Biotechnology *and* Biomass

A CORE ELEMENT OF A GLOBAL ENERGY TECHNOLOGY STRATEGY TO ADDRESS CLIMATE CHANGE

A TECHNOLOGY REPORT FROM THE SECOND PHASE OF THE GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM

GTSP

Global Energy Technology Strategy Program

Biotechnology *and* Biomass

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PHASE 2 FINDINGS FROM AN INTERNATIONAL PUBLIC-PRIVATE SPONSORED RESEARCH PROGRAM

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May 2007

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Printed in the United States of America

TO THE READER

This report reflects research conducted as part of the Global Energy Technology Strategy Program (GTSP) at the Joint Global Change Research Institute and in collaboration with partner research institutions around the world. The first phase of the GTSP began at a time when the importance of a technology strategy in addressing climate change was unappreciated. GTSP Phase 1 made the case that a technology strategy was an important part of a larger strategy to address climate change and needed to be included along with the other major components: climate science research, adaptation to climate change, and emissions mitigation.

The second phase of the GTSP recognized that to craft a global energy technology strategy it was important to develop a deeper understanding of potentially important technologies and technology systems, and to embed that knowledge in the context of the larger global energy and economic systems. In Phase 2 we identified six energy technologies and technology systems with the potential to play a major role in a climate-constrained world: CO_2 capture and storage, biotechnology, hydrogen systems, nuclear energy, other renewable energy, and end-use technologies that might be deployed in buildings, industry and transportation. Knowledge gained in each area has been integrated into a larger global energy-economy-climate frame. That combination of depth of study and integrated assessment produced a unique strategic perspective and a bounty of fresh insights. In this document, we have distilled and summarized some of the most salient.

The past nine years have flown by and, looking back from the present, it is amazing to see how far we have come. The GTSP has accomplished much, but much work remains. As we enter Phase 3, we will build on the knowledge gained thus far. We will continue to deepen our understanding of technology and we will continue to integrate that understanding into a larger energy and economic context. And, we will add a new dimension to our work to provide a deeper understanding of the *regional* and *institutional* contexts in which technology is developed and deployed.

Our research has been supported by numerous firms, nongovernmental organizations, and government agencies. Their support has enabled us to continue to explore the implications of designing and implementing a technology strategy. Moreover, we have received the help of many peer reviewers, who throughout the process of developing this document provided their expertise and advice. And for that support we are grateful. Of course, the views and opinions of the authors expressed herein do not necessarily state or reflect those of the sponsoring, participating institutions, or reviewers and any errors that remain are our own.

Jae Edmonds
May 2007

Biotechnology and Biomass

Technologies based on biological processes are attractive both from a climate perspective and for their potential to diversify energy supplies. Biotechnology includes increasing the quality and quantity of biomass energy supply, the use of bio-based fuels, and the enhancement of carbon sequestration in soils and forests. Biomass fuels, whose combustion-related CO_2 emissions are roughly nullified by the CO_2 removed during plant growth, have both foundations as the oldest energy sources used by people and new promise as engineered fuels that can be utilized in many different economic sectors. GTSP insights include the following:

- Fuels derived from biomass energy crops could make a significant contribution to the global energy system whether there are climate policies or not. Biomass "byproducts," such as corn stover, rice straw, or forest residues are particularly attractive in the near term. If demand for biomass increases sufficiently, then the production of biomass crops, such as switchgrass, could be ubiquitous.

- The production of bioenergy crops will increase faster and will be larger in absolute terms in a world that has constraints on greenhouse gas emissions. By the end of this century, bioenergy could contribute an amount of carbon-neutral energy equal to the world's current use of oil.

- Improving cellulosic conversion processes (i.e., breaking down the cellulose in plants to make liquid fuels) can greatly reduce both the cost and net energy requirements for bio-liquid fuel production. The continued development and deployment of technologies that are capable of using various biofuels are also necessary components of expanding the use of bioenergy crops.

- In the mid to long term, whether bioenergy crops can become a truly significant aspect of the global energy system is a function of available cropland that can be freed from other uses (e.g., growing food crops), which in turn is a function of the extent to which continued advances in agricultural productivity for food crops can be sustained.

