



Global Climate & Energy Project  
STANFORD UNIVERSITY



# Assessment Report from the GCEP Workshop on Energy Supply with Negative Carbon Emissions

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## Abstract

As part of its assessment towards energy technologies that reduce greenhouse gas (GHG) emissions, The Global Climate and Energy Project (GCEP) held a workshop at Stanford University on June 15, 2012, on the topic of Energy Supply with Negative Carbon Emissions. The workshop addressed 4 main topics: Biomass Energy with Negative Emissions; Carbon Capture, Conversion and Storage; Addressing Other Contributions to Carbon Emissions; and System Modeling. This report summarizes the discussion and highlights research needs that were identified at the workshop by speakers and participants. The unparalleled ability of biological systems to capture and cycle carbon, and the potential to use these systems as part of an energy supply that leads to negative emissions, was brought to the forefront

at this workshop, as well as the need for integrated systems of supply, conversion and storage. Reaching net negative carbon emissions on a global scale could also be possible without the use of bioenergy with carbon capture and storage, but the predicted costs of carbon in these energy technology scenarios would be extraordinarily high. Studies aimed at understanding and overcoming the limits to technologies for bioenergy with negative emissions, identification of integrated and optimized systems for negative emissions, and research towards novel carbon storage technologies would represent groundbreaking steps towards technologies that could achieve net negative carbon emissions in our energy supply.

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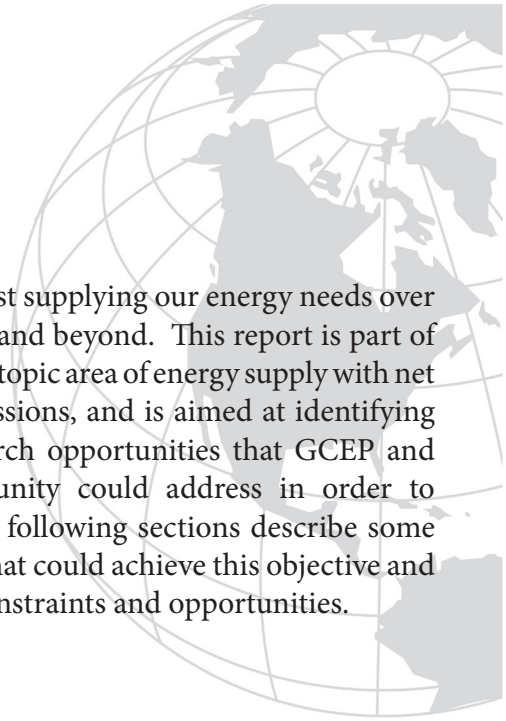
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## Foreword

This assessment report includes summaries of the presentations and discussions at a workshop on “Energy Supply with Negative Carbon Emissions” held at Stanford University on June 15, 2012, and organized by the Global Climate and Energy Project.

The authors would like to extend our sincere thanks and gratitude to the speakers for sharing their knowledge and insight with us and for their contributions to this report. Thanks to Larry Baxter, *Brigham Young University*; Sarah Davis, *University of Illinois at Urbana-Champaign*; Jae Edmonds, *Joint Global Research Institute, PNNL and University of Maryland*; Paul Fennell, *Imperial College London*; Taku Ide, *Koveva*; Henrik Karlsson, *Biorecro*; David Keith, *Harvard University*; Joris Koornneef, *Ecofys*; Jose R. Moreira, *University of Sao Paulo*; Olivia Ricci, *Université d’Orléans*; William Stewart, *University California at Berkeley*; Lisamarie Windham-Myers, *U.S. Geological Survey*; and Dominic Woolf, *Cornell University*.



## Introduction

Many scenarios that project global carbon dioxide (CO<sub>2</sub>) emissions over the coming decades show that levels of CO<sub>2</sub> in the atmosphere and the ocean may rise to values that affect the ecological infrastructure on which we depend for food and water resources. Projections show that ocean acidification may cause corrosive conditions for coral reefs, threatening a major lifeline for many oceanic species and key food resources for the human population (Cao and Caldeira, 2008). While the sources of these rising emissions are many, our primary energy supply is a major contributor (Davis *et al.*, 2010). In the energy space there are key issues that could be addressed to lower these emissions while providing energy to meet the needs of a growing world population.

The generation of CO<sub>2</sub> is a direct consequence of extracting energy from fossil fuels and biomass. Electricity generation alone accounts for approximately a third of the global emissions. In addition, methane (CH<sub>4</sub>) – a potent greenhouse gas (GHG) – is released from the natural gas system and many other sources. To meet the GHG targets of keeping CO<sub>2</sub> levels below the 350-400ppm limit that is predicted to lead to a 2 degrees Celsius increase above the pre-industrial mean global temperature, many energy supply scenarios require the use of technologies that capture and sequester CO<sub>2</sub>. Newer emissions scenarios with climate forcing of less than about 3 watts/m<sup>2</sup> tend to include net negative CO<sub>2</sub> emissions, some as early as the middle of the 21st century, Figure 1 (Moss, R., *et al.*, 2010).

A sustainable energy future requires strategies to facilitate the use of energy resources that enable the reduction of concentrations of CO<sub>2</sub> and/or CH<sub>4</sub> in the atmosphere. Low-cost, sustainable ways to achieve net negative carbon emissions from a segment of the primary energy sector will have the additional benefit of allowing continued use of fossil-based energy sources in a portfolio that is at zero emissions overall.

GCEP and its sponsors support fundamental research that could lead to energy technologies that reduce

GHG emissions whilst supplying our energy needs over the next 10-50 years and beyond. This report is part of the assessment of the topic area of energy supply with net negative carbon emissions, and is aimed at identifying the needs and research opportunities that GCEP and the research community could address in order to reach this goal. The following sections describe some of the technologies that could achieve this objective and outline important constraints and opportunities.

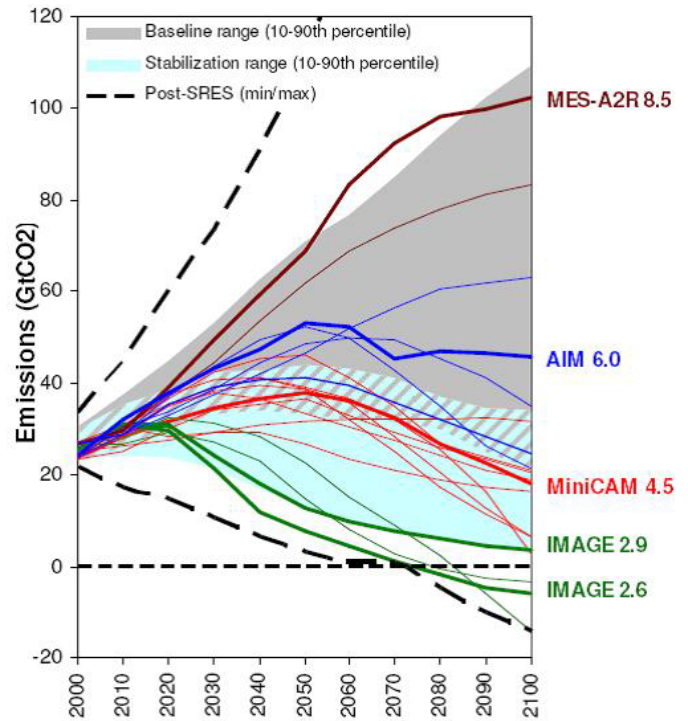


Figure 1: Predicted carbon emissions showing the stabilization range from 2000 to 2100. Models (MES-A2R 8.5, AIM 6.0, MiniCAM 4.5, IMAGE 2.9, IMAGE 2.6) include various technology scenarios and predict that technologies with net negative emissions will be an important component to achieve stabilization goals (from Chris Field, presentation; and Moss, R., *et al.*, 2010).



## Biomass Energy with Negative Emissions

Net negative emissions can be achieved when more GHGs are sequestered or stored than are released to the atmosphere over a given time. In the case of CO<sub>2</sub> this can be achieved by introducing biomass into a conversion cycle with carbon capture and storage (CCS), Figure 2. Photosynthesis captures CO<sub>2</sub> from the atmosphere and stores it as biomass. On conversion of the biomass for electricity and/or liquid fuel and/or materials (such as pulp for paper production, or bioplastics), CO<sub>2</sub> is released back to the atmosphere. When CCS technology is added to recapture the CO<sub>2</sub> from the flue gas, there is a net negative effect. The technologies for this exist today, but there are important constraints and considerations that will limit deployment, some of which are summarized in the following sections. It may be possible to achieve substantial emissions reductions in just the supply chain of biomass, which will be discussed in this section under, “Negative emissions in the bioenergy lifecycle.”

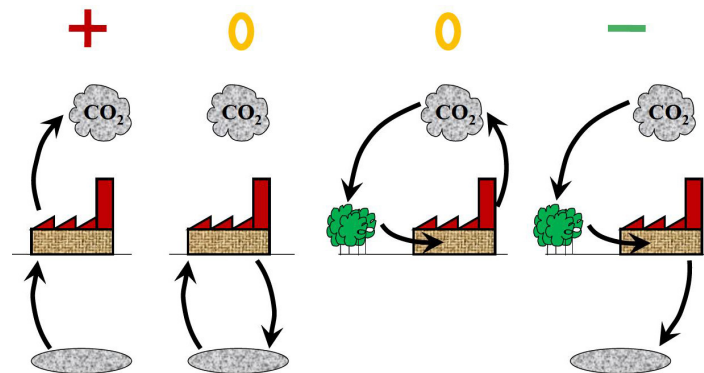


Figure 2: Image denotes the potential net emissions that can be achieved from a power plant or industry. Adding carbon capture and geological storage to a fossil fuel facility could ideally lead to a zero net emission, as could a dedicated biomass facility. The combination of biomass and carbon capture and storage could lead to a net reduction in atmospheric CO<sub>2</sub> levels from the lifecycle of the process (from Henrik Karlsson, presentation).

