engine vehicle of comparable performance, because the fuel cell vehicle would be more than twice as energy-efficient. Finally, CBM resources would be adequate to support over the long term very high levels of transportation services based on coal/CBM-derived H_2.

82. Because China presently has very little HC fuel infrastructures in place for transportation and because its domestic oil resources are limited whereas its coal and CBM resources are abundant, it has the opportunity to “leapfrog” directly to H_2 fuel cell technology in transportation, obviating the need for the costly HC-fueled fuel cell transition technology that is being considered for launching fuel cells in transportation markets in some industrialized countries.

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Appendix: Program for STAP Brainstorming Session on Carbon Sequestration
16 June 1998, Washington, DC

8:30	Opening remarks (Pier Vellinga, STAP)
8:45	Short Overview of Two Approaches to Carbon Sequestration (Robert Williams, STAP)

Biomass Session

9:00	Growing of biomass on degraded lands: an Indian case study (Jyoti Parikh, STAP)
10:00	Forests for Carbon Sequestration or Fossil Fuel Substitution? (Greg Marland, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA)
10:30	Discussion
12:00	Summarizing Statement (Williams)
12:30	Lunch

Fuels Decarbonization/CO_2 Sequestration Session

14:00	Norwegian Activities Relating to Fossil Fuel Decarbonization and CO_2 Sequestration (Werner Soyez, Hydro Agri Europe, Brussels, Belgium)
14:45	CO_2 Sequestration in Conjunction with Coal Bed Methane Recovery (Williams)
15:30	Discussion
17:00	Summarizing Statement (Williams)
17:15	Meeting Adjourned