- As carbon prices increase under stabilization scenarios, the market for bioenergy changes. At relatively low carbon prices, biomass is employed predominantly in the production of electricity. At higher carbon prices, biomass becomes increasingly attractive as a carbon-neutral liquid fuel in transportation.

- If the widespread deployment of CO_2 capture and storage systems coupled to bioenergy-fueled electric power plants is possible, the use of biomass to generate electricity and capture and store CO_2 would result in negative emissions with potentially large reductions in the cost of stabilizing atmospheric CO_2 concentrations.

- In order to avoid a large, inadvertent release of carbon to the atmosphere from the excessive clearing of land to grow bioenergy crops, emissions mitigation regimes must also value carbon emissions from deforestation and soils in the same way as they value carbon emissions from fossil fuels.

- Increased carbon sequestration in plants and soils can have an early, significant impact on net emissions.

WHAT DO WE MEAN BY BIOMASS AND BIOTECHNOLOGY?

In this report, biomass refers to material that contains hydrocarbons created through photosynthesis. Land-use change has altered the amount of carbon stored in soils and plants, and opportunities exist to increase these stores of carbon as part of climate mitigation (see Box 1). Biotechnology refers to the set of processes to improve the quality of biomass through traditional agronomics and to convert it to more useful forms through genetic engineering.

The critical physical process in the production of biomass is photosynthesis, through which the energy in sunlight creates hydrocarbons from water and CO_2. The most important characteristic of biomass for climate stabilization is that the use of sustainably produced biomass as a fuel is a mechanism for recycling CO_2 from the atmosphere. Unlike burning fossil fuels, this rapid cycling of carbon does not lead to an increase in the overall CO_2 content of the atmosphere.

This chapter focuses on biomass and biotechnology in their role as energy technologies that can help play a critical role in addressing climate change, although they have other values in terms of energy security and the development of new sources of chemical feedstocks.

BIOMASS FOR ENERGY

Biotechnologies that produce energy are versatile. Biofuels can be made available in the forms of liquids, gases, or solids. In research conducted by the GTSP as well as by researchers around the world, there is a clear expectation that the use of bioenergy will grow in the future regardless of whether there are explicit climate policies or not.

Figure 1 shows the contribution of bioenergy since 1850, along with future scenarios to 2100: the GTSP Reference Scenario and a 550 ppm CO_2 stabilization scenario. Until the 1970s, biomass use was fairly constant, but then the curve began to rise. After 2000, the model results show projected bioenergy use under a reference case and under a 550 ppm CO_2 stabilization case. These two scenarios suggest a doubling of bioenergy in the next few decades with even more pronounced growth in the second half of the century. By the end of the century, bioenergy's contribution to the global energy system could be as large as today's global oil industry.

Bioenergy today is more than the developing world's use of wood and other traditional fuels. In Denmark, wind only recently passed biomass combustion as a primary source of energy; and in Korea 92 percent of non-hydro renewable energy comes from the combustion

Box 1. ALTERING LAND-USE PRACTICES AS A PART OF CLIMATE MITIGATION PORTFOLIO

Soils around the world contain an enormous quantity of stored carbon, and land management practices in agriculture in particular have a significant effect on soil carbon. Approximately 1200 to 1500 gigatons of carbon (GtC) is currently stored in soils around the world.

Conventional agricultural soil tilling practices expose soils to the air and thereby oxidize some of the stored carbon, moving it from the soils to the atmosphere. Estimates of the historic losses of carbon from soils due to agricultural practices are estimated at about 55 GtC. However, agricultural cultivation practices such as low-till and no-till expose less soil to the atmosphere and can lead to increases of soil carbon levels. Low-till and no-till practices already make economic sense in some areas even without consideration of climate change. If undertaken for climate reasons, these practices must result in effective and verifiable reduction in net emissions to the Earth's atmosphere. Measuring and monitoring the carbon content of land is a major challenge.