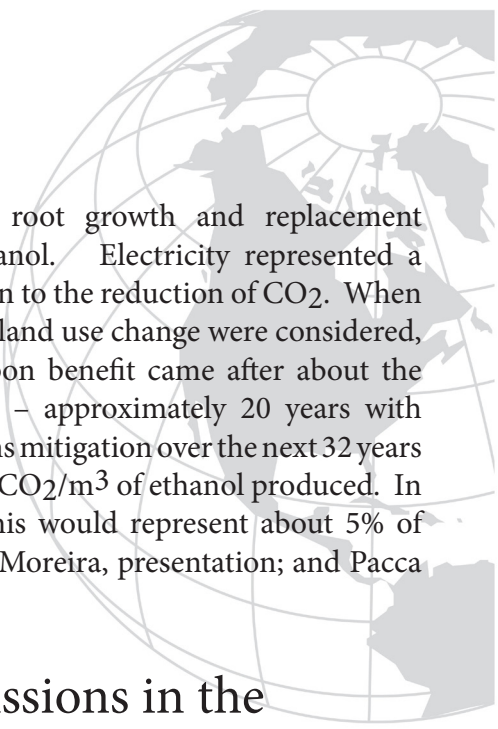
## Bioenergy with Carbon Capture and Storage (BECCS)

BECCS uses existing technologies for biomass energy conversion coupled to carbon capture and sequestration. There are currently 16 projects worldwide at various stages of completion (Figure 3), but this technology faces challenges. One is the fluctuating price on carbon. Another is the absence of recognizing “negative emissions” in the existing CO<sub>2</sub> reduction incentive schemes (e.g., EU ETS), and hence adequate incentives for capturing CO<sub>2</sub> do not exist on a global basis.

Another challenge is the scale-up and availability of a sustainable biomass resource. In an IEA GHG study (Koornneef *et al.*, 2011), the technical potential of different BECCS technologies to produce power, biofuels and biomethane is compared. The study predicts that net negative GHG emissions from BECCS could be as much as 10 Gt of CO<sub>2</sub> per year in 2050 (Figure 4). However, providing an adequate supply of biomass and overcoming the high cost of CCS are important to the success of these technology options. Supply chain optimization and matching all aspects of the infrastructure for power, biomass, CO<sub>2</sub> (demand) and natural gas are also important issues.

The types of feedstock to be used, time of use and available technology are important criteria for the feasibility of BECCS technology and its effectiveness in reducing CO<sub>2</sub> levels (Joris Koornneef, presentation). Various studies have estimated the biomass resource to be 65, 42 and 19-35 exajoules (EJ) per year for energy crops, agricultural residues and forest residues, respectively (Larry Baxter, presentation), suggesting that biomass resources are diverse and significant.

The economic potential is smaller compared to the technical potential. Up to one-third to one-half of the technical potential can be considered economically attractive, but this is strongly dependent on a price incentive for reducing CO<sub>2</sub> emissions and on the price of competing (low carbon) energy solutions. It is therefore important to look for early opportunities with low CCS cost or with revenues from CO<sub>2</sub> utilization.



An example is the capture of CO<sub>2</sub> from biofuel production that already produces relatively pure CO<sub>2</sub> streams, e.g., bioethanol production (Joris Koornneef, personal communication, and Koornneef *et al.*, 2011).

Co-firing of biomass and fossil fuels could be an option to reduce overall production cost of conversion installations and to achieve economies of scale for the CCS infrastructure.

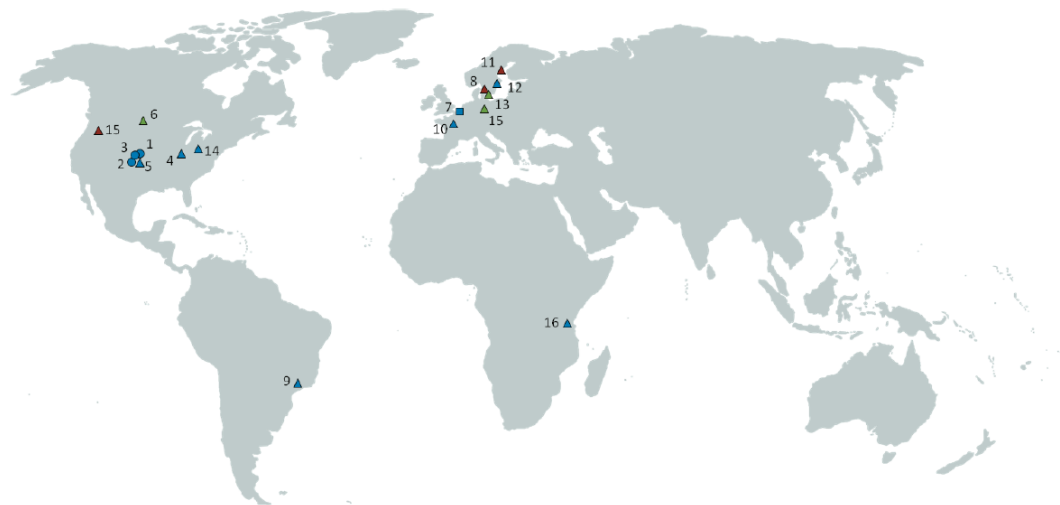
## Ethanol program in Brazil

Modeling of the historical carbon budget of the ethanol program in Brazil over the last 32 years shows that the net effect has been a reduction in carbon emissions (Jose Moreira, presentation). Ethanol production from sugar cane in Brazil, a system that has been supplying ethanol since 1975, is modeled to have a net capture of 1.5 tCO<sub>2</sub>/m<sup>3</sup> of ethanol produced up to year 2007. In this model, the system took 18 years to recoup carbon emissions, with most reductions coming from soil

replenishment from root growth and replacement of gasoline with ethanol. Electricity represented a negligible contribution to the reduction of CO<sub>2</sub>. When the effects of indirect land use change were considered, the net negative carbon benefit came after about the same period of time – approximately 20 years with accumulated emissions mitigation over the next 32 years predicted to be 4.77 t CO<sub>2</sub>/m<sup>3</sup> of ethanol produced. In the global context, this would represent about 5% of CO<sub>2</sub> emissions (Jose Moreira, presentation; and Pacca and Moreira, 2009).

## Negative emissions in the bioenergy lifecycle

Recent research suggests that it may be possible to achieve negative emissions in the bioenergy lifecycle without CCS, provided that the biomass resource is managed appropriately. Data presented by Sarah Davis show that up to 66% of emissions from a particular



**CAPTURE FACILITY**

- Pulp and Paper
- Ethanol
- Gasification and others

**STORAGE TYPE**

- △ Geological
- Beneficial reuse
- Geological and/or beneficial reuse

Source: Biorecro, Global CCS Institute, 2011

Figure 3: Biomass energy with carbon capture, utilization and storage projects worldwide. Indicated are the type of capture facility, storage type and the stage of the project as of June 2012. Completed projects are numbered: 1. Russel, Kansas, United States. Operating projects are: 2. Liberal, Kansas, to Booker, Texas, United States; 3. Garden City to Stuart Field, Kansas, United States; and 4. Decatur, Illinois, United States. Projects under construction are: 5. Wellington, Kansas, United States. Evaluated projects are: 6. North Dakota, United States; 7. Rotterdam, The Netherlands; 8. Värö, Sweden; 9. São Paulo, Brazil; 10. Artenay, France. Identified potential sites are: 11. Domsjö, Sweden; 12. Norrköping, Sweden; 13. Skåne, Sweden. Cancelled projects are: 14. Greenville, Ohio, United States; 15. Wallula, Washington, United States; and 16. Rufiji cluster, Tanzania (from Henrik Karlsson, presentation; and Biorecro, Global CCS Institute, 2011).

bioenergy lifecycle are emitted in the biomass production chain, Table 1 (Scown *et al.*, 2012), and that a change in management strategy can “swing” emissions from positive to negative or visa versa (Davis *et al.*, in press). Among the factors involved are previous land use, removal of biomass and residue, harvest frequency and nutrient management. Crop choice can also swing emissions from positive to negative (Davis *et al.*, 2011). In the case of woody feedstocks, total carbon emissions over a given time horizon vary with the harvesting interval and intensity. Abandoned lands can be an opportunity for bioenergy crops depending on time since abandonment and current use.

Interestingly, a study on forest biomass suggests that achieving negative emissions using this biomass resource could involve two pathways where high-value wood is used as an energy-efficient building material and lower-value wood is used directly for energy

(William Stewart, presentation). Wood is the number one biomass used worldwide, but growing wood purely for energy is currently not cost-competitive in regions where much of the wood goes to high-value lumber (Figure 5). On the other hand, regions with lower production costs and greater distances from lumber markets, such as Brazil, could focus on short-rotation plantations primarily for energy production. Analysis of scenarios for biofuels end-uses and other competing end-uses suggests that indirect negative carbon benefits of the energy savings from using wood instead of steel and cement in buildings will have to occur in Asia where most of the world’s future construction will occur. In areas where sustainably managed forests are close to urban regions, direct net negative carbon benefits may come from sawmill residues, post-consumer residues, logging residues and forest mortality, which together can make up 5-100% of the feedstock for cogeneration plants with CO<sub>2</sub> capture and storage (William Stewart, presentation).

