Status Report

Carbon Sequestration National Impacts and Benefits Analysis Model (CarBen)

Modeling System Description, Data Sources, And Assumptions,

SEQUESTRATION BENEFITS ANALYSIS MODEL
NATIONAL ENERGY TECHNOLOGY LABORATORY
JANUARY, 2003

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PREFACE

This document provides a status report on the development of the CarBen (Carbon Sequestration Benefits) model for estimating the benefits of pursuing advanced technologies for carbon sequestration as part of a broad portfolio of greenhouse gas (GHG) emission mitigation options. A number of technical papers, presented and published during 2002, provide additional detail on the results of using the modeling system described herein. A specific example is the paper "Economic Benefits of a Technology Strategy and R&D Program in Carbon Sequestration", in the proceedings of the Sixth International Conference on Greenhouse Gas Control Technologies (GHGT6), forthcoming.

This document contains a detailed description of the key data, assumptions and methodology of the CarBen modeling system. In addition, the document presents an updated example calculation of the potential benefits of an intensive National Program of Sequestration research, development, and demonstration (RD&D), plus market-based incentives for one test scenario. The model uses the latest Energy Information Administration's Annual Energy Outlook 2003 (AEO2003) and other recent GHG projections and studies.

The CarBen model is a "work-in-progress," with significant further updates and improvements expected in 2003.

EXECUTIVE SUMMARY

The CarBen model is being developed to provide a capability to analyze questions such as: "If deep reductions in greenhouse gas emissions are necessary over the next half-century, could the United States (U.S.) realize significant economic benefits from having conducted an intensive public/private investment in carbon sequestration research, development and demonstration?" This technology investment and its application would occur over the next 50 years -- a time frame long enough to pursue a strategy of sustained economic growth while stabilizing greenhouse gas (GHG) emissions.

The role for carbon sequestration technology is to be part of a portfolio of strategies and actions. These represent one set of cost-effective actions that could be pursued to fill the gap between a Reduced GHG Emissions scenario and the Reference Case projections for GHG emissions, as set forth in Department of Energy (DOE)/Energy Information Administrations's (EIA) Annual Energy Outlook (AEO) 2003, and extrapolated to 2050 by the model. The Reduced Emissions scenario assumed in this report is based upon achieving the President's Global Climate Change Initiative (GCCI) through 2012, followed by further reductions in the carbon intensity of the Gross Domestic Product (GDP) through 2050. It is but one of many scenarios which could be examined using CarBen.

A portfolio of mitigation options, including advanced technology-based energy supply and demand efficiency, renewables, reduced emissions of methane and carbon sequestration, can be assessed with CarBen for meeting future greenhouse gas emission reduction needs. Fundamental questions that can be examined include -- could an aggressive RD&D effort, coupled with market-based incentives, stimulate industry to apply carbon sequestration technology; and, would having the sequestration option available provide a more cost-effective means for reducing GHG emissions, than if this option were not part of the portfolio?

For the Reduced Emissions scenario presented in this document, the annual benefits from including carbon sequestration in the portfolio of GHG emission reduction options are estimated as follows - - 36 million metric tons of carbon (MMTC) of reduced emissions of greenhouse gases in 2012, 100 MMTC of reductions in 2020, and over 900 MMTC of reductions in 2050, as further discussed below and in related materials.

In addition, the advanced technology programs in methane reduction and enhanced soil/terrestrial uptake of carbon, two areas where the DOE/Fossil Energy (FE) is working collaboratively with Environmental Protection Agency (EPA) and United States Department of Agriculture (USDA), could provide as much as another 8 MMTC of GHG emission reductions in 2012, 15 MMTC in 2020, and over 30 MMTC in 2050.

In the Reference Case scenario, U.S. GHG emissions are estimated to double in the next 50 years, increasing from 1,928 million metric tons of carbon equivalent per year (MMTCE/yr) in 2000 to over 3,880 MMTC/yr in 2050. Under the Reduced Emissions scenario, the carbon intensity of U.S. GDP is reduced by 18% by 2012 to $150 metric tons of carbon (TC) per million dollars of GDP (in $2001), consistent with the President's Global Climate Change Initiative (GCCI). Between 2013 and 2020, emissions are assumed to grow at half the rate projected in the

AEO Reference Case. And, after 2020, emissions are assumed to be stabilized at year 2020 rates. To reach the emission limits in the Reduced Emissions scenario, there would be an increasing need for a robust portfolio of GHG emission mitigation options capable of providing 1,570 MMTC/yr of reductions by 2050.

Table ES1 shows the estimated contributions one such portfolio of options could make toward meeting the assumed scenario of future GHG emission reduction needs, with carbon sequestration making an increasing contribution in the mid- and longer-term.

Table ES1. Portfolio of Mitigation Options for Reducing U.S. GHG Emissions*
(Million Metric Tons of Carbon Equivalent - MMTCE)

		2012	2020	2050
Annual U.S. GHG Emission Reduction Needs		***100***	***240***	***1,570***
Contributions Toward Reductions	Advanced Technology Energy Supply and Demand Efficiency and Renewables	28	68	500
	Reduction in Methane Emissions	9	19	40
	High Technology Reductions in Methane Emissions	5	9	20
	Reduction in Other Non-CO_2 GHGs Emissions	4	9	20
	Forestry & Land Use Changes	15	30	60
	High Technology Forestry & Land Use Changes	3	6	10
	Sub-total for Non-Sequestration	**64**	**140**	**650**
	Early Value-Added Geologic Sequestration	**23**	**70**	**140**
	Target for Advanced Sequestration Technology	**13**	**30**	**780**
	Total	**100**	**240**	**1,570**

*At a carbon shadow price of $50 per metric ton.

I. BACKGROUND AND SCOPE

The President's Global Climate Change Initiative (GCCI), announced in early 2002, emphasized an advanced technology strategy that would enable the United States to provide energy-based goods and services with low net greenhouse gas (GHG) emissions while sustaining economic growth. Carbon sequestration is one part of this advanced technology strategy with the potential to play a significant role. As shown by the example used in this status report, carbon sequestration could become the critical third option that, when combined with advanced technology options of increased energy supply and demand efficiency and renewable energy, can help meet this goal.

The purpose of this document is to articulate the methodology for estimating the benefits (metrics) that could result from an investment in carbon sequestration technology development, demonstration and incentives through an intensive National RD&D Program. This document provides an explanation of the data, assumptions and methodology used to calculate these benefits for one example scenario.

Economic benefits of having carbon sequestration technology in the portfolio of mitigation options would derive from having a more cost-effective portfolio for managing and controlling GHG emissions. Achieving these benefits would require a sustained investment in sequestration RD&D and incentives that could produce environmentally acceptable capture, storage and conversion options. The longer-term goals of the DOE/FE Program are to support the development and introduction of technologies that will: (1) add less than 10% to the cost of energy services for direct capture and sequestration; and, (2) cost less than $10/ton (carbon) for indirect capture and sequestration.

In addition to reducing GHG emissions, carbon sequestration could provide significant value-added benefits. For example, planting trees can stop soil erosion and pollutant run-off and, CO_2 storage in depleting oil reservoirs can provide additional recovery of crude oil. Value-added benefits can also take the form of avoided costs. For example, the use of CO_2 capture and sequestration can lead to lower-cost SO_x, NO_x, and Hg control. The above cost performance goals are net of these value-added byproducts.