Approximately 550 GtC is stored in above-ground biomass, mostly in trees. From 1850 to 1998, approximately 136 GtC has been released into the atmosphere through land-use change, largely deforestation. Planting trees and allowing them to grow to maturity would sequester rather than emit CO_2 to the atmosphere. In contrast, deforestation continues—and every ton of carbon not deforested and thereby not released as CO_2 to the atmosphere is equivalent to the mitigation of a ton of fossil fuel CO_2. Placing a value on carbon stored in ecosystems (discussed in the main body of the chapter) provides an incentive to preserve carbon in existing ecosystems and to expand their extent.

of municipal waste, largely biomass. Much of Brazil's transportation sector utilizes biofuels from sugarcane. And in the United States biomass provides about as much primary renewable energy as hydroelectricity.

In the future, the large-scale expansion of a bioenergy industry is contingent upon a transition from waste and residue biomass, e.g., crop residues and landfill gas, to purpose-grown bioenergy crops. Residues are a broad class of feedstocks, ranging from agricultural and forestry residues to municipal solid waste. Residues are an important component of some industrial (e.g., pulp and paper production) and even national energy systems.

Purpose-grown energy crops are even more varied and range from the oil crops like soy and palm oils to corn and the cellulose crops like switchgrass and hybrid poplar trees. Figure 2 shows three options for biomass energy crops. Large-scale bioenergy crop production differs from the use of residue streams in that the primary purpose of the crop is energy, and the value of the energy product motivates the growing, processing, transport, concentration, and refining of the fuel.

By the end of the century, bioenergy's contribution to the global energy system could be as large as today's global oil industry.

The current technology for using biomass is generally direct combustion. This is the simplest and least expensive method of use. Biomass is also a hydrocarbon and therefore in principle amenable to transformation into liquid, gas, or solid forms. But plant material is more complex than fossil fuels and therefore more difficult to transform, particularly in comparison to, for example, natural gas. In order to use biomass in higher-valued end uses such as liquid fuels, advanced technologies that enable lower-cost transformation of biomass feedstocks are needed.

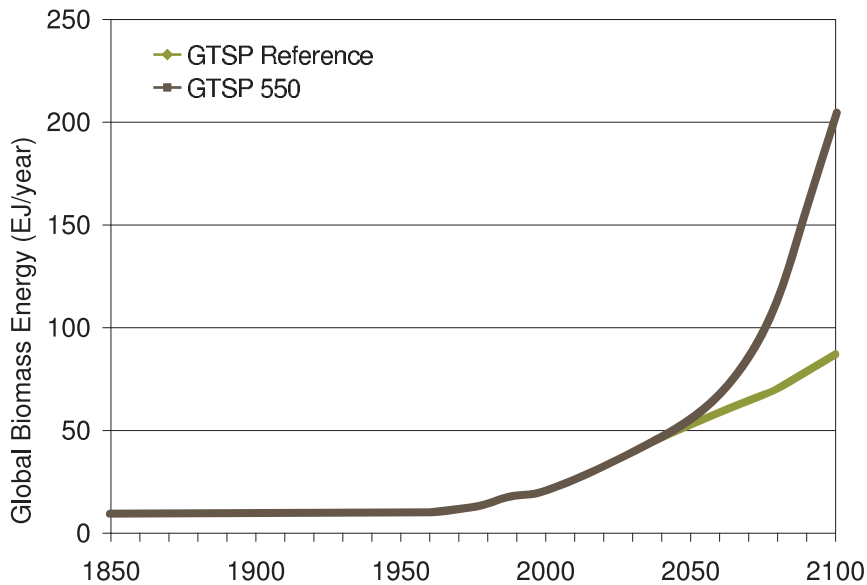

Figure 1. Biomass deployment with and without greenhouse gas emission constraints.

One particularly promising technology is cellulosic production of ethanol. In this process, the tightly bound sugars that comprise plant cellulose and hemicellulose are released and converted to ethanol. Unlike current ethanol production processes, a cellulosic conversion plant would use no net energy, with the process heat needed for the conversion coming from non-cellulosic plant material. Greatly improved cellulosic conversion processes are needed in order to lower the cost of ethanol derived from cellulosic feedstocks such as rice straw, switchgrass, or wood.