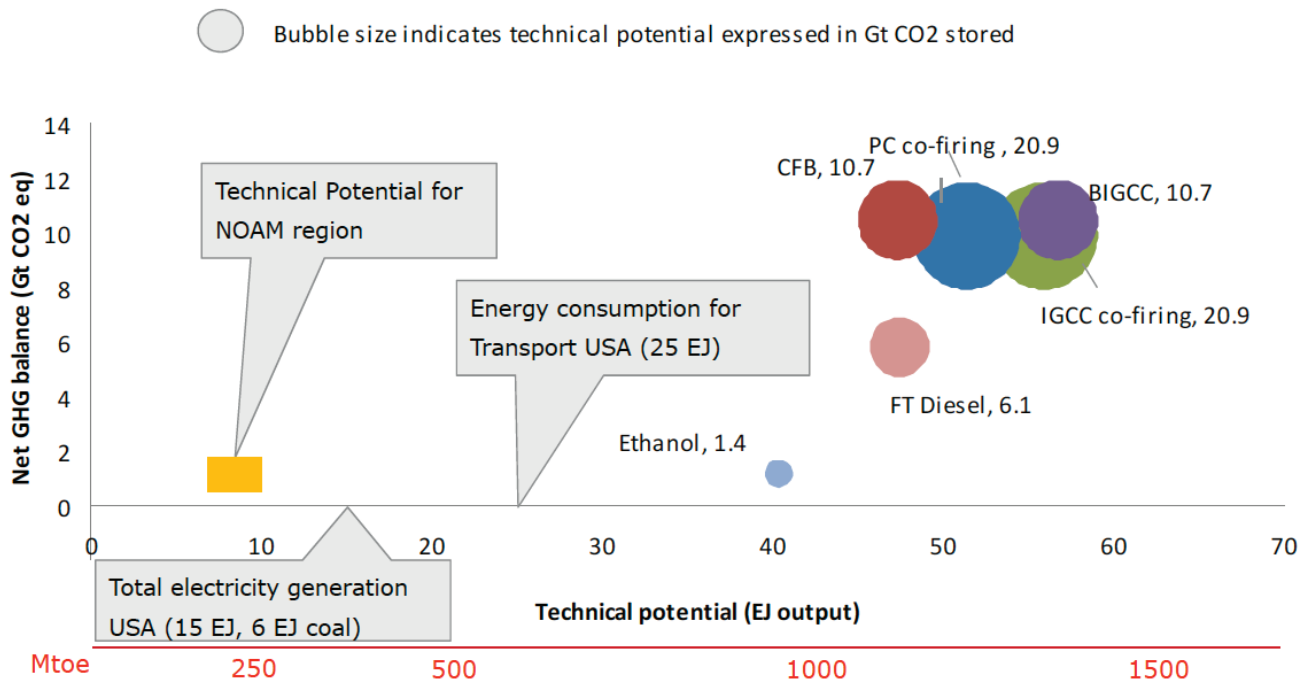
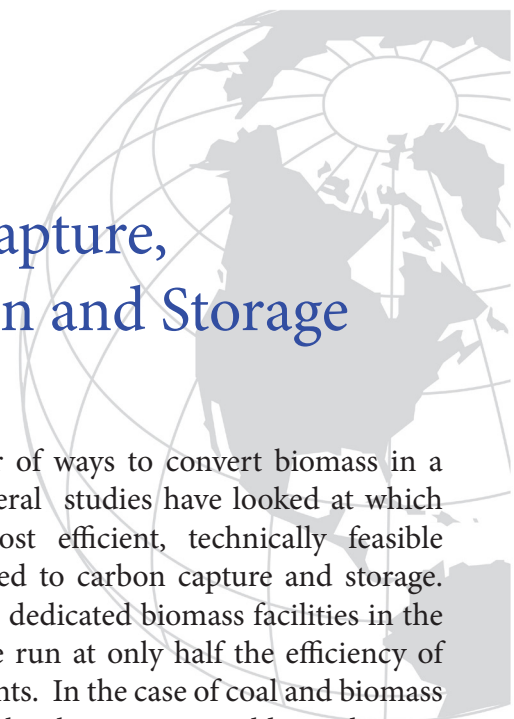


Figure 4: Technical potential of conversion technologies for bioenergy with carbon capture and storage in 2050 (from Joris Koornneef, presentation; and Koornneef *et al.*, 2011). These data consider the full chain of biomass to power, including pretreatment, conversion and end-use. Three biomass sources – agriculture residue, forest residue and energy crops – were included, and densification/torrefaction and transport of the biomass considered. Conversion and CO<sub>2</sub> capture; end-use as a liquid biofuel (bioethanol, biodiesel) and electricity; type of capture method - post combustion capture, pre-combustion capture; and fermentation/digestion, were also considered. CFB = circulating fluidized bed combustion plant (100% biomass). PC = pulverized coal (30-50% co-firing). IGCC = integrated gasification combined cycle (30-50% biomass). BIGCC = biomass integrated gasification combined cycle (100% biomass). FT = Fischer-Tropsch diesel. “Ethanol” assumes only lignocellulosic biomass feedstock for fermentation.





## Carbon Capture, Conversion and Storage

### Conversion

There are a number of ways to convert biomass in a BECCS system. Several studies have looked at which conversions are most efficient, technically feasible and can be integrated to carbon capture and storage. There are already 73 dedicated biomass facilities in the U.S. However these run at only half the efficiency of coal-fired power plants. In the case of coal and biomass co-fired facilities, the best case could reach 95% efficiency of a coal-fired power plant. That translates to an approximate 40% overall efficiency for a biomass co-fired power plant, and any process that proposes to convert biomass into electricity should be able to compete with that level of efficiency. In reality however, the average efficiency of 73 existing, dedicated biomass plants is only 11%. This low average rate, although partially due to poor heat integration (which can be overcome), largely results from inefficiencies inherent in small-scale operations, such as lack of reheat cycles, low steam temperatures and pressures, and highly variable fuel feeds (Larry Baxter, presentation).

Studies show that mixing biomass with fossil fuel is more efficient than operating a dedicated biomass plant. Significant issues to overcome in both dedicated and co-fired biomass installations include: pollutant formation, carbon conversion, ash management and balance-of-process issues (e.g., fuel supply and storage, fuel preparation and ash utilization). Corrosion caused by the formation of potassium chloride is also a problem in boilers. Many fast-growing plant species that are good candidates for providing large quantities of sustainable biomass have high levels of potassium, which can lead to the formation of the corrosive potassium chloride. In some cases, however, a blend of biomass with coal can facilitate a reduction in corrosive species and harmful emissions. In such cases, the biomass captures sulfur from coal and forms potassium sulfate, which is less corrosive than potassium chloride. Whilst there are solutions to all of these issues, avoiding the consequences of corrosion requires further attention from the

The seasonal availability of biomass, improvements in crop yields, the ability to use aquatic biomass (algae) and other sources, and optimization of biomass pretreatment, logistics and conversion technologies for flexibility, reliability and scale are important considerations and opportunities for research. Systems studies that help to identify ways to achieve sustainable biomass supply are an essential component to understanding the global potential of this technology.

Table 1: Greenhouse gas (GHG) fluxes, expressed as the equivalent GHG potential of a megagram of CO<sub>2</sub> (Mg CO<sub>2</sub>eq), on a crop area basis as estimated in previous literature. From Sarah Davis presentation and Davis *et al.* 2009.

Biofuel crop	GHG Mg CO <sub>2</sub> eq/ha/yr
Corn	-89
Sugarcane	-9.8
Prairie on marginal crop land	-7.8
Prairie on abandoned crop land	-4.3
Early successional species	-2.11
Switchgrass	-1.66
Corn	-1.2
Reed canarygrass	-0.85
Corn-soy	-0.49
Corn stover	0.84
Corn-soy-wheat rotation	1.14
Switchgrass	1.32
Switchgrass	2.28
Corn	5.14
Corn	8.71
Switchgrass	9.6

Delivered Wood Price Trends in the Southeast US (www.TimberMart-South.com)

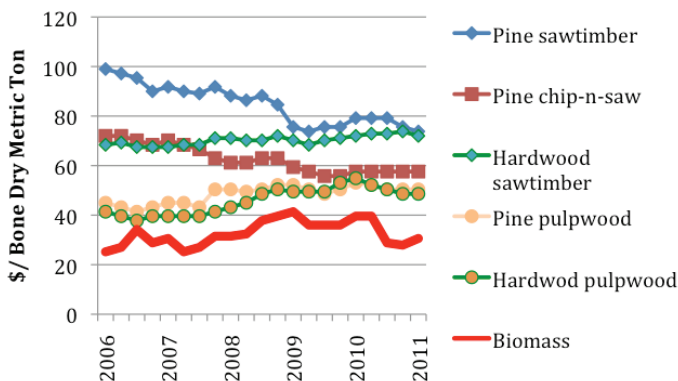


Figure 5: Graph illustrates the difference in the value of wood for different end-uses. The price for sawtimber is 3-4 times greater than for wood for biomass energy. Rational landowners will sell to the highest bidder, and that bidder changes over time (from William Stewart, presentation).

research community (Larry Baxter, presentation).

The advantages and disadvantages associated with different types of biomass are only partially understood and thus provide a number of fundamental research opportunities. For example, almost any use of biomass residues – such as agricultural residues (straw, stover, etc.), forest product residues, and industrial or municipal waste – provides better lifecycle performance than do energy crops, since most of the economic and environmental costs of creating the fuel are borne by the food and/or products. The characteristics of different feedstocks, particle size of the biomass and dynamics of the flame are important aspects to consider when incorporating biomass into a co-firing conversion cycle. From an engineering perspective, co-firing with up to 50% biomass is possible, but based on biomass supply, we can likely only achieve 10% at most. This number could change for small burners or abundant biomass supply (Larry Baxter, presentation).

## Capture

The economics and efficiency of negative CO<sub>2</sub> emissions benefit significantly if processes that capture CO<sub>2</sub> from concentrated sources are incrementally increased to capture very high percentages of the stream. The most obvious choices for such processes are combustion-based carbon capture systems.

When capture and storage of CO<sub>2</sub> is combined with biomass co-firing, negative carbon emissions can be achieved. The most advanced capture method is amine scrubbing, which can trap up to 90% of the CO<sub>2</sub> in flue gas. However, amine scrubbing technology costs an estimated \$50-\$80 U.S. per ton of CO<sub>2</sub>, accounting for most of the cost of the CCS system. The energy penalty for using carbon capture is about 30% of the power plant. Amine scrubbing and most of the other most widely discussed capture alternatives struggle economically and technically to efficiently capture more than 90% of the CO<sub>2</sub> in the flue gas.

A relatively new method of carbon capture, called Cryogenic Carbon Capture (CCC) and presented by

Larry Baxter, reduces costs and energy consumption of capture by a factor of two and can be pushed to high efficiency with modest increases in marginal capture costs or energy demands, Figures 6 and 7 (and Larry Baxter presentation). The proposal to capture more than 99% of the CO<sub>2</sub> (i.e., an additional 10%) from stationary sources would make a significant difference and is more feasible than capturing all of the carbon produced from distributed sources, such as transportation (Larry Baxter, presentation).