In this report, all GHG emission quantities are reported in carbon equivalents. Metric tons of CO_2 are multiplied by the factor 0.273 to convert CO_2 to carbon. Non-CO_2 GHG emissions are converted to equivalent metric tons of CO_2 using 100-year global warming potentials (GWPs) from the Intergovernmental Panel on Climate Change (IPCC) [1]. Importantly, there is not complete agreement in the scientific community as to the most appropriate method for comparing different greenhouse gases. If one looks at shorter GWPs (e.g., 20 to 50 years), the impact of methane emissions on global warming is significantly higher, calling for increased emphasis on controlling this energy related GHG source [2].

Should the model user wish to translate the emission reduction quantity benefits into economic benefits, discounting of costs and benefits will be a key point to consider. Typical cost-of-capital rates of 5 to 15% applied in a standard cash flow model make costs and benefits beyond 20 years inconsequential. Some researchers propose using a low social discount rate of 2 to 3%, or using no discounting at all, for future environment enhancing investments. (Another approach is to use "real options" methodology to provide a more rigorous assessment of the costs and benefits over a range of future scenarios.) An option in the CarBen model is to calculate annual future economic benefits in constant year 2001 dollars. As such, the model discounts the economic benefits at the rate of future inflation.

The structure, calculations and data contained in the CarBen model have been developed by Advanced Resources International (ARI). As shown in Figure 1, the CarBen modeling system is founded on the general equilibrium results from the Energy Information Administration's (EIA's) National Energy Modeling System (NEMS). CarBen integrates the results from NEMS with the Value-Added Geologic Sequestration sub-model, the marginal abatement cost curves (MACs) for non-CO_2 greenhouse gases from EPA, and expectations for the role of forestry and land use changes from USDA and other sources to provide a robust simulation of domestic GHG mitigation options. CarBen incorporates technology progress, including pursuit of DOE's Carbon Sequestration Program cost goals, in a manner consistent with technology progress methodology in NEMS. And, it includes the ability to assess market-based incentives for carbon sequestration.

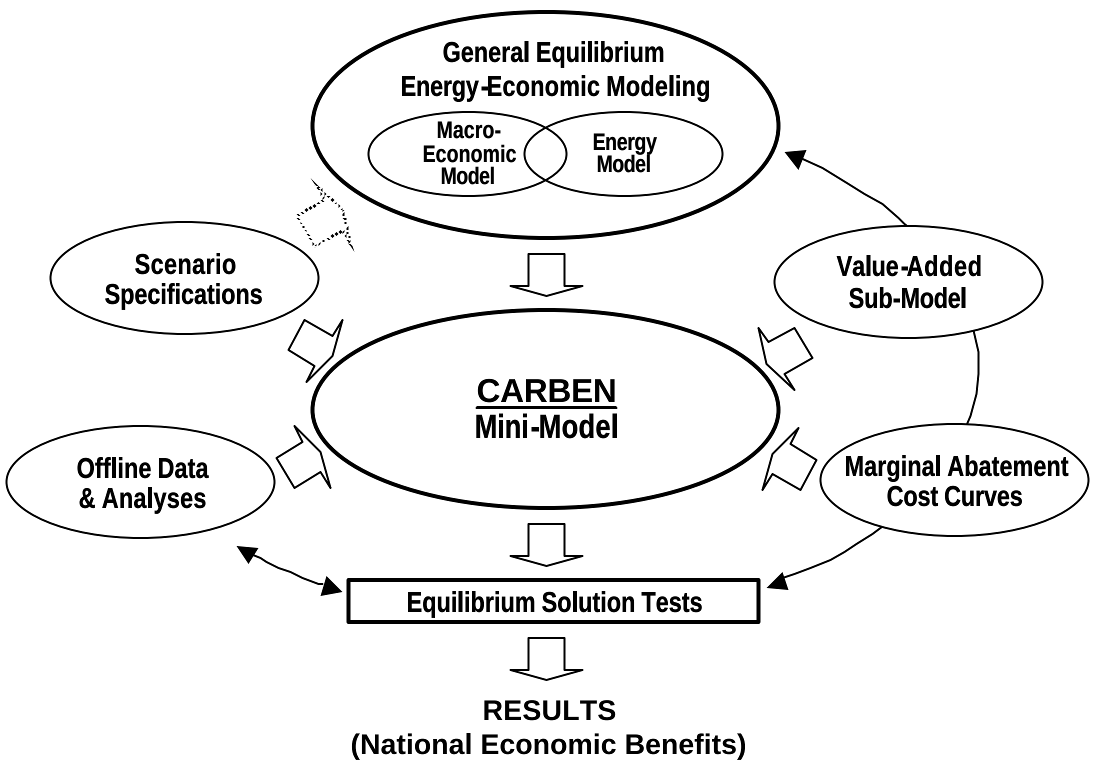


Figure 1. CarBen Modeling System

The CarBen model contains a set of sub-models that employ marginal cost versus emissions reduction supply functions. These are dynamic over time, based upon user-specified "technology advancement", "time of availability" and "market penetration" parameters. The model then calculates the economically competitive quantities of emission reductions from each sub-model based upon a shadow price for the assumed GHG emission constraint, as derived from general equilibrium modeling and the Reduced Emissions scenario.

CarBen extrapolates the near-to-mid-term GHG emission projections from NEMS, EPA and other sources to year 2050. The 50-year time frame is needed to fully evaluate the strategy of sustaining economic growth while or reducing GHG emissions. Attempts to model the costs and performance of specific technologies for more than 50 years are too uncertain for the technology-based assessments central to CarBen.

In summary, CarBen calculates -- for each 5 year time period through 2050 -- the cost-effective contributions that carbon sequestration and other advanced technologies can provide for meeting the Reduced Emissions scenario.

The CarBen model and individual sub-models continue to be expanded and updated using ongoing studies and improved technology data. Alternative reduced emissions scenarios are also being considered for examining different “pathways to stabilization.” The results of these updates will become available later in 2003.

II. BENEFITS ANALYSIS MODEL AND SCENARIOS

This section describes the scenarios, data and assumptions used by CarBen to calculate the benefits of carbon sequestration technology. The input data in this version of CarBen are based on the most recent modeling runs, emission inventories and studies. As such, the results represent an update to previous papers and presentations that have been based on the CarBen model.

A. Reference Case Scenario

The Reference Case GHG emissions scenario includes CO_2 emissions from energy use, CO_2 from other sources, and non-CO_2 GHGs leading to a doubling of GHG emissions between now and 2050, as shown on Table 1. A discussion of the data sources and assumptions for each GHG emission source follows.