In the longer term, whether or not bioenergy crops can become a truly significant aspect of the global energy system is a function of available cropland that can be freed up from other uses (e.g., growing food crops), which in turn is a function of the extent to which continued advances in agricultural productivity for food crops can be sustained. (See the later section on Resource Limitations.) Another factor is the potential for the genetic engineering of energy crops (see Box 2).

Figure 3 reveals a key GTSP insight about the shifting nature of bioenergy utilization in the economy over the course of this century and in the context of varying carbon prices and technology availability. The upper left-hand chart shows the allocation of biomass in a no-climate policy reference case. As can be seen, the dominant use of bioenergy shifts from stationary industrial applications (the "other" category, e.g., the use of biowaste products in a pulp and paper mill) towards the use for electricity production. In this reference case, bioenergy also makes a contribution to the transport sector (bio-liquids), but this is not a dominant use for bioenergy.

Figure 2. Purpose-grown biomass energy crops. Various energy crops include switchgrass, sugarcane, and alfalfa.

Box 2. ADVANCED BIOTECHNOLOGY

The genomics revolution is rapidly opening up new knowledge of how biological processes work. It has led to new therapies for diseases and new diagnostic approaches. Genomic research may also make it possible, for instance, to isolate an organism that produces hydrogen by splitting water into its constituent parts using waste heat. It is likely that advances in knowledge will provide more efficient means by which to transform biological materials such as switchgrass into ethanol.

Other roles for advanced biotechnology might include

Using biological processes to lower energy input requirements for key conversion processes. While these processes operate at relatively low temperatures, research is needed to improve reaction and throughput rates.

Genetically engineering energy crops to not only improve yields, but to better "match" crop properties to the conversion processes that turn them into more useful fuels.

Using biological processes to generate energy products from low-grade resources such as waste heat.