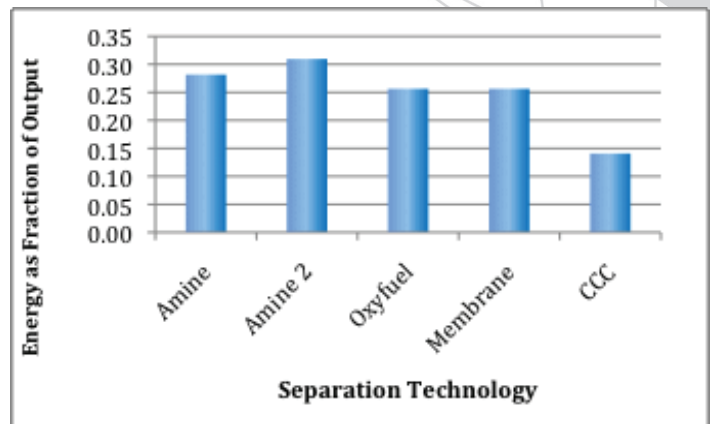


Figure 6: Comparison of energy consumed by different capture technologies as a fraction of total energy output of power facility. CCC is cryogenic capture and can reduce the cost by about a factor of 2 relative to the other capture methods. [Data from Department of Energy (DOE) reports 2007/1281, 2007/1291, and Larry Baxter, presentation].

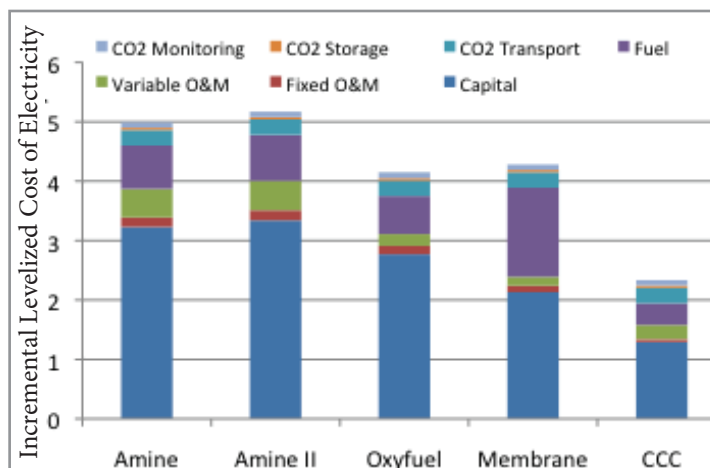
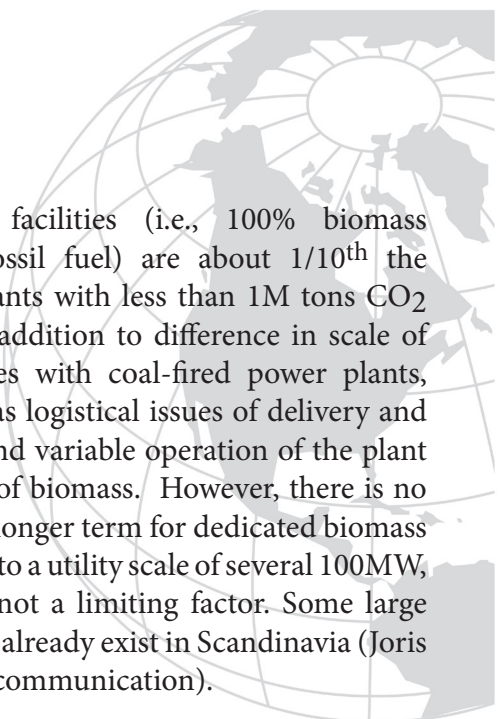


Figure 7: Costs are dominated by equipment and fuel. Both issues can be technically addressed (Data from DOE reports 2007/1281, 2007/1291, and Larry Baxter, presentation).





In the example shown in Figure 8, even without co-firing with biomass, CCC can achieve negative overall CO<sub>2</sub> emissions at operating temperatures easily within current technical and economic limits at about -143 °C. If the same system is co-fired with 10% biomass, negative CO<sub>2</sub> emissions would be achieved at about -117 °C. While negative emissions can be achieved without co-firing (due to capture of some atmospheric CO<sub>2</sub>) and probably at costs significantly less than alternative negative emission systems, the absolute amount of negative CO<sub>2</sub> emissions, as well as the economic and energy costs, improve markedly when co-firing biomass with coal (Larry Baxter, presentation).

Dedicated biomass facilities (i.e., 100% biomass feedstock and no fossil fuel) are about 1/10<sup>th</sup> the scale of fossil fuel plants with less than 1M tons CO<sub>2</sub> per year emitted. In addition to difference in scale of biomass-fired facilities with coal-fired power plants, concerns exist, such as logistical issues of delivery and storage of biomass, and variable operation of the plant based on availability of biomass. However, there is no technical limit in the longer term for dedicated biomass power plants to move to a utility scale of several 100MW, if biomass supply is not a limiting factor. Some large biomass power plants already exist in Scandinavia (Joris Koornneef, personal communication).

## Storage

### CCS

The scalability and implementation of CCS with bio-feedstocks was considered, and some of the issues that might be faced with large-scale deployment of BECCS discussed.

A dedicated facility would also need to obtain biomass feedstock for 30-50 years, and there may be other aspects of using biomass feedstock that present new challenges. For example the flue gas composition may differ from that of a coal-fired facility, may require adjustments in capture options and may vary with biomass feedstock. Co-location of geologic storage, biomass resources, electricity and heat demand are important factors to

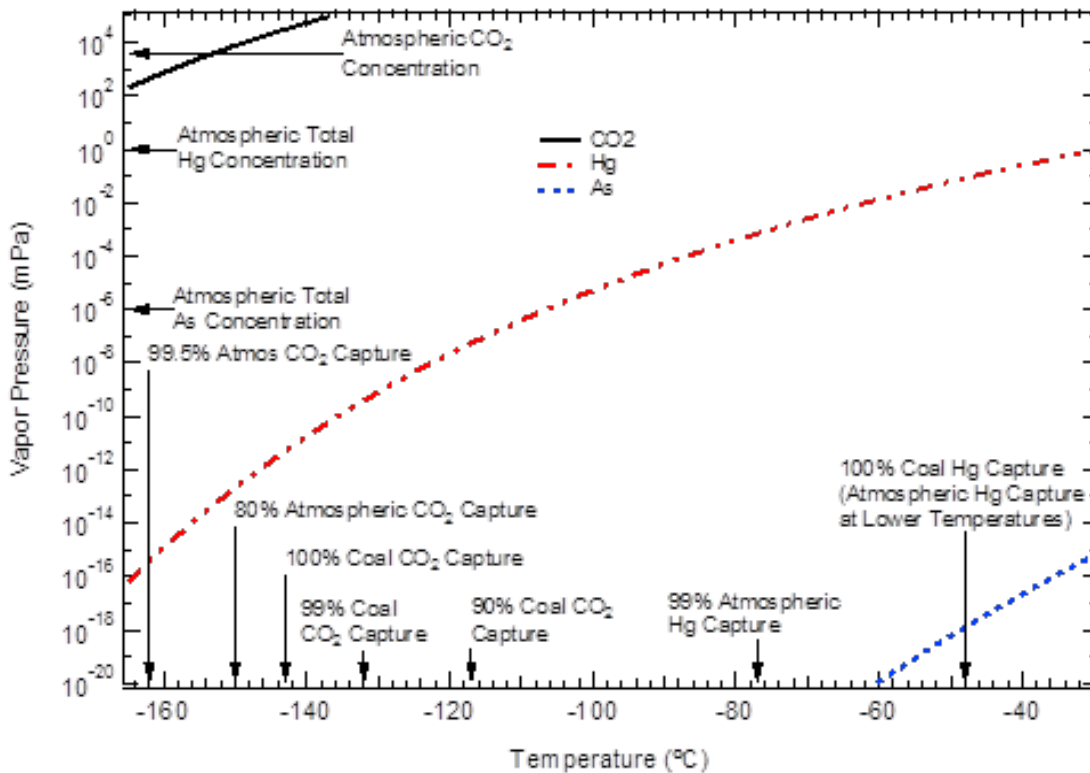
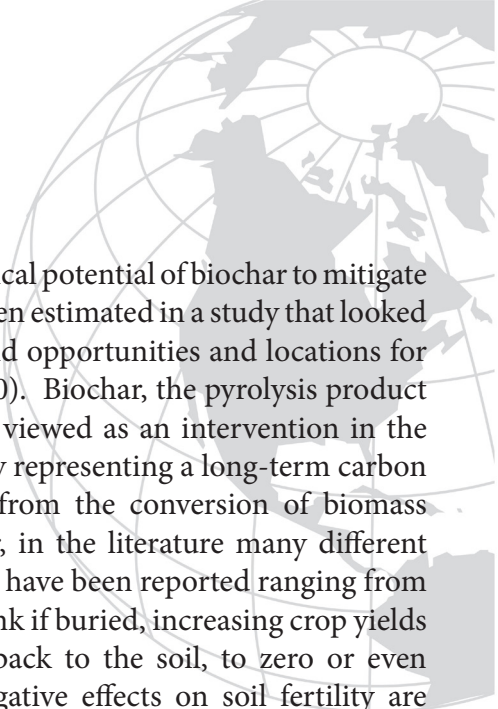


Figure 8: Vapor pressure of CO<sub>2</sub> and selected air toxics as a function of temperature. The markers along the abscissa indicate the minimum temperature that must be achieved to remove the indicated pollutant. For a given % capture of coal pollutant, this means 100% of the pollutant associated with coal combustion is captured, with further capture removing portions of the pollutant in the background air used for combustion. A given amount of atmospheric capture means all of the pollutant from the coal and the given percentage of the pollutant in the background air are captured at that point (Larry Baxter, presentation).



consider and likely requirements for success (Figure 9). Another important factor for large-scale biomass conversion is that it requires the transport and intermediate storage of large amounts of biomass. Biomass pre-treatment to reduce moisture content and increase specific heat content is an important prerequisite for large-scale biomass supply chains (Joris Koornneef, personal communication).