Table 1. Reference Case Scenario for U.S. GHG Emissions
(Million Metric Tons of Carbon Equivalent – MMTCE)

		2000	2012	2020	2050
CO_2 Emissions from Energy Use	Petroleum	659	797	902	
	Natural Gas	341	415	472	
	Coal	579	650	709	
	Sub-Total	1,578	1,862	2,083	3,246
	CO_2 Adjustments	(13)	(12)	(12)	(12)
	Total CO_2 from Energy	***1,565***	***1,850***	***2,071***	***3,234***
Other CO_2 Emissions	Gas Flaring	2	2	2	2
	Natural Gas Processing	5	7	9	10
	Cement Production	11	14	15	24
	Other Industrial Activity	14	17	19	30
	Total CO_2 from Other	***32***	***40***	***45***	***66***
	Total CO_2	***1,598***	***1,890***	***2,116***	***3,300***
Non-CO_2 GHGs Emissions	Methane, Natural Gas	38	44	50	52
	Methane, Coal Mines	21	22	21	21
	Methane, Energy Other	10	12	13	15
	Methane, Energy-Subtotal	69	78	84	88
	Methane, Landfills	57	54	48	40
	Methane, Other	52	52	52	52
	Methane, Sub-Total	178	184	184	180
	N_2O	118	129	138	168
	High GWP Gases	34	66	112	232
	Total Non-CO_2 GHG	***330***	***379***	***434***	***580***
Total Reference Case GHG Emissions		**1,928**	**2,269**	**2,550**	**3,880**
Reduced Emissions Scenario		**--**	**2,169**	**2,310**	**2,310**
GHG Emissions Reduction Needs		**--**	**100**	**240**	**1,570**

1. CO_2 from Energy Use. CO_2 emissions from energy consumption are from the Reference Case projections in the Annual Energy Outlook (AEO) 2003, Table A19 [3]. The AEO 2003 projections to year 2025 assume an average GDP growth of 3% per year and an average reduction in carbon intensity of GDP of 1.5% per year. This gives a net growth in emissions of CO_2 from energy use of 1.5% per year. CarBen extrapolates the EIA projections beyond 2025, by continuing the 1.5% rate of GHG emissions growth through 2050. As such, CO_2 emissions from energy consumption of 1,578 MMTC in 2000 and 1,862 MMTC in 2012 are estimated to increase to 3,246 MMTC in 2050.

Adjustments to U.S. energy consumption emissions are made to: (1) add emissions from U.S. Territories (14.3 MMTC in 2000), and; (2) remove military and international bunker fuels (27.6 MMTC in 2000). These adjustments are estimated to reduce carbon emissions totals by 13 MMTC in 2000 and by 12 MMTC per year thereafter.

2. Other CO_2 Emissions. The other CO_2 emission estimates for year 2000 are from the EIA 2002 report, "Emissions of Greenhouse Gases in the United States 2001" [4]. The main areas are gas flaring, natural gas processing, cement production, and other industrial activity including waste combustion.

Emissions of CO_2 from gas flaring are assumed to remain constant at 2 MMTC per year through 2050 as potential emissions due to increased natural gas production and refinery capacity are countered by industry's efforts to reduce flaring.

Emissions of CO_2 from natural gas processing are assumed to grow at a higher rate than overall domestic natural gas production due to the expected pursuit of deeper and higher CO_2 content natural gas deposits. (Advanced Resources International (ARI) estimates that the average CO_2 content of natural gas will increase by 50% between 2000 and 2025 and remain constant after that date.)

CO_2 emissions from cement production and other industrial activity (including waste combustion) are assumed to grow at a rate of 1.5% per year, consistent with growth of domestic GDP of 3% per year and a reduction in energy intensity of 1.5% per year.

Total other CO_2 emissions are projected to increase from 32 MMTC in 2000 to 40 MMTC in 2012, consistent with estimates in the "U.S. Climate Action Report " (CAR) [5], and are estimated to further grow to 66 MMTC by 2050.

3. Non-CO_2 GHG Emissions. Non-CO_2 GHGs include methane (CH_4), nitrous oxide (N_2O), and high global warming potential (HGWP) gases.

Anthropogenic emissions of CH_4 are from three main sources: energy use (e.g., natural gas systems, coal mining, oil production plus transport, and combustion of wood and fossil fuels); landfills; and, other sources (e.g., livestock manure, enteric fermentation).

Projections of CH_4 emissions from energy use through 2025 are taken from AEO 2003 [3]. EIA projections for methane emissions from energy use (as opposed to estimates provided in the CAR) are used in CarBen for consistency with the AEO 2003 Reference Case. Estimates of methane emissions from energy use after year 2025 are held constant.

The estimates for CH_4 emissions from landfills and other sources are taken from two EPA documents, "Final Report on U.S. Methane Emissions 1990-2020" [6], and "Addendum to U.S. Methane Emissions 1990-2020" [7]. Emissions from landfills are expected to begin to decrease after 2005 due to the deployment of mandated landfill gas recovery systems and are expected to continue their decline through 2050. Methane emissions from other sources are estimated to remain relatively stable throughout the forecast period.

Overall methane emissions are expected to increase slightly from 2000 to 2010 and remain relatively stable after this time as methane capture from landfills and coal mines counters increases in emissions from natural gas systems and combustion of wood and fossil fuels.

It is important to note that the estimates for methane emissions in the Reference Case already account for the significant voluntary emission reductions being achieved by EPA's Climate Change Action plan (CCAP), including the exemplary Natural Gas Star and Coalbed Methane Outreach programs. These voluntary programs are estimated by the EPA to reduce "baseline" methane emissions (emission estimates absent EPA efforts) by 20 million metric tons in 2010 [6]. As such, methane emissions in the Reference Case are estimated at 178 MMTC for 2000, 184 MMTC for 2012 and 180 MMTC for 2050.

N_2O emissions are primarily from agriculture and mobile combustion, with power plants contributing roughly 4% of year 2000 emissions. The estimates for N_2O emissions in CarBen are taken from the "U.S. Climate Action Report" (CAR) [5]. The CAR's N_2O emissions projections for 2000 through 2020 show a growth of 1 MMTC per year. This annual increase in N_2O emissions is maintained through 2050. Based on this, N_20 emissions in the Reference Case are estimated at 118 MMTC for 2000, 129 MMTC for 2012, and 168 MMTC for 2050.

Information on High Global Warming Potential (HGWP) emissions is from the "U.S. Climate Action Report" (CAR) and the EPA 2001 report, "U.S. High GWP Gas Emissions 1990-2010: Inventories, Projections, and Opportunities for Reductions" [8]. Annual emissions of HGWPs have increased by 30% over the past ten years, and the CAR projects an annual increase of about 4 MMTC per year between 2000 and 2020.

The CAR HGWP projections assume that the Clean Air Act authorized Significant Next Alternative Policy (SNAP) program will lead to HGWP emissions reduction of 43 MMTCE in 2010 and that successful implementation of EPA's voluntary programs will reduce HGWP emissions by 17 MMTCE by 2010. The CAR HGWP projections are used through 2020 and the CAR projected annual increase in HGWPs emissions is maintained through 2050. HGWP emissions in the Reference Case are estimated at 34 MMTC for 2000, 66 MMTC for 2012, and 232 MMTC for 2050.

Total non-CO_2 GHG emissions in the Reference Case are estimated at 330 MMTC in 2000, 379 MMTC in 2012 and 580 MMTC in 2050.

4. Total CO_2 Emissions. The combination of GHG emissions sources presented above lead to Reference Case carbon emissions of 1,928 MMTC in 2000, 2,269 MMTC in 2012 and 3,880 MMTC in 2050, as shown previously in Table 1.

B. Reduced Emissions Scenario

1. Calculation of Needed Reductions. The Reduced Emissions scenario in this report is based on the following assumptions with respect to future GHG emissions:

- 2002 – 2012: GHG intensity is reduced to 150 metric tons carbon (TC) per million $GDP, 18% below the estimated year 2002 GHG intensity, as set forth in the GCCI.
- 2013 – 2020: Annual GHG emissions growth rate is set at 50% of the AEO 2003 Reference Case growth rate.
- 2021 – 2050: Annual GHG emissions are assumed stabilized at year 2020 levels.