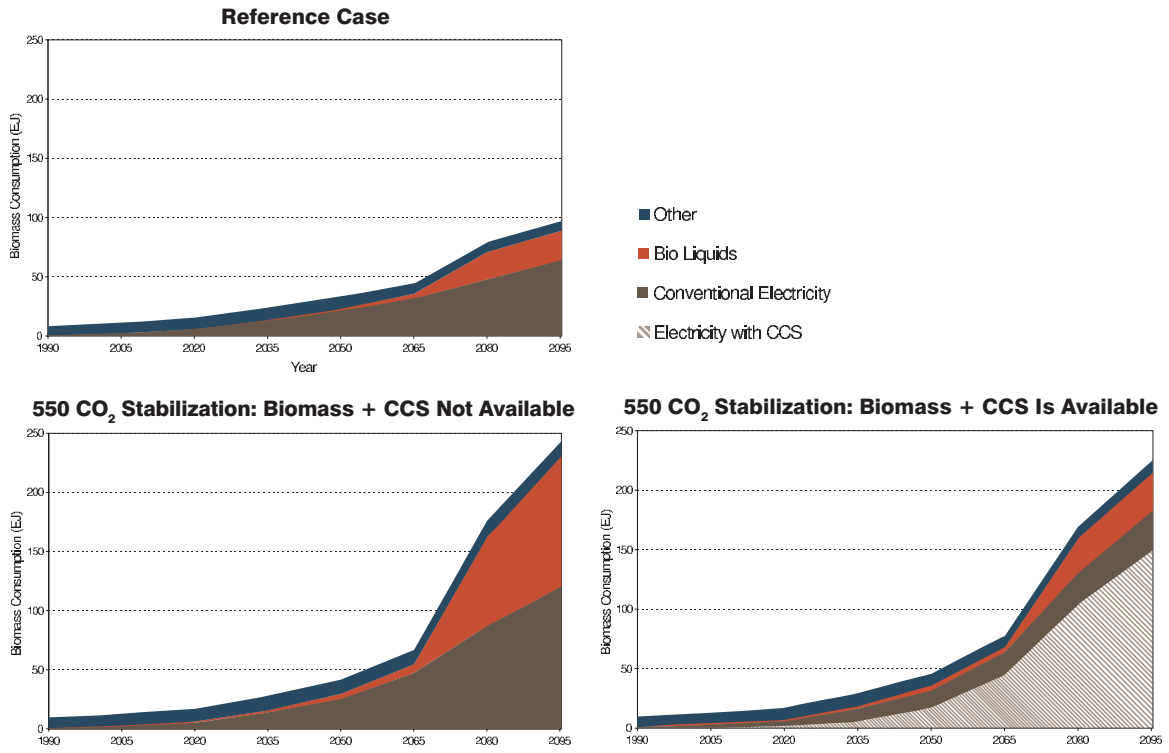

Figure 3. Biomass production and use with and without CCS. How biomass is used in the global economy depends on the presence of a climate policy and the existence of the complementary technologies of carbon dioxide capture and storage (CCS). See the text for a discussion of the reference case (top) and emissions policy cases without CCS (lower left) and with CCS (lower right).

The lower left-hand chart shows how the use of bioenergy production changes in the presence of an emissions policy that is designed to stabilize atmospheric concentrations of greenhouse gases. The general allocation of bioenergy across these economic uses is roughly the same as in the reference case; however, the amount of biomass in this stabilization case is significantly larger than in the reference case. It is only towards the end of the century, when carbon prices rise to hundreds of dollars per ton of carbon, that a significant fraction of the bioenergy being grown on the planet is dedicated to biofuels for the transport sector. The point at which biomass use shifts to the production of liquid fuels depends strongly on the cost of cellulosic conversion technologies.

These two cases demonstrate an important trend. As carbon prices increase in stabilization scenarios, societies will use bioenergy crops in progressively higher value-added applications. A significant shift towards biomass in the production of electricity appears to be a dominant use of bioenergy.

The lower right-hand chart in this figure explores how the use of bioenergy might change, if CO_2 could be captured and stored from facilities that produce electricity from biomass (bio-electricity with CCS). At present there are no operational biomass-fueled electric power plants with CCS. Yet there is considerable interest in the possible deployment of these systems because of the potential for net carbon removal from the atmosphere. A biomass-fired power plant that captured and stored CO_2 in a suitable deep geologic reservoir would not only generate clean electricity but also generate emissions offsets. These "negative emissions" could be used to lessen the need to reduce emissions from sectors of the economy that have particularly high abatement costs. Bio-electricity with CCS would produce both electricity and in effect scrub the atmosphere of some of its CO_2.

In the stabilization case, assuming that bio-electricity with CCS systems are developed and built, and that institutional arrangements can be crafted to pay the price of carbon to those who store carbon obtained from bio-electricity with CCS facilities. Bio-electricity with CCS becomes the dominant use of bioenergy shortly after the middle of the century. The stored CO_2 can be used to offset a significant portion of emissions from sectors where mitigation is more expensive, e.g., the tailpipe emissions from the transportation sector.

RESOURCE LIMITATIONS

The question of widespread deployment of bioenergy crops as a significant climate technology relates to the availability of and competition for land. All renewable energy sources that rely on solar energy as the primary input use the land as the collector of energy. In the long run, food, fiber, and energy production may all compete for land. The models used within the GTSP explicitly account for these interactions with a finite amount of potential agricultural land available for food, bioenergy, or other uses. In addition, there are other critical uses of the land which include support of biodiversity, ecosystem services (i.e., provision of clean water), recreation and preservation (as in parks).

Research by the GTSP has demonstrated that a successful deployment of large-scale bioenergy depends not only on progress in growing, processing, and using bioenergy crops, but also on continued productivity improvements in traditional crops. Without that productivity gain there will be no land for bioenergy. All of the land will be needed just to feed a larger and richer world population, as illustrated in Figure 4. Worse still, failure to continue productivity improvements in crops will place heavy pressure on forests, which will be an attractive target as potential new land for food production. Even with growth in agricultural productivity, the production of hundreds of exajoules per year or more of bioenergy crops requires significant land.

In Figure 4, the left panel shows the pattern of global land use when the concentration of CO_2 is stabilized at 550 ppm and agricultural productivity does not improve. Not only is there no biomass energy production when agricultural productivity growth is zero, but the share of land that remains in unmanaged ecosystems falls precipitously. The loss of unmanaged ecosystems means significantly higher land-use emissions, e.g., deforestation. As a counter example, the right panel shows the land-use implications of a 0.5 percent per year rate of agricultural crop productivity growth combined with a limit on the CO_2 concentration of 550 ppm. Demand for cropland and pressure on unmanaged ecosystems are reduced and land made available for biomass energy production.