In principle there are no technical limitations to small-scale CO<sub>2</sub> storage, but the major cost drivers are likely to be scale dependent. Information is needed on which capture technology scales most effectively, best manages variable biomass feedstock and operates most reliably in regions where BECCS will be deployed (Sally Benson, presentation). Co-firing as a strategy may be much simpler than the alternative, and several studies presented at the GCEP workshop support this conversion method as a feasible option.

## Biochar

The sustainable technical potential of biochar to mitigate climate change has been estimated in a study that looked at biochar stability and opportunities and locations for use (Woolf *et al.*, 2010). Biochar, the pyrolysis product of biomass, could be viewed as an intervention in the global carbon cycle by representing a long-term carbon store that is gained from the conversion of biomass for energy. However, in the literature many different carbon storage effects have been reported ranging from biochar being a net sink if buried, increasing crop yields and adding fertility back to the soil, to zero or even negative effects. Negative effects on soil fertility are possible in some cases if the biochar properties are not well matched to the soil requirements by mechanisms such as nitrogen immobilization or aggravated pH constraints. Ensuring positive responses to biochar requires that feedstock and pyrolysis conditions are suited to the target soil (Dominic Woolf, presentation).

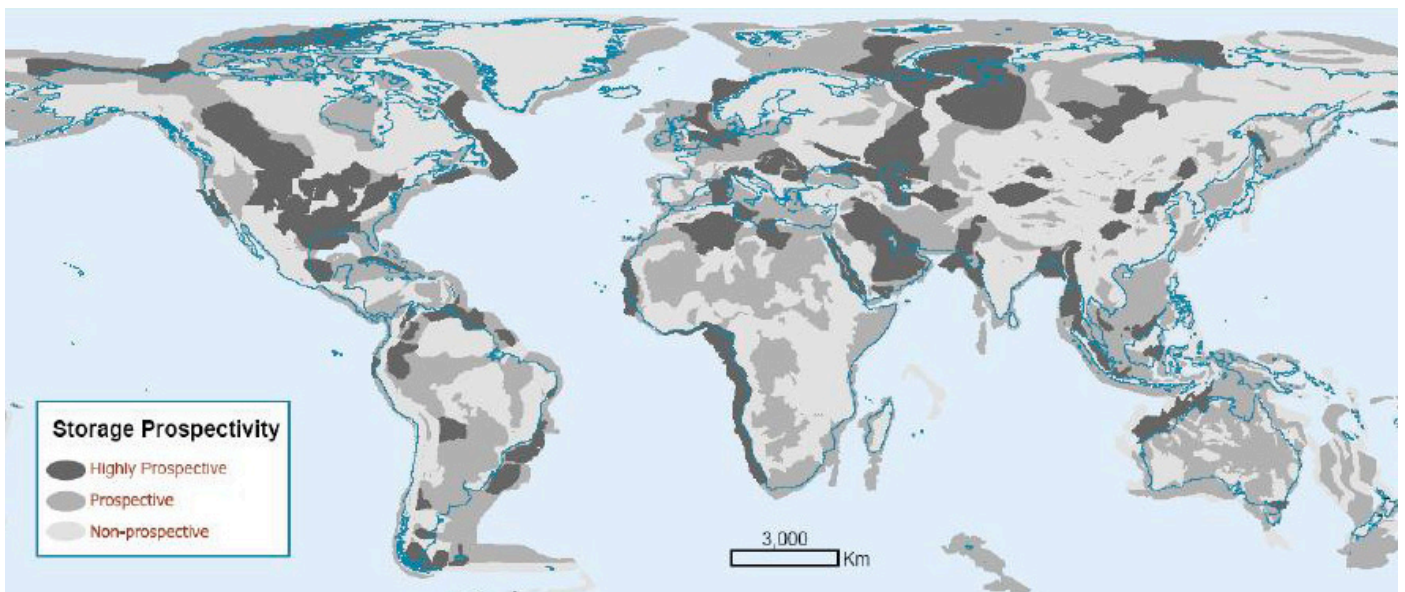


Figure 9: World map showing the location of potential sites for geologic storage. It is interesting to note that many of the highly prospective sites in the U.S. for geologic storage coincide with regions that are suitable for growing biomass (from Sally Benson, presentation).

In common with all biomass-based technologies, net avoided GHG emissions are strongly dependent on the manner in which feedstock is procured. Biochar systems will be net carbon sinks if they utilize waste biomass, sustainably-harvested crop-residues, biomass crops grown on abandoned land that has not reverted to forest, agroforestry timber, or animal manures where their overproduction is a pollutant. On the other hand, production systems that use long-lived carbon stocks (such as woodland), or that require or drive land-use change with a large carbon debt, may cause a net increase in GHG emissions (Dominic Woolf, personal communication).

The stability of biochar depends on the chemical composition of the feedstock from which it is made and on the conversion process. Biochar consists of both labile and recalcitrant components, and the overall stability will depend on the half-life of the recalcitrant fraction and on the labile fraction. Long-term biochar sequestration would require high biochar stability (perhaps with a half-life  $\geq 500$  years over a 500-year time scale). Estimates of biochar half-life vary greatly from  $10^1$  to  $10^7$  years and correlate with the oxygen-to-carbon ratio of the substance, with lower O:C corresponding to a higher half-life. The type of feedstock also contributes to stability, with woods being more stable than grasses and manure. Results suggests that a half-life  $> 1000$  years can be achieved by use of slow pyrolysis at temperatures  $>500$  °C (Dominic Woolf, presentation; and Spokas, 2011). Figure 10

shows a comparison of biomass feedstock converted to biochar and the effects on emissions in three scenarios.

The benefits that biochar can make to the soil depends largely on the nature of the soil to which it is being added. Measures of plant productivity show that benefits from biochar can be gained in very low-fertility soils, but already fertile soils benefit very little. One advantage of biochar over other technologies is that it is simple, distributed and can produce useful products. Comparisons between uses of biomass must consider not just economics, energy and GHGs, but also wider issues, including soil conservation, biodiversity, hydrology and nutrient cycling.

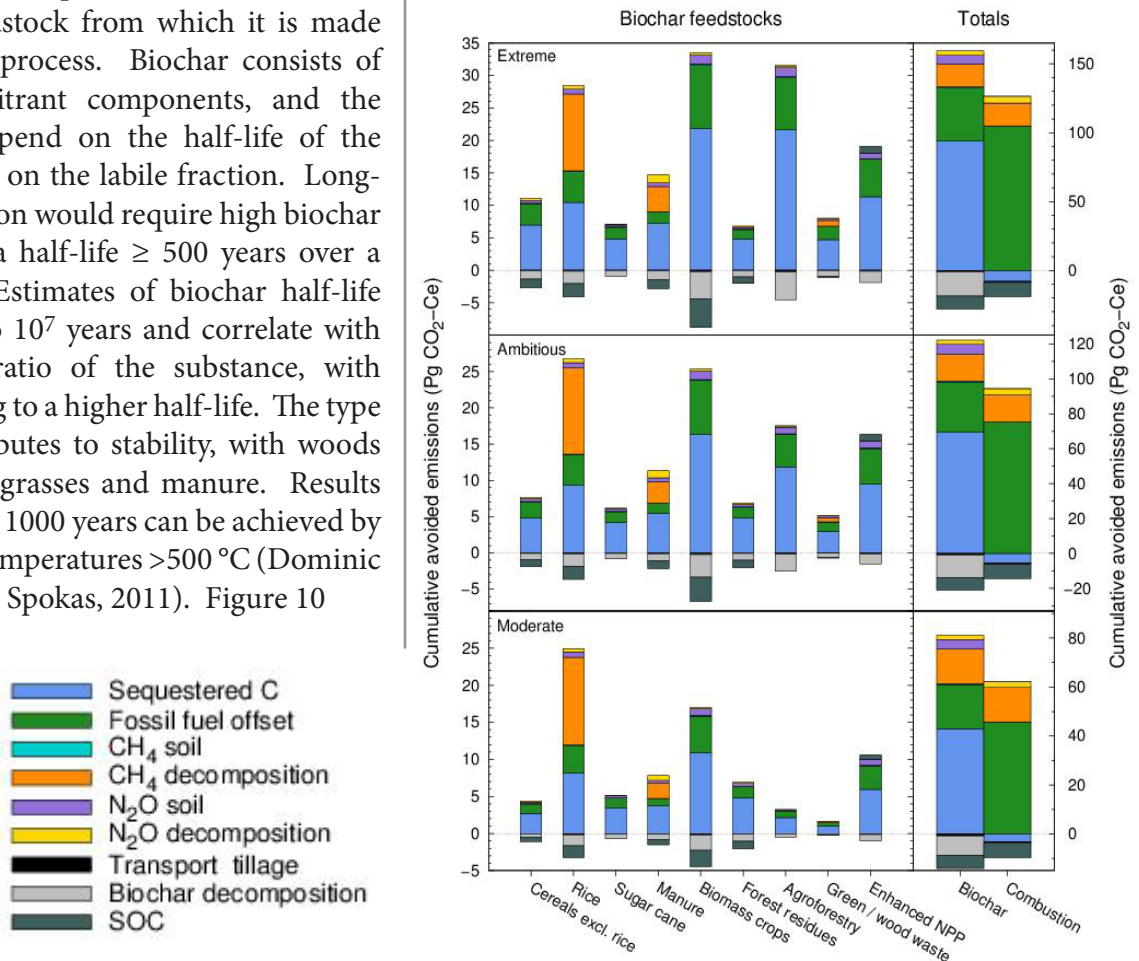
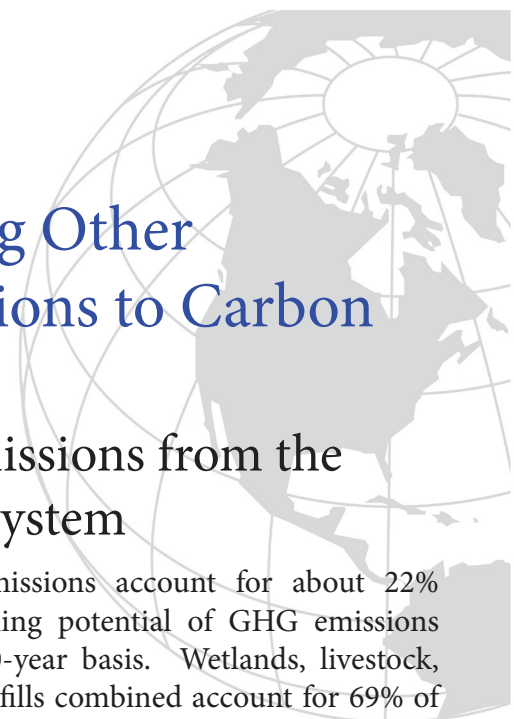


Figure 10: Charts show the estimated cumulative avoided emissions of carbon dioxide for biochar feedstocks from various sources, under three scenarios. The data are for three model scenarios over 100 years by feedstock and factor (extreme, ambitious or moderate). The left side of the figure displays results for eight feedstock types and the additional biomass residues that are attributed to net primary productivity (NPP) increases from biochar amendments; the right side displays total results by scenario for both biochar (left column) and biomass combustion (right column). For each column, the total emission-avoiding and emission-generating contributions are given, respectively, by the height of the columns above and below the zero line. The net avoided emissions are calculated as the difference between these two values. Within each column, the portion of its contribution caused by each of six emission-avoiding mechanisms and three emission-generating mechanisms is shown by a different color. (From Dominic Woolf, presentation; and Woolf *et al.*, 2010).