This scenario is but one of many which could be examined. The emissions reduction need, shown on the bottom row of Table 1, is equal to the difference between the Reference Case and Reduced Emissions scenario. Based on the latest EIA AEO 2003 Reference Case projections for carbon emissions in 2012, an additional reduction of 100 MMTC will be required in 2012 to meet the 150 MMTC per million $GDP that underlies the 18% GHG intensity goal set forth in the GCCI.

The quantity of domestic GHG emissions reduction required (or needed) is calculated as the difference between the Reference Case scenario and the Reduced Emissions scenario, as follows:

$$Q_{need} = Q_{ref} – Q_{red}$$

where:

Q_{need} Annual U.S. GHG emissions reduction need

Q_{ref} U.S. GHG emissions under the Reference Case scenario (in this case, the AEO 2003 Reference Case)

Q_{red} Reduced U.S. GHG emissions under a Reduced Emissions scenario

2. Emissions Reduction Backstop. The model currently includes a "non-sequestration backstop" costing $50 per metric ton carbon (TC), which is set to remain constant throughout the analysis period. In energy modeling terms, this is implemented through the use of a supply curve or a demand reduction function that can provide an infinite quantity of GHG emission reductions at $50/TC. Alternative backstop forms can be examined.

Table 3 shows the results of several published analyses of CO_2 and multi-pollutant emission reduction costs performed by EIA in response to requests from Congress. (These EIA analyses are summarized in AEO 2003.) The results from these EIA studies project that the cost for CO_2 emissions reductions could vary from $54 to $135/TC for these cases.

The reader should note that there are several important differences between the EIA analyses and the assumptions used in this report. For example, the EIA cases analyzed for Congress allow for international carbon trading. The cases also require more aggressive near-term reductions in carbon emissions than used in the Reduced Emissions scenario and allow more shift from coal to natural gas than in the AEO Reference Case or the Integrated High Technology Case used in CarBen.

Table 3. Estimates of the Cost of CO_2 Emission Reductions from Existing EIA Analyses

Requester	Conditions	Cost of CO_2 emission allowances ($/mtC)	
		2010	2020
House Committee on Government Reform	CO_2 capped at 1990 level	84	71-135
Smith-Voiovich-Brownback	CO_2 capped at 2008 level, (NO_x 50% below 1997, SO_2 50% below Title IV, Hg 50% below 1999)	-	54
Jeffords and Lieberman	CO_2 reduced to the 1990 level, (NO_x 75% below 1997, SO_2 75% below Title IV, Hg 90% below 1999)	69-93	58-122

In the assumed emission reduction scenario, beyond 2020, the amount of emissions reduction needed increases dramatically as emissions are stabilized (or reduced) while the economy continues to grow, implying a higher carbon shadow price to meet reduction needs. At the same time, advances in technology could introduce other options for mitigating CO_2 emissions. The current version of the CarBen model assumes that these two factors cancel each other and that the shadow price of non-sequestration emissions reduction remains at $50/TC throughout the analysis period.

On balance, it is likely that the $50/TC backstop assumption will prove to be optimistically low, given the large quantities of emission reductions already imbedded in the Reference Case and in the Integrated High Technology Case (as extrapolated). A higher value for the backstop would increase the amounts of cost-effective emission reductions needed from carbon sequestration technologies.

C. Emissions Reduction Options

Carbon sequestration is one of the technologies, from a portfolio of GHG mitigation options, used to meet the emissions reduction need. (The current version of the model assumes that emission reductions would be achieved without purchase of GHG emissions credits from foreign countries.) The equation below lists the technologies and approaches considered in the model.

$Q_{need} - (Q_{eff\&rnew} + Q_{terr} + Q_{HTterr} + Q_{nonCO2} + Q_{HTnonCO2}) = \mathbf{Q_{VAgeoseq} + Q_{ADVseq}}$

Where:

Q_{need}	The U.S. carbon emissions reduction need
$Q_{eff\&rnew}$	Reductions achieved with energy supply and demand efficiency and renewables
Q_{soil}	Reductions achieved with increased carbon storage in soils and terrestrial ecosystems.
Q_{HTsoil}	Increased reductions in soils and terrestrial eco systems with advanced technology
Q_{nonCO2}	Reductions achieved in non-CO_2 GHGs
$Q_{HTnonCO2}$	Increased reduction of non-CO_2 GHGs with advanced technology
$\mathbf{Q_{VAgeoseq}}$	**Reductions achieved with early value-added geologic storage**
$\mathbf{Q_{ADVseq}}$	**Reductions met with advanced sequestration technology**

As noted in the equation above, both current technology and advanced technology options are assumed for carbon uptake in soils and terrestial systems, for reduction of non-CO_2 GHG emissions, and for early value-added geologic storage.

The contribution from advanced technology-based energy supply and demand efficiency, renewables, terrestial systems, and non-CO_2 GHGs are estimated independently and their sum is subtracted from the emissions reduction need. Value-added geological storage is applied next, with residual emissions reduction assumed to be met by advanced sequestration technology. Q_{ADVseq} represents all capture and sequestration options not included in "early value-added" or other categories.

The methodologies and assumptions behind the estimated contribution from each of the options are discussed below. Table 2 summarizes the model outputs assuming a shadow price for carbon of $50/TC, and the Reduced Emissions scenario.

Table 2. Potential Sources of GHG Emission Reductions in the U.S. through 2050 (Million Metric Tons, Carbon Equivalents)

	2012	2020	2050
*Annual U.S. GHG Emission Reduction Needs**	***100***	***240***	***1,570***
Advanced Technologies for Energy Supply and Demand Efficiency and Renewables	28	68	500
Reduction in Methane Emissions	9	19	40
High Technology Reduction in Methane Emissions	5	9	20
Reduction in Other Non-CO_2 GHGs	4	9	20
Forestry and Land Use Changes	15	30	60
High Technology Forestry Land Use Changes	3	6	10
Sub-Total for Non-Sequestration	**64**	**140**	**650**
Early Value-Added Geologic Sequestration	**23**	**70**	**140**
Target for Advanced Sequestration Technology	**13**	**30**	**780**
Total	**100**	**240**	**1,570**

**At a carbon shadow price of $50 per metric ton.*

1. ***Advanced Technology Energy Supply and Demand Efficiency and Renewable Energy Systems.*** The Reference Case in AEO 2003 already assumes significant increases in the use of renewables and improvements in energy supply and demand efficiency. The following are a few examples of the rates of change in selected renewable energy sources and efficiency improvements between 2000 and 2025 contained in the AEO 2003 Reference Case:

- 550% increase in the use of wind power for power generation,
- 140% increase in the use of ethanol fuel for transportation,
- 100% increase in solar thermal heating systems, and
- 9% increase in the fuel efficiency of new light duty vehicles (24.1 to 26.1 mpg).

The Reference Case also includes efficiency improvements in coal, oil, and natural gas production as well advanced fossil fuel conversion systems. For example, the use of higher efficiency combined heat and power for electricity generation is assumed to increase by 45% by year 2025.