A recent innovation in the GTSP's work reveals another potential limit to the adoption of bioenergy technologies. In a greenhouse-gas-constrained world with a rising carbon price, a strong economic incentive is sent to clear additional land in order to grow bioenergy crops, e.g., to turn a forest into cropland to meet the market's demand for more biofuels. However, the clearing of new land for growing bioenergy crops can release a significant amount of carbon stored in the forests and soils into the atmosphere, which is counterproductive in terms of stabilizing concentrations of greenhouse gases.

In order to avoid such a large, inadvertent release of carbon to the atmosphere from the excessive clearing of land to grow bioenergy crops, emissions mitigation regimes must also place a value on the carbon in forests, other ecosystems, and soils. Since all carbon is alike to the atmosphere, the appropriate value to place on the carbon on the land, in forests and soils and other lands, is the same as the value on carbon resident in fossil fuels.

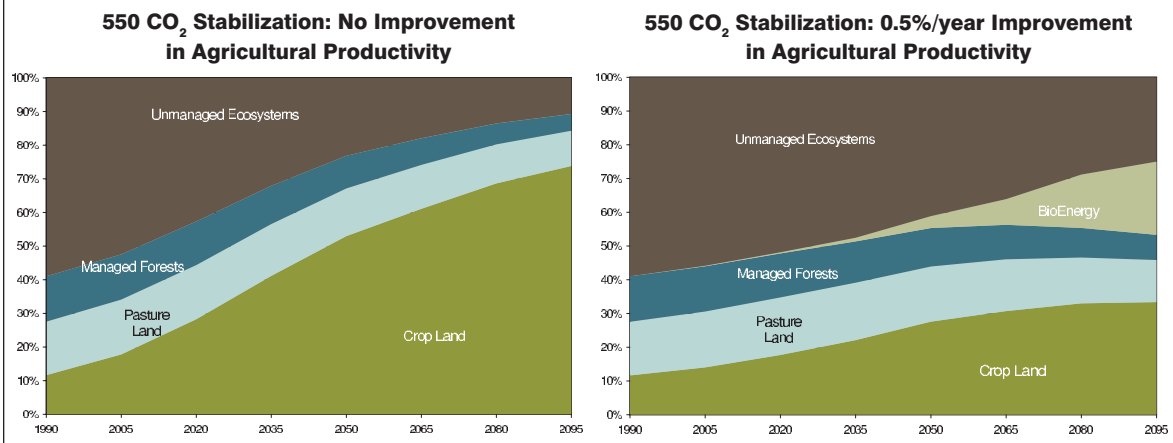

Figure 4. The effect of agricultural productivity growth on land allocation under an emissions-reduction policy. Without improvement in agricultural productivity (left panel), less and less land will be available for energy crops. Continued improvement in agricultural productivity allows land to be used for bioenergy (right panel).

If the price of carbon is low, the effect of less-than-ideal valuation of natural carbon stocks is modest. But if the carbon price is high, then the effect can be large. Figure 5 shows the amount of carbon emitted by land systems, including the effects of increased carbon uptake by plants as previously deforested areas regenerate and CO_2 levels rise as well as the release of carbon through deforestation. At present, a small net uptake of carbon by land was estimated, resulting in the negative emissions seen in the figure. In other words, plants and soils are thought to be removing more carbon from the atmosphere than being released by deforestation. The lower line tracks the net uptake of carbon by plants and soils in a scenario that stabilizes CO_2 concentrations at 450 ppm, with a price of carbon applied equally to carbon emissions wherever they occur regardless of whether the source is from deforestation or fossil fuel use. The upper line shows the consequence of only valuing fossil fuel carbon, i.e., ignoring the value of terrestrial carbon. In this scenario, emissions from land-use change such as deforestation overwhelm the land's ability to absorb carbon as a consequence of too much land clearing to create places to grow biomass.