## Addressing Other Contributions to Carbon Emissions

### Methane emissions from the natural gas system

Methane (CH<sub>4</sub>) emissions account for about 22% of the global warming potential of GHG emissions in the U.S, on a 20-year basis. Wetlands, livestock, agriculture and landfills combined account for 69% of these emissions. The natural gas system accounts for the remaining 31%, primarily from transmission and distribution with approximately 3% coming from well completions (Figure 11). Emissions from natural gas systems can be addressed, but adequate incentives will need to be in place for natural gas entities to invest in preventing these leakages from the infrastructure (Taku Ide, presentation).

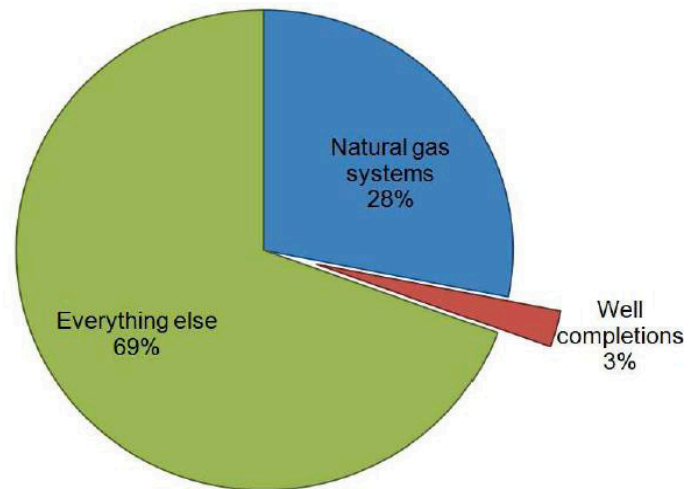


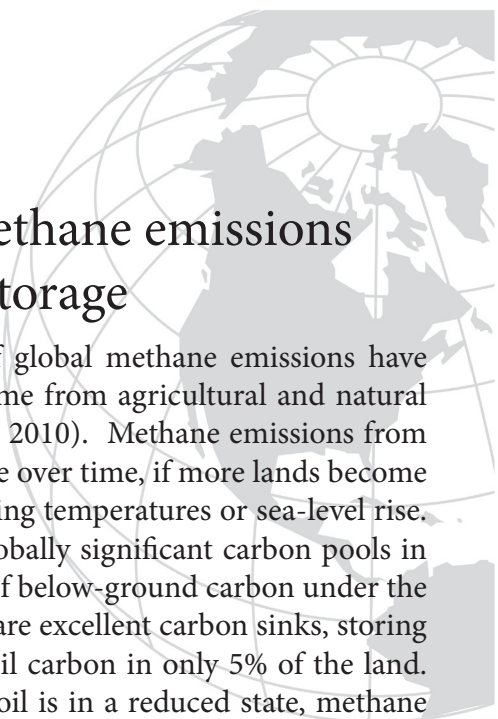
Figure 11: Percentage share of U.S. methane emissions due to well completions for natural gas from shale (from Taku Ide, presentation, and EPA, 2010).

## Oceans and carbon storage

Ocean acidification occurs as the ocean equilibrates with atmospheric levels of CO<sub>2</sub>. This increased uptake of CO<sub>2</sub> in seawater is causing acidification in the upper levels of the ocean, the effects of which can be observed in the dissolution of coral reefs. Adding alkalinity to the oceans is possible, but benefits from this process are limited by slow kinetics (David Keith, presentation). The research community is exploring a number of methods, including adding magnesium (Mg) carbonate and other minerals that interact with CO<sub>2</sub>.

An augmented ocean disposal process was also considered as a technology for negative emissions, as this avoids the need for storage of CO<sub>2</sub> underground. This technology has the potential to be coupled with solids looping calcium carbonate (CaCO<sub>3</sub>)-based BECCS (Paul Fennell, presentation). The mitigation potential of this process could be large due to the large reserves of relevant minerals. Lime production is long established and can be fitted with CCS readily. Ocean disposal is less understood, and the associated risks to the marine environment need to be adequately assessed. Full lifecycle analyses to understand whole-life emissions – including those associated with mining, size reduction, transport and environmental impacts – provide opportunities for research.

Effective ways to sink carbon to the deep ocean to act as a carbon store remain elusive. Precipitation is one mechanism, but it is also important to gain an understanding of the kinetics of the processes and how an augmented ocean disposal method would work. Wetlands can act as a carbon store, and some research suggests that the capacity of certain wetland types to store carbon could be significant. This is discussed in more detail in the following section where methane emissions are also considered.



These emissions may be set to grow over the coming decades (U.S. EIA, 2011), as demand for shale gas increases. Even if the growth path is as predicted, emissions from shale gas operations are small in comparison to other sources of CH<sub>4</sub> in the U.S. and in CO<sub>2</sub> equivalents (being calculated at 48 billion cubic feet per year, which is about 0.6% of U.S. total CH<sub>4</sub> emissions in CO<sub>2</sub> equivalents). However, the impacts may be substantially more if large shale gas developments are not regulated. The lowest hanging fruit to curb these emissions would be to target those from well completions, which mostly occur at the wellhead during flow back (in the case of hydraulic fracturing). Almost all of these emissions can be avoided by implementing existing technologies and careful management practices. Interestingly, even though these leakages represent only 0.2% of the yearly natural gas demand in the U.S, the revenue loss is about \$200M U.S. per year.

To curb methane emissions, EPA has instructed all operators to follow “green completion” guidelines aimed at curbing other gas emissions, such as sulfur dioxide and NO<sub>x</sub>. These guidelines should ensure that CH<sub>4</sub> emissions are kept low provided all contractors comply. Although using existing technologies could prevent emissions from well completions, some of the procedures involved have problems, such as safety and cost competitiveness. There are several opportunities in fundamental science that could help address these issues. For example, minimizing the number of wells drilled with a better understanding of flow physics and subsurface would help shed light on decline curves of some wells, which might then be deemed non-productive due to fast drop off; better defining a “wildcat” well along with better characterization can be used to engineer enhanced oil and gas recovery methods from unconventional shale plays (Taku Ide, and Professor Blasingame).

## Wetlands: methane emissions and carbon storage

As much as 39% of global methane emissions have been estimated to come from agricultural and natural wetlands (Laanbroek, 2010). Methane emissions from wetlands may increase over time, if more lands become submerged due to rising temperatures or sea-level rise. Wetlands generate globally significant carbon pools in soil through storage of below-ground carbon under the water column. They are excellent carbon sinks, storing 20% of the world’s soil carbon in only 5% of the land. However, when the soil is in a reduced state, methane and nitrous oxide are released, which can change wetlands from being a net sink to a net source. At higher latitudes, boreal wetlands are abundant, but a wide variety of wetlands with a wide range of carbon storage and GHG fluxes are found in temperate and tropical zones (Lisamarie Windham-Myers, presentation).

Wetlands in temperate and tropical zones produce methane, and water-depth and temperature changes can determine whether these wetlands are net sources or sinks. In addition, some data suggest that elevated levels of CO<sub>2</sub> might lead to stimulated production of GHGs in wetlands. Where water level is rising, the carbon could potentially remain there forever. But it is hard to quantify the amount of carbon sequestration in wetlands with computer models, since methane emissions also need to be considered, as well as variability in landscape, salinity and plant species (Lisamarie Windham-Myers, presentation).

Some amazing results of carbon storage have been achieved by creating shallowly flooded wetlands to grow “protopeat.” In a field study in California’s San Francisco Bay Delta, protopeat was seen to grow at an average of 2 inches per year, Figure 12. This peat was generated by below-ground growth and was strongly net negative CO<sub>2</sub>.

## System Modeling of Net Negative Carbon Emissions Technologies

A number of speakers discussed the global technical and economic potential of negative emissions technologies. One study from Imperial College, London, compared five potential options for CO<sub>2</sub> capture (negative emissions) technologies: BECCS, artificial trees, lime soda process, augmented ocean disposal and biochar. With a focus on the U.K., estimates saw the potential of BECCS to offset 4-15% of emissions from 9-32% of power demand, adding that a realistic U.K. system would have to get a percentage of its biomass from imports. Several barriers would need to be overcome to realize these potential offsets, including some of the same barriers to adoption facing CCS technology, as well as potential impacts of large-scale biomass plantation, a lack of clarity on direct/indirect land use effects and competition from liquid fuels markets (Paul Fennell, presentation).

In a study for the U.K. Energy Technologies Institute, 28 options for BECCS were screened, including short, medium and long-term options for the CCS component, with different variations of gasification and combustion (Bhave *et al.*, 2012). These options were considered against a number of criteria, including plant efficiency, capital costs with capture, suitability for small scale, deployment potential and technical issues. Further analysis and modeling on a number of potentially viable technologies (and their integration) were presented at the GCEP workshop. Post-combustion calcium looping and integration with ocean liming (Calcliner) was identified as one of the most promising ways to sequester CO<sub>2</sub>. Combinations of conversion technologies with and without biomass, a calcium-oxide based sequestration and a post-combustion calcium looping process were modeled. Preliminary results show a unique synergy between BECCS and ocean liming, where the costs of CO<sub>2</sub> abatement were lower than most other methods, but the cost of electricity may be doubled, Figure 13 (Paul Fennell, presentation).