In CarBen, the advanced technology energy supply and demand efficiency and renewables module calls for these contributions toward emissions reduction in addition to the contributions already imbedded in the AEO 2003 Reference Case. The AEO 2003 contains an "Integrated High Technology Case" (Table F4) which assumes that increased spending on research and development will result in earlier introduction, lower costs, and higher efficiencies for end use technologies than assumed in the Reference Case. This case (like the Reference Case) assumes the continuation of existing market incentives for efficiency and renewables.

In this "Integrated High Technology Case," which combines the high technology cases for the residential, commercial, industrial, transportation and electric power sectors, carbon dioxide emissions in 2012 are projected to be 55 MMTC less than in the Reference Case. As such, the EIA Integrated High Technology Case project, overall energy intensity to decline by about 1.8% per year through 2025, compared to 1.5% per year in the Reference Case, due to the introduction of new practices and technologies.

The "Integrated High Technology Case" assumes that significant additional advances will occur in energy efficiency and renewables [9], for example:

	Reference Case	**High Technology Case**
Wind Power (in 2015)		
• Capital Cost ($/kW)	$992	$919
• Capacity Factor	42%	46%
Solar Thermal (in 2015)		
• Capital Cost ($/kW)	$2,292	$2,999
• Capacity Factor	42%	75%
Advanced Coal (in 2015)		
• Capital Cost ($/kWh)	$1,290	$998
• Heat Rate (Btu/kWh)	7,200	6,104

CarBen takes a "risk adjusted" approach for incorporating the additional emission reductions identified in the EIA "Integrated High Technology Case." In the Reduced Emissions scenario reported here, the model assumes that advances technologies in energy supply and demand efficiencies for renewables will lead to annual declines in energy intensity of 1.65% per year by 2025, increasing to the full 1.8% annual decline in energy intensity by 2050. The emission reductions presented in Table 2 are the "expected value" of additional contributions of advanced energy supply and demand efficiency and renewables to reductions in carbon emissions, beyond the substantial contributions already included in the Reference Case. Alternative "risk-adjusted" can also be examined.

2. Reduction in Emissions of Non-CO_2 GHGs. Cost-effective reductions of methane emissions can be achieved in exploration and production, coal mines, landfills, transportation systems, and refineries. Similarly, additional reductions of nitrous oxides (N_2O) and high greenhouse warning potential (HGWP) gas emissions are also possible. These emission reductions are in addition to the substantial methane and other non-CO_2 GHG emission reductions already being achieved by EPA's voluntary programs and captured in the Reference Case.

The Reference Case estimates account for approximately 20 MMTC of reductions in methane emissions due to the successful implementation of EPA's Climate Change Action Plan (CCAP). However, the emission reductions beyond those achieved by voluntary actions are assumed to require a shadow price or an incentive. The marginal abatement curves (MACs) for best available technology (BAT), from EPA's initial methane inventory report of September, 1999, with updates provided in December, 2001 [5,6], are used in CarBen to estimate these additional reductions in methane and HGWP emissions.

For example, at a $50 per metric ton of carbon shadow price, the EPA MACs shows an ultimate methane reduction potential of 57 MMTC. The EPA estimates that 20 MMTC of these emission reductions, primarily the reductions available at no net costs, will occur by 2010 due to EPA's voluntary programs in their Climate Action Plan. These voluntary emission reductions are already included in the reduced methane projections in the Reference Case. As such, the available MAC for 2010 at a $50 per MMTC shadow price is 37 MMTC.

Industry's implementation of methane reductions is expected to follow a classical market penetration curve, with twenty-five percent implementation by 2012, fifty percent by 2020 and one hundred percent by 2050. The front-end shifted market penetration curve assumes EPA's early success in transferring "best available" technology.

A similar MAC approach is used for estimating emission reduction opportunities for HGWP gases, using the data provided by EPA in June 2001, "U.S. High GWP Gas Emissions 1990-2010" [8]. The expected reduction in HGWP emissions due to EPA's voluntary climate action programs is estimated by EPA at 17.4 MMTCE by 2010. The available HGWP MAC for 2010 at a $50 per MMTC shadow price is reduced by this quantity.

At the time of the latest CarBen model run, MACs were not available for N_2O. As such, only the voluntary reductions achieved by EPA's programs, already imbedded the Reference Case, are considered at this time. Future work is contemplated to make the treatment of N_2O in CarBen consistent with the other non-CO_2 GHGs.

3. High Technology Reductions in Non-CO_2 GHGs. The assumption is that DOE/FE will work collaboratively with the EPA methane emissions reduction program to pursue R&D-based advances in methane emissions reduction technology. Specifically, DOE/FE has plans to undertake a series of R&D efforts that would shift the MACs for methane emissions such that fifty percent more methane emissions reductions are available at each shadow price compared to implementation of currently best available technology.

4. Sequestration in Soils and Terrestrial Systems. The USDA, in cooperation with EPA, is leading the national effort to develop land management techniques for increasing the amount of carbon stored in forests and agricultural soils. Technologies developed by DOE's Carbon Sequestration Program could complement the efforts by USDA and be valuable for enabling large-scale, economically attractive domestic agriculture and forestry sequestration projects to receive credit for GHG emission reductions.

McCarl and others have performed an analysis of domestic opportunities for carbon sequestration in soils and terrestrial ecosystems and have developed cost-supply curves for sequestration potential in agricultural soils and forests in the United States [10]. Their cost-supply curves are used to estimate the annual sequestration rate achievable at a given GHG emissions shadow price. The cost-supply curve in CarBen for this area accounts for competition for land from various uses and also for the costs of long-term maintenance and monitoring. The cost-supply curves from McCarl and others for agricultural soils for afforestation (an area with considerable uncertainty) are adjusted to account for the expected reduced carbon uptake of lands converted from grasslands to forests and the potential for higher transaction and monitoring costs.

The CarBen model assumes that full market penetration of terrestrial sequestration technology is achieved by 2050, with twenty-five percent of the ultimate rate deployed by 2012, half by 2020, and the remainder between 2020 and 2050. The delay in reaching the ultimate sequestration rate recognizes practical limitations on the deployment of new technologies and practices in the agriculture and forestry sector. The somewhat front-shifted deployment curve is based on the projected significant low-cost carbon sequestration applications that could be implemented relatively quickly in this area.

McCarl and others also include biomass, animal methane, nitrous oxides, and other emissions in their analyses. In CarBen, only the emission reduction quantities for afforestation and land use changes are used. Biomass offsets are included under advanced efficiency and renewables, and options for reducing emissions of methane and nitrous oxides are included under non-CO_2 GHG emissions.

Much of the uncertainty in the estimates for the role of afforestation and soil management stems from uncertainty about the physical limit of carbon that can be stored in soils and plants. Kern's analysis [11] indicates the limit for incremental storage in soils in the contiguous U.S. to be 1 to 2 billion metric tons of carbon. Lal estimates the total U.S. terrestrial storage limit to be 5 billion metric tons of carbon [12]. There is much more to be learned from research and the technical literature [13,14,15,16] and as improved understanding of the role of terrestrial systems and soil management for carbon sequestration emerges, the authors will update the estimates in CarBen as appropriate.

There is an emerging view that, absent policy and technology changes, the natural carbon uptake in soils will likely decrease over the next 30 years, primarily due to the aging of second growth forests in the northeast and the reduced uptake of lands converted from grasslands to forests [17]. For example, the CAR projections show that annual carbon sequestration in forests and agricultural lands are expected to decline from 329 MMTC in year 2000 to 288 MMTC in year

2020. These estimates are incorporated in the CarBen projections of carbon sequestration in agricultural soils and forests.