As can be seen from Figure 5, not taking into account the need to value the carbon stored in forests and soils can lead to over-exploitation of natural resources and excessive production of bioenergy.

THE VALUE OF CONTINUED RESEARCH AND DEVELOPMENT

To realize the large-scale potential for commercial bioenergy and terrestrial sequestration, continued advancement across a wide variety of biological, agricultural, and engineering fields will be required.

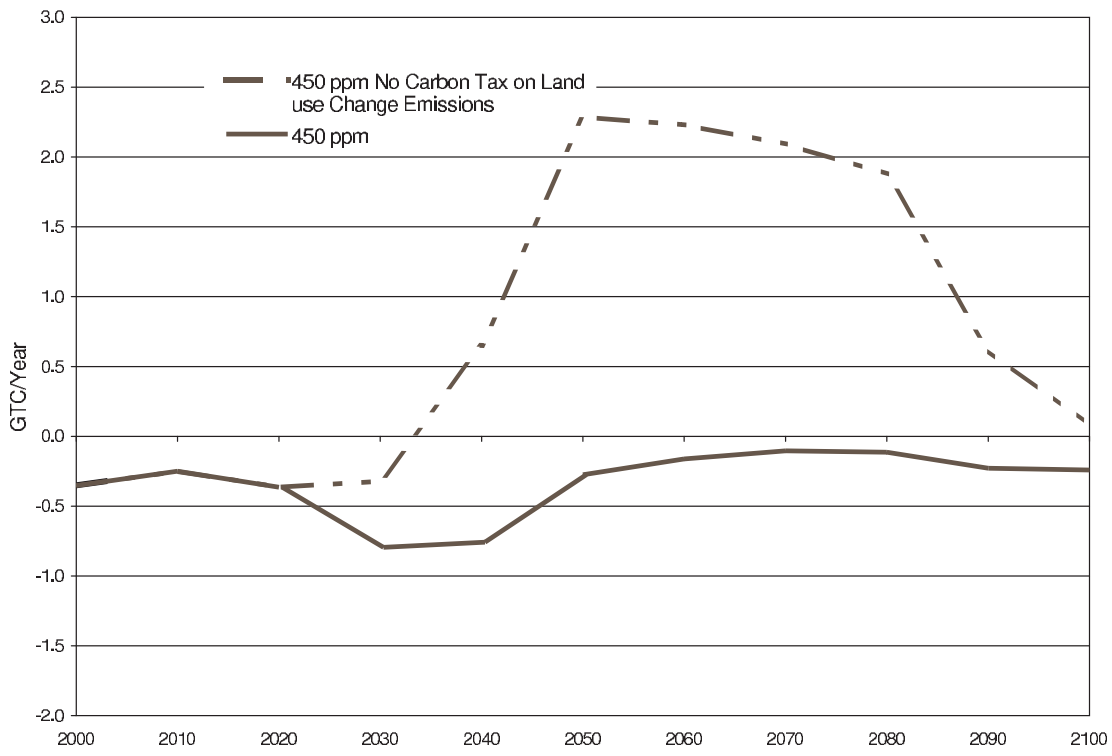

Figure 5. These two climate-stabilization cases have the same goal; however, the upper line demonstrates the potential consequence of not accounting for the value of carbon emissions from deforestation and other land-use changes.

Selected R&D, demonstration, commercial deployment challenges and opportunities for biotechnology and bioenergy include:

- Continue to improve the efficiency and lower the cost of cellulosic conversion processes.
- Continue to deliver increases in agricultural productivity for both food and energy crops, increases that must be sustained over the course of this century.
- Develop and deploy end-use energy systems across a number of different economic sectors that are adapted and optimized to the use of biofuels.
- Conduct research, field testing and likely large-scale demonstration projects to better understand the real-world potential for biomass energy systems coupled with CO_2 capture and storage technologies.
- Actively pursue the rapidly expanding field of genomic research to better understand how these techniques and technologies can be applied to produce and transform biological materials into large-scale clean energy.
- Improve methods for measuring and monitoring of carbon stocks in soils and standing biomass to help significantly expand already established practices such as low-till and no-till agricultural practices.