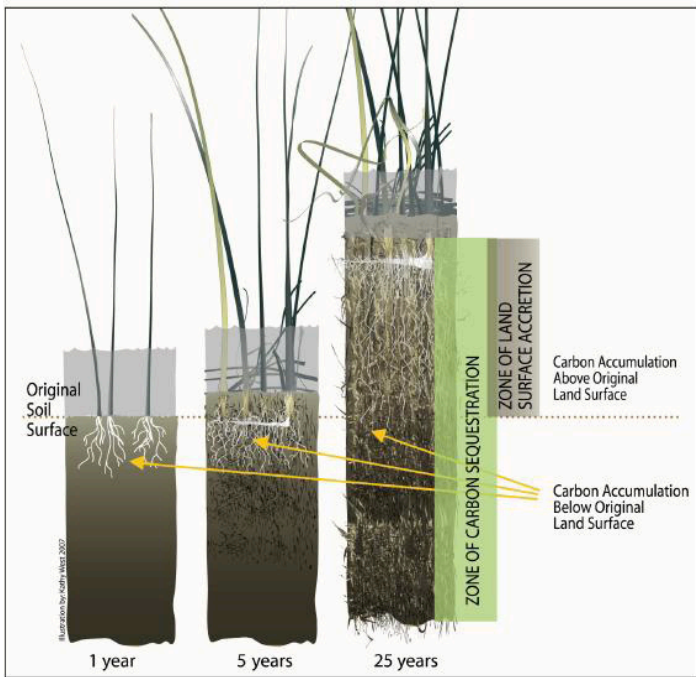
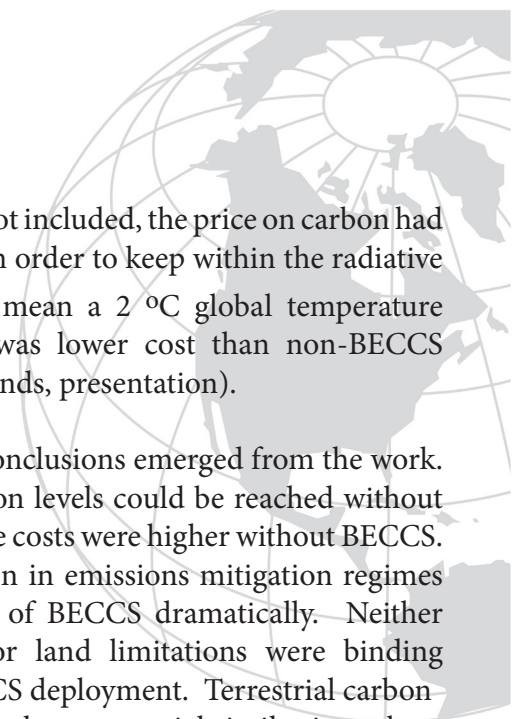


Figure 12: Restoration experiment in the San Francisco Bay Delta. Protopeat growth was at a rate of about 2 inches per year, sequestering 1 kg C/ m<sup>2</sup> annually (from Lisamarie Windham-Myers, presentation).

The carbon storage is impressive, about 1kg C /m<sup>2</sup> per year, rivaling Amazon forest carbon sequestration rates. This represents a new net uptake of CO<sub>2</sub> (~37 Mg CO<sub>2</sub> /ha/yr) in addition to avoided CO<sub>2</sub> emissions due to peat drainage (~20 Mg CO<sub>2</sub> /ha/yr). Temperate conditions promoting high photosynthetic rates during the day and low respiration at night may be particularly beneficial to generating a wetland carbon sink. With moderate methane emissions, GHG balances are net negative CO<sub>2</sub>-eq in this managed wetland, but wider prediction across time and wetland types is difficult due to spatial and temporal variability in methane and nitrous oxide fluxes. Salt marshes are also globally important carbon stores, as there is a lack of methane release but this carbon is sequestered at about one third the rate of the managed freshwater system as described above (Lisamarie Windham-Myers, presentation).





In an integrated assessment using the Global Change Assessment Model (GCAM), Jae Edmonds asked, “Can low stabilization levels be achieved without bioenergy and CCS?” This study considered five technology regimes as shown in Table 2. The most comprehensive suite is referred to as T1 (ref) and includes BECCS. More details on these regimes can be found in Calvin, *et al.*, (2011); Kyle *et al.*, 2009, 2010; Wise *et al.*, (2010); and Clarke *et al.*, (2009). T2 – T4 assume that a technology, such as nuclear, CCS or bioenergy, may not be available. In addition, T5 is a low-technology regime with no CCS or bioenergy, and assumes that existing nuclear will be phased out and no new nuclear plants built.

In these scenarios, neither limits to land availability for biomass nor geologic storage capacity represented constraints on the ability of BECCS to contribute to deep reductions in carbon emissions. A number of important assumptions were made in this assessment that include improvement of crop yields for food products and application of carbon prices to land use change emissions that are incorporated into land rents and therefore food prices. The feasibility of each scenario depends on a price on carbon and many of the lowest cost scenarios involved the use of BECCS (Figure 14).

When BECCS was not included, the price on carbon had to be much higher in order to keep within the radiative forcing that would mean a 2 °C global temperature increase. BECCS was lower cost than non-BECCS scenarios (Jae Edmonds, presentation).

Several important conclusions emerged from the work. First, low stabilization levels could be reached without BECCS; however, the costs were higher without BECCS. Delayed participation in emissions mitigation regimes increased the value of BECCS dramatically. Neither geologic storage nor land limitations were binding constraints on BECCS deployment. Terrestrial carbon storage was shown to have potential similar in scale to geologic storage in GCAM scenarios.

CCS is a high-cost abatement option and a technically immature technology. Therefore, economic and financial instruments are needed to provide incentives to the private sector to invest in CCS. BECCS or technologies that enable net negative carbon should get specific additional incentives.

In one analysis on BECCS, it was found that a subsidy per unit of captured emission from biomass is an

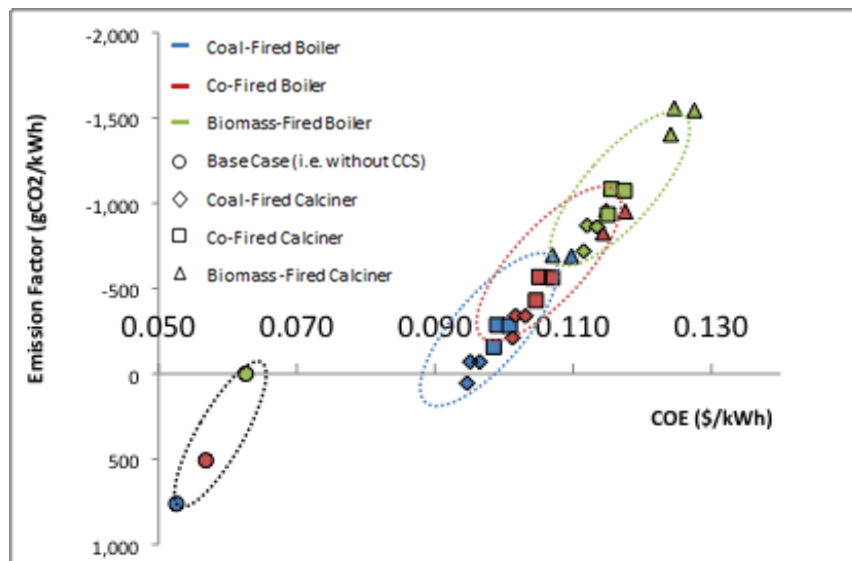


Figure 13: Comparison of the potential cost of electricity (COE) of different technologies with carbon capture as a function of carbon dioxide emissions per unit of power (Emissions Factor gCO<sub>2</sub>/kwh; from Paul Fennell).

adequate incentive for BECCS. Moreover, to meet ambitious climate targets, a cost-effective policy would be to implement a carbon tax and to recycle its revenues to subsidize captured emissions from biomass (Olivia Ricci, presentation, and Ricci, 2012). The carbon tax raises the cost of carbon emissions and increases the competitiveness of CCS, while the emission subsidy encourages BECCS deployment. Moreover, investment

subsidies are also needed to alleviate the initial capital costs of this technology; and whilst financial incentives are probably a necessary part of the future success of BECCS, there are a number of ways to do this. Making the most of the potential of using the captured carbon for the synthesis of fuels or chemicals may be a driver to further enable technologies for carbon capture, storage and utilization that also lead to net negative emissions.

Table 2: Alternative technology assumptions made for each scenario in Figure 14 (from Jae Edmonds, presentation and Luckow *et al.*, 2012).

Technology Set	CCS	Bioenergy	Nuclear Power	Other Technology
T1 (Ref)	Yes	Yes	Ref	Ref
T2 (No CCS)	No	Yes	Ref	Ref
T3 (No Bio)	Yes	No	Ref	Ref
T4 (No Bio & No CCS)	No	No	Ref	Ref
T5 (LowTech)	No	No	Phased out	Ref

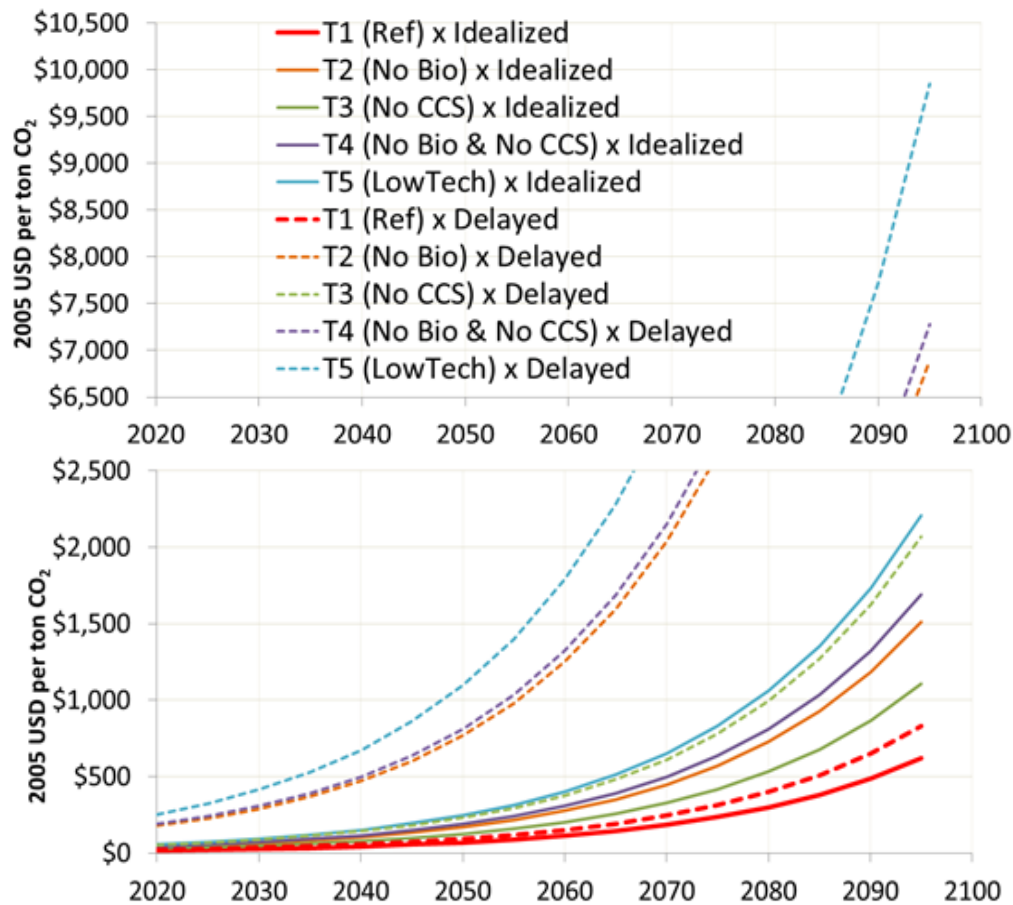
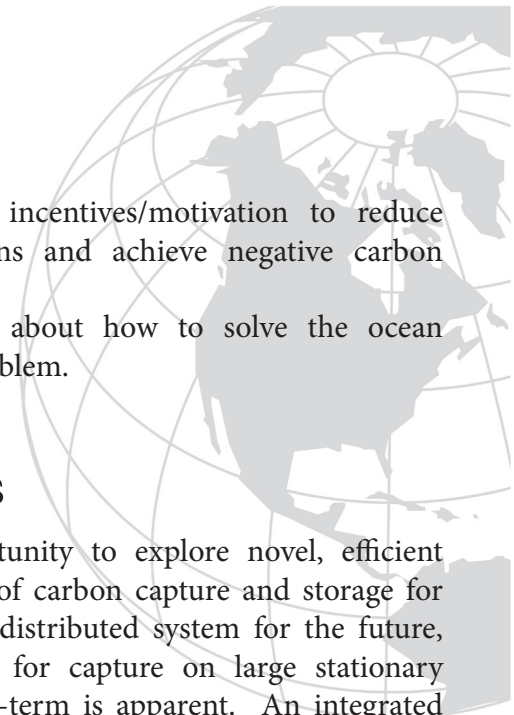


Figure 14: Projected costs of scenarios in the PNNL/JGCRI Global Change Assessment Model Version 3.0 (GCAM 3.0) for mitigation of CO<sub>2</sub>. T1 (ref) x Idealized includes CCS, bioenergy and nuclear. T2 is as T1 but with no bioenergy, T3 is as T1 but with no carbon capture and storage, T4 is as T1 but with neither bioenergy nor CCS, T5 is the low- technology scenario that is like T4 but without nuclear power and lower rates of end-use technology improvements. Delayed scenarios denote a delay until 2030 for phase-in of technologies for Australia and New Zealand, Canada, China, Korea and the U.S.; 2050 for India, Latin America, other South and East Asia; and 2070 for Africa, FSU and the Middle East (from Jae Edmonds, presentation and Luckow *et al.*, 2012).



## Summary

The theme that came out of many of the presentations at the GCEP workshop was that we are in an environment where incentives for reducing emissions are not well established, but motivation is strong, and there are many opportunities to make progress on tomorrow’s carbon emissions whilst simultaneously addressing another problem. If we can begin to focus on ways to capitalize on win-win opportunities that don’t necessarily depend on a price on carbon, we may have a chance at meeting the carbon reductions needed to reach global CO<sub>2</sub> stabilization.

All CO<sub>2</sub> is the same, and there are multiple things we need to do to make a difference. We need to prevent emissions, increase biomass carbon storage and increase efficiency of energy production systems. High efficiency as well as negative emissions systems on large, stationary sources may be essential to successful global climate change management. The need to consider energy and ecosystem in an integrated way is paramount to gaining ground on the runaway emissions predicted in our current trajectory. Also apparent is the need for understanding more fully the roles and implications of parts of the system, from downstream capture to how we manage the land.

In contrast to other energy technologies, there are important constraints and limits on parts of the net negative energy system portfolio. In some cases these constraints are apparent, in others they remain uncertain. What these constraints are at the fundamental technical and economic levels, and how we can push back the limits, are key questions that need to be addressed. The following are some of the major challenges identified at the workshop:

- Need to identify the limits to technologies—availability (and best use) of biomass, land use, availability of alkaline soils for carbon storage by biochar, scalability of CCS systems (up/down).
- Need to develop optimized conversion and storage systems.

- Need financial incentives/motivation to reduce carbon emissions and achieve negative carbon emissions.
- Need to think about how to solve the ocean acidification problem.

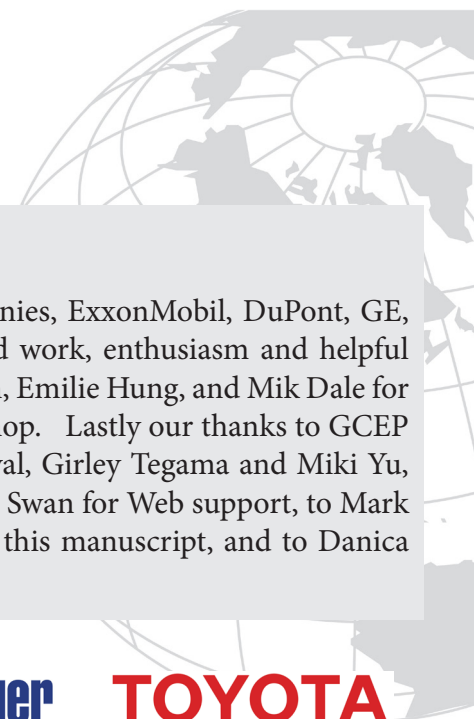
## Conclusions

There is an opportunity to explore novel, efficient and low-cost ways of carbon capture and storage for a potentially more distributed system for the future, although the need for capture on large stationary sources in the near-term is apparent. An integrated system of biomass and fossil fuel with capture may be one of the most cost-effective, efficient and practical ways to move toward achieving net negative emissions on large stationary sources. The potential to increase net negative emissions through the production lifecycle of biomass for this purpose and others is a powerful incentive for this approach.

GCEP could play a key role in identifying the limits discussed above and in addressing them with fundamental research. Some of the important opportunities for GCEP are outlined below:

- Maximized yields for biomass supply with negative emissions—thinking about the whole bioenergy lifecycle from supply and harvesting to processing and conversion, and where negative emissions can be achieved at low cost.
- Integrated and optimized systems (including supply, conversion and storage)—considering the best use of biomass (e.g., use agricultural residues and push down into more marginal fuels, contaminated material/waste and unharvested biomass), optimizing the combustion system and achieving high CO<sub>2</sub> capture (>99%).
- Analysis/combination of a natural system for soil carbon stocks (e.g., protopeat) vs. an engineered system.
- Novel carbon storage and/or utilization technologies (such as augmented ocean disposal as discussed herein).





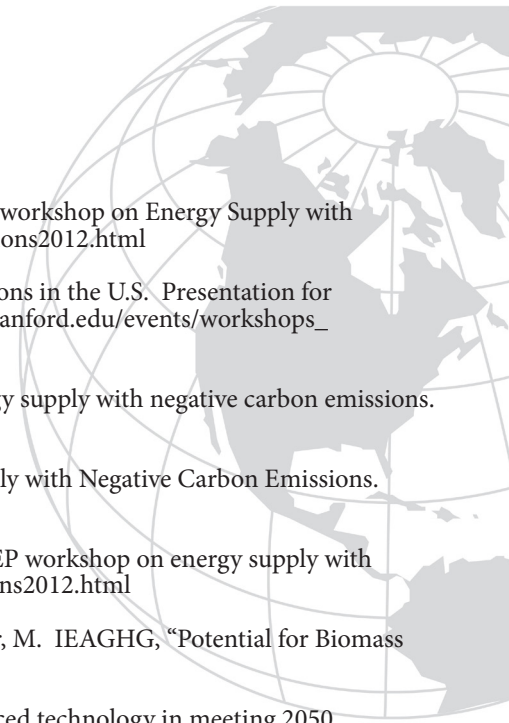
## Acknowledgements

We gratefully acknowledge the generous support of our GCEP sponsor companies, ExxonMobil, DuPont, GE, Schlumberger and Toyota. Thanks especially to all the speakers for their hard work, enthusiasm and helpful comments in finalizing this report. Thanks also to Sally Benson, Richard Sassoon, Emilie Hung, and Mik Dale for their support and intellectual input, which helped make this a successful workshop. Lastly our thanks to GCEP and Precourt Institute for Energy staff especially Leigh Johnson, Nancy Sandoval, Girley Tegama and Miki Yu, for working hard on the meeting logistics and ensuring a smooth event, to Clare Swan for Web support, to Mark Shwartz for capturing photos at the workshop and for his thorough editing of this manuscript, and to Danica Sarlya for her fabulous work on the visual presentation of this final manuscript.



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