5. High Technology Terrestrial Sequestration. The supply curve developed by McCarl and others is based on current technology. CarBen incorporates a high technology option in which the activities of the DOE Carbon Sequestration Program, in concert with other accelerated efforts in the areas of silviculture, genetic engineering, as well as education and outreach, shift the supply curve so that 20% more capacity is available at each shadow price compared to the volumes available with current technology.

6. Early Entry of Value-Added Geologic Storage. This module includes two geologic options that have demonstrated their value-added potential - - enhanced oil recovery (EOR) and enhanced coal bed methane recovery (ECBM), using low-cost, opportunity sources of CO_2.

Assuming a shadow price (or incentive) of $50 per metric ton of carbon and an aggressive R&D program, the ARI Value-Added sub-model estimates the capacity of carbon sequestered using enhanced oil recovery to be 16 MMTC per year in 2012 and 43 MMTC per year in 2020. Similarly ARI estimates the amount of carbon sequestered in unminable coal seams to be 7 MMTC per year in 2012 and 27 MMTC per year in 2020.

With continuation of RD&D and incentives (or an equivalent shadow prices for carbon), the ARI model estimates that the total carbon sequestered in depleting oil reservoirs and deep coal seams would increase from 70 MMTC per year in 2020 to 140 MMTC per year in 2050. These estimates are based on marginal cost abatement curves developed by ARI from a basin-by-basin analysis of domestic oil and coalbed methane reservoirs and are an update of the sequestration capacity data contained in two studies prepared by ARI for the International Energy Agency's GHG Programme [18, 19].

Value-added sequestration is modeled with oil and gas prices from the general equilibrium model and is assumed to be actions beyond those already included in the EIA Reference Case for AEO 2003. While the quantities of byproduct oil and gas are not sufficient to enable CO_2-based EOR/ECBM sequestration projects to become economic on their own, they do significantly reduce the net cost of sequestration. Also, since the quantities are "at-the-margin" of the equilibrium solution, it is assumed they do not perturb oil and gas prices. Future increases in oil and gas prices, above the projections in AEO 2003, would expand the number of economically viable sites and increase the value-added sequestration estimates.

Value-added geologic sequestration relies on a supply of inexpensive to capture CO_2, potentially available from a diverse set of industrial processes that exhaust highly pure streams of CO_2. As further discussed in Appendix A, about 40 MMTC/yr of high concentration CO_2 is currently available with about 5% of this total currently used for EOR. Also, many of these high CO_2 concentration point sources are geographically co-located with opportunities for value-added geologic sequestration. These high purity sources of CO_2 include natural gas processing, hydrogen production from natural gas or other hydrocarbons, cement manufacturing, ammonia and ethanol production, and other uses of oxygen blown gasification, and helium production. The amount of high-purity CO_2 from point sources could grow to a range of 80 to 120 MMTC/yr by 2020, as hydrogen-rich transportation fuels demand increases and existing capital stock is replaced with advanced technologies more amenable to producing and capturing high CO_2 concentration exhaust streams.

The quantity of economically sequestered CO_2 that could be achieved by EOR/ECBM in 2012 and 2020 is highly dependant upon the level of RD&D investment (both public and private) and the level of market-based incentives assumed. An aggressive set of RD&D and market-based incentives and initiatives for value-added geologic sequestration were presented in the White Paper, "CO_2 Capture and Storage in Geologic Formations" prepared for the National Climate Change Technology Initiative (NCCTI) [20], which has been available on the NETL website since February, 2002. The results reported here for value-added geologic storage and advanced technology sequestration assume the full funding and successful implementation of these initiatives.

7. Advanced Sequestration Technology. Advanced sequestration is carried in the CarBen model as the technology of "last resort" and contains a portfolio of advanced sequestration technologies and options. Unlike the other categories, the advanced sequestration quantities in CarBen are not currently based on "bottom-up" marginal cost estimates. Rather, this category represents the additional GHG emission reductions needed from advanced technologies for achieving the full emissions reduction need defined by the assumed scenario.

The advanced sequestration category encompasses all direct carbon capture technologies and all geologic storage options except EOR and ECBM (which are currently included in the early "value-added" category) and includes potential future value-added sequestration opportunities such as depleting gas fields, hydrocarbon-rich shales, and cost-avoided acid gas injection. The advanced sequestration technology also includes CO_2 injection into deep saline formations and other long-term carbon storage options. Advanced carbon sequestration competes with other carbon emission reduction options under an assumed shadow price of $50 per metric ton.

The alternatives currently embedded in the advanced carbon sequestration technology category reflect a wide range of marginal abatement cost curves. Certain of these technologies, such as capture of CO_2 from gasification of coke or refinery residuals, have marginal abatement cost close to the $50 per metric ton shadow price. These costs are assumed to decline, due to an aggressive RD&D effort, at a rate of 3% per year. The 3% rate is consistent with technology progress assumptions in other studies. For example, the NPC natural gas study uses 4% annual cost reductions for deepwater platforms and 3.5% annual reductions for D&C costs. Also, EIA uses 3% annual cost reductions for offshore drilling in their Rapid Technology Progress Case.

Given this mix of alternatives and the assumed rate of technology progress, advanced carbon sequestration could contribute 13 MMTC toward carbon emission reductions in 2012 and 785 MMTC in 2050 under a $50/TC shadow price.

Within the next year, the data and capability to explicitly estimate quantities that could be achieved from a number of these advanced sequestration technologies at various shadow prices will be added to CarBen. The Carbon Sequestration Technology Roadmap and the NCCTI White Paper provide RD&D strategies and research initiatives that would support the development of these technologies. Both of these have been available on the NETL website since early 2002. The Roadmap is being updated, and a revised document will be available on the NETL website soon, along with this Status Report.

III. REDUCED EMISSIONS SCENARIO CALCULATION

In CarBen, the DOE/FE contribution toward emission reductions is currently calculated for value-added geologic, advanced carbon sequestration, high technology for methane emission reductions and high technology forestry and land use changes. While the USDA and EPA respectively are the lead organizations in methane emission reductions and forestry/land use, DOE/FE is working collaboratively with these two agencies to advance the state of technology. For example, the DOE/FE program is currently involved in RD&D on terrestrial sequestration measurement and reductions in coalbed methane emissions. Because of the newness of these efforts, the impacts of DOE/FEs efforts in these two areas are still being evaluated. Future analyses will seek to further quantify the DOE sequestration program benefits in methane emission reductions and terrestrial sequestration.

A significant national effort will be required to achieve the carbon emission reductions called for by the GCCI for 2012 and beyond. Carbon sequestration, as part of a portfolio of actions, has the potential to play a significant role in meeting these emission reductions goals.

- On the capture side, the U.S. DOE is working collaboratively with other nations to improve technology and reduce the costs of CO_2 capture and separation from power plants, to improve the application of non-CO_2 GHG emission reduction practices, and to promote increases in energy supply and demand efficiencies and renewable energy.