To realize the large-scale potential for commercial bioenergy and terrestrial sequestration, continued advancement across a wide variety of biological, agricultural, and engineering fields will be required.

APPENDIX Notes and References

Most of the CO_2 emissions in this study are stated in units of million or billions of tons of carbon (MtC or GtC, respectively). This differs from the conventions of the CCS technical community, which expresses values in millions or billions of tons of CO_2 ($MtCO_2$ or $GtCO_2$, respectively). Cost data can be converted to dollars per ton of ($/$tCO_2$) by dividing by 3.667, and mass data can be converted to CO_2-based units of the climate change technical community by multiplying the mass expressed in carbon-based units by 3.667.

This report makes frequent use of a very large measure of mass known as a "gigaton." A gigaton of CO_2 ($GtCO_2$) is a standard measure for scientists and policy makers familiar with carbon management, yet for most other audiences the magnitude of this unit is sometimes hard to comprehend. A gigaton is approximately equal to 77 Empire State Buildings if they were made completely of lead, 10,718 aircraft carriers the size of the USS Enterprise, or all of the iron ore annually mined in the world. For more examples of how massive a gigaton is please consult C.L. Davidson and J.J. Dooley, "A Gigaton Is…" PNWD-3299, Joint Global Change Research Institute, Battelle Pacific Northwest Division (July 2003).

Unless otherwise indicated, all scenarios and analyses result from the GTSP research, using several well-established modeling tools.

Box 1. The estimate of carbon lost from soils comes from V. Cole, C. Cerri, K. Minami, A. Moser, N. Rosenberg, and D. Sauerbeck, "Agricultural Options for Mitigation of Greenhouse Gas Emissions," in Intergovernmental Panel on Climate Change, *Climate Change 1995: Impacts, Adaptations and Mitigation of Climate Change: Scientific-Technical Analysis*, eds. R.T. Watson, M.C. Zinyowera, and R.H. Moss, Cambridge University Press, Cambridge (1996). The estimate of loss from land-use change is from R.C. Watson, I.R. Nobel, B. Bolin, N.H. Ravindranath, D.J. Verardo, and D.J. Dokken, *IPCC Special Report on Land Use, Land-Use Change, and Forestry*, Cambridge University Press, Cambridge (2000).

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THE **GLOBAL ENERGY TECHNOLOGY STRATEGY PROGRAM**

The Global Energy Technology Strategy Program (GTSP) began in 1998 with the goal of better understanding the role that energy technologies might play in addressing the problem of global climate change. The GTSP is unique, a global, public and private sector sponsored research program, whose sponsors and research collaborators are drawn from around the world.

The completion of the first phase of the GTSP in 2001 was marked by the release of a seminal report during a special session of the Sixth Conference of the Parties to the United Nations Framework Convention on Climate Change. This report, *A Global Energy Technology Strategy Project Addressing Climate Change: Initial Findings from an International Public-Private Collaboration,* demonstrated the importance of technology development and deployment as key cornerstones of a broader set of activities designed to address climate change. A central conclusion was that a robust technology strategy required the development of a *technology portfolio*. It found no evidence for a single technology whose development promised to "solve" the climate problem. That is, *a priori*, there is no technological "silver bullet." Rather, the GTSP concluded that various technologies and technology systems show promise for making a substantially expanded contribution to the global energy system in a climate-constrained world. These included biotechnology, hydrogen energy and other advanced transportation technology systems, nuclear power, renewable energy technologies, end-use energy technologies, and carbon dioxide capture and storage. The first phase of the GTSP produced groundbreaking research, including many results that have made their way into the frequently cited literature. This phase of the GTSP successfully added to the dialogue about responses to climate change a new, previously missing, element—technology. But building productive, long-term, real-world technology strategies to address climate change requires a deeper understanding of technologies and their potential. Thus, the GTSP launched its second phase in 2002. GTSP Phase 2 pushed the frontiers of our knowledge to gain a much deeper understanding of how these key carbon management and advanced energy technologies will deploy in practice, and the means for launching and sustaining a meaningful global energy technology strategy.

GTSP Phase 3 will delve into the regional diversity and institutional dimensions of developing and deploying technologies to address climate change.

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