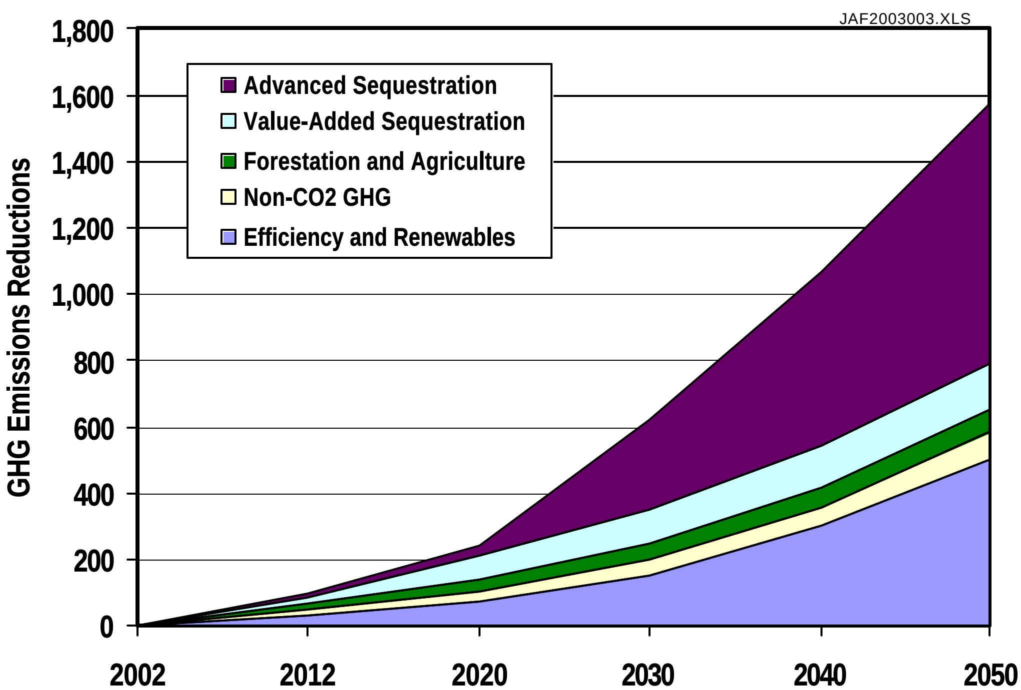
- On the storage side, the U.S. DOE is working to further define the capacities, costs and feasibility of using its vast forests and prairies, its massive saline formations, its depleting oil and gas reservoirs, and its unmineable coal seams to store centuries worth of GHG emissions. These options for CO2 storage also have the potential to provide value-added benefits. For example, tree plantings, no-till farming and other terrestrial sequestration options can prevent soil erosion and pollutant runoff into streams and rivers. CO2 storage into depleting oil reservoirs and unmineable coal seams can enhance the recovery of crude oil and natural gas respectively while leaving a significant portion of the greenhouse gas sequestered.

The contribution of an intensive National Sequestration R&D plus incentives effort toward the GCCI goals for 2012 could be significant and grow over time as shown in Table 4 and Figure 2.

Table 4
Contributions of Carbon Sequestration Efforts to Reduce U.S. GHG Emissions
(Million Metric Tons of Carbon Equivalent – MMTCE)

	2012	2020	2050
Annual U.S. GHG Emissions Reductions Needs	100	240	1,570
Contributions from Carbon Sequestration			
♠ Value-Added Geologic Sequestration	23	70	140
♠ High Tech for FLUC and Reduced Methane Emissions	8	12	30
♠ Advanced Sequestration Technology	13	30	780
Total Contributions	44	112	950
% of Emission Reductions	44%	47%	60%

Figure 2. PotentialContribution of a Portfolio of Options for Reducing GHG Emissions



This model development effort recognizes that until a substantial market emerges for carbon credits, emissions reduction can only be achieved at a cost. In the absence of such a market, incentives will be required to initiate early action in carbon sequestration to achieve significant quantities of reductions. . Appendix B contains calculations of the cost of some of the existing incentive programs per metric ton of carbon emissions reduced. The calculations indicate that an incentive of $50/metric ton "carbon-avoided", or even larger, for carbon sequestration would be comparable with existing incentives available to advance renewables technologies.

IV. OPTIONS FOR USING CARBEN

This report describes the key features of CarBen, presents one "Reduced Emissions scenario", and incorporates the EIA/AEO 2003 projections. However, the model has the flexibility to consider a wide range of different scenarios and assumptions, some of which are described below.

A. Reduced Emissions Scenarios

The reduced emissions scenario used as the example for CarBen incorporates a series of sequential decision milestones where decisions are made to further reduce and finally stabilize emissions. There are many variations of such a scenario which the model could use. The model is capable of examining a wide range of different emission reduction scenarios, some of which will be examined in early 2003.

B. Non-Sequestration Backstops and Marginal Abatement Curves

The CarBen model has the ability to examine different forms of backstops and vary the date of availability and costs of advanced technologies.

C. Integrated High Technology Case

During the CarBen model development phase the focus has been to use published and well documented projection which cover the broadest range of advanced technology options derived from general equilibrium modeling. The best available choice has been the AEO Integrated High Technology Case.

Another possible option would be to use a case based on AEO 2003, but run with the "Reduced Emissions scenario" as a constraint. In that case, shadow prices for use in CarBen could be derived directly, as opposed to being independently assumed.

D. Summary

CarBen is a flexible, modular modeling system which can be used in a variety of ways to derive insights, including a wide range of "what if?" sensitivity cases and risk analysis approaches. The model is a "work-in-progress, with significant further updates and improvements expected in 2003.

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APPENDIX A

HIGH CONCENTRATION CO_2 EMISSIONS IN THE U.S.

Summary of Results

The great bulk of CO_2 emissions are from the combustion of fossil fuels in air, a process that exhausts a dilute stream of CO_2. Industries that emit CO_2 as part of a stoichiometric chemical reaction typically emit a much higher concentration of CO_2.

This Appendix presents estimates for domestic high CO_2 concentration emissions. These are defined for point source having a concentrations of at least 90% CO_2 by volume, with a quantity of at least 0.02 MMTC emitted per year.

Based on a review of available data, there are roughly 240 such point sources, emitting over 40 million metric tons carbon (MMTC) per year. Table A1 shows the types and number of sources of higher CO_2 concentration emissions.

Table A1. Selected High Concentration CO_2 Vents in the U.S.

Type of CO_2 Vent	Number of Vents in 2000	Aggregate CO_2 Emissions (MMTC)	
		2000	Projected 2020
Oxygen-blown Gasification	11	15	29
Natural Gas Processing	50	5	19
Cement Production	37	11	15
Ammonia Production	40	4	8
Hydrogen (Production in Refineries)	40	4	6
Ethanol Production	34	1	4
Helium production		-	9
Advanced coal-fired power generation		-	0-40
Total		**40**	**80-120**

The amount of CO_2 emitted in concentrated streams in the U.S. is projected to increase to a range of 80 to 120 million metric tons by 2020. Sustained economic growth, the deployment of advanced fossil fuel conversion technologies, and other factors will drive this increase:

- Crude oil production and imports are trending toward heavier, more sour crudes. These crudes require increased hydrotreating, and will provide increased volumes of petroleum residues as feedstocks for gasification.
- Low-sulfur diesel and reformatted gasoline regulations will require increased hydrogen consumption per gallon of gasoline produced.
- Natural gas production is moving to deposits with higher concentrations of CO_2, increasing CO_2 emissions from natural gas processing.
- MTBE phase-out will increase the need for domestically produced ethanol.
- Increased use of hydrogen and other advanced transportation fuels will require upstream decarbonization of fossil resources.
- Advanced coal-fired gasification can be designed to emit highly concentrated shows of CO_2.

Industry by Industry Results

Oxygen-Blown Gasification:

Type of CO_2 Vent	Number Vents in 2000	Emissions in 2000 (MMTC)	Emissions Projected 2020 (MMTC)
Oxygen-blown gasification	11	15	29

Syngas from an oxygen-fired gasifier is largely H_2 and CO_2. CO_2 can be separated from syngas prior to use, and CO_2 capture can be combined with sulfur removal. There are currently 11 gasifiers in the U.S (SFA Pacific/Gasification Technologies Council, Gasification Database, 2001). The average emissions from existing gasifiers is 1.4 MMTC/yr high-concentration CO_2.

It is assumed that 10 new gasifiers would be built in the United States over the next 18 years, increasing the total number to 21. The 10 new gasifiers are assumed to emit at the same rate as the existing 11 gasifiers.

Natural Gas Processing:

Type of CO_2 Vent	Number Vents in 2000	Emissions in 2000 (MMTC)	Emissions Projected 2020 (MMTC)
Natural gas processing	50	5	9

CO_2 from natural gas processing is 5 million metric tons per year. This was calculated based on total natural gas processing volumes, multiplied by a fraction assumed to be CO_2. Gas processing plants in Colorado, Louisiana, New Mexico, Wyoming, Utah and Texas were assumed to have an average of 3 % CO_2, by volume in the natural gas. All other states were assumed to have an average composition of 2 % CO_2. The calculation was done on a state-by state basis.

In the current case 5 MMTC is emitted from 19.59 Qbtu (10^{12} btu) of natural gas production (AEO 2002, Table A1), or 0.36 MMmtC / Qbtu. EIA projects 2020 natural gas production to be 29.25 Qbtu. It is assumed that the average CO_2 emissions rate increases to 0.46 MMmtC / Qbtu based on a trend toward lower quality resources with larger CO_2 concentrations. The outcome is 9 MMTC in 2020 from natural gas processing.

Sweetening of natural gas removes sulfur, nitrogen and CO_2 from the methane. Recent data indicate there are 278 centralized gas plants that perform some level of sweetening,[i] out of a total of 697 natural gas processing facilities in the U.S. Most information sources focus on the production of natural gas, not of natural gas conditioning, so composition estimates are difficult. According to a study by the Gas Technology Institute,[ii] high CO_2 concentration in natural gas deposits occurs largely in the Rockies, the Permian Basin, and the Gulf Coast. (High CO_2 is defined as greater that 2 %.) Carbon dioxide content of natural gas has been increasing due to the growth of production fields with high CO_2 component in the Midwest, the Green River Basin in Wyoming, and the San Juan Basin and Piceance Basin coal bed gas fields. Since 1990, the volume of CO_2 coproduced with natural gas has risen by 23.4 % to 5 million metric tons carbon.[iii]

- In 1997, CO_2 component of nonassociated gas produced was 2.5 % compared with 0.2 % for associated-dissolved natural gas
- 69 % of carbon dioxide emissions occur during gas production, with the remainder in transmission, distribution, and consumption
- Natural gas production in 2000 was 20.0 trillion cubic feet[iv]
- Four states account for 73 % of total 2000 U.S. natural gas production. Texas: 31 %, Louisiana: 25 %, Oklahoma: 8 %, and New Mexico: 8 %.

Figure 5 Natural gas processing schematic

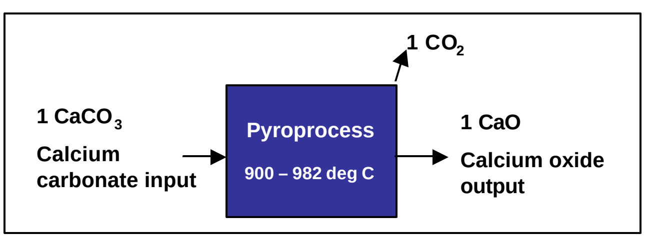
Cement Production:

Type of CO_2 Vent	Number Vents in 2000	Emissions in 2000 (MMTC)	Emissions Projected 2020 (MMTC)
Cement manufacture	37	11	15

Approximately 84 million tons of cement were produced from 99 U.S. plants in 2000. Of these, 37 meet the minimum size criteria. CO_2 emissions were estimated by applying an emission factor to the total amount of cement produced. The emission factor used in this analysis of 500 kg CO_2 per metric ton of cement produced is obtained from the EPA document Emission Factor Documentation for AP-42[v] which measures CO_2 emissions from stoichiometric processes

Cement production is estimated to grow at 3% per years (with GDP) countered by a 1.5% dcline in energy intensity leading to 15 MMTC of CO_2 emissions in 2020.

CO_2 emissions from cement manufacture are created by the chemical reaction of calcining limestone. During calcination, each mole of CaCO3 (i.e., limestone) heated in the cement kiln forms one mole of lime (CaO) and one mole of CO_2. California, Texas, Pennsylvania, Michigan, Missouri and Alabama produce 49% of cement.



Ammonia Production:

Type of CO_2 Vent	Number Vents in 2000	Emissions in 2000 (MMTC)	Emissions Projected 2020 (MMTC)
Ammonia Production	40	4	8

According to the EPA Inventory of U.S. GHG Emissions and Sinks, 2002, 15 million tons of ammonia were produced in 2000 from 60 plants. CO_2 emissions were estimated using an emission factor of 0.97 kg CO_2 per kg ammonia produced (from Emission Factor Documentation AP-42, Section 5.2). Twenty sources of less than 0.02 MMmtC/yr were omitted.

It is assumed that ammonia production tracks with growth in industrial gross output (AEO 2002 Table A20), leading to a 76% increase between 2000 and 2020 or 8 MMTC of CO_2 emissions in 2020.

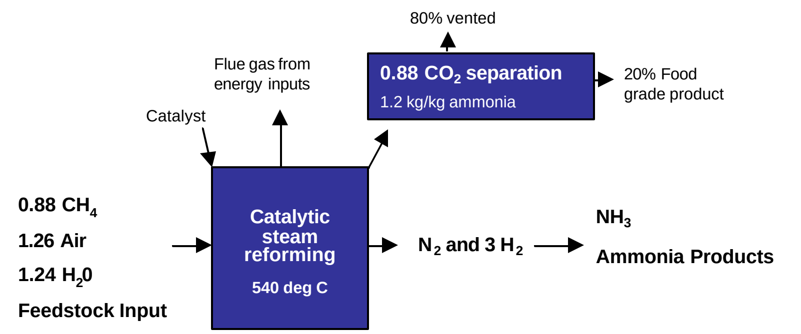


Figure 2 Ammonia production schematic

The CO_2 is included in a waste gas stream with other process impurities and is absorbed by a scrubber solution. In regenerating the scrubber solution, CO_2 is released. Louisiana and Oklahoma produce 54% of total U.S. ammonia.

Hydrogen (Productions in Refineries):

Type of CO_2 Vent	Number Vents in 2000	Emissions in 2000 (MMTC)	Emissions Projected 2020 (MMTC)
Steam Reforming in an Oil Refinery	40	4	6

Approximately 3,243 million cubic feet of hydrogen were produced per day from 64 point sources in 2000. CO_2 emissions were calculated using the factor 0.26 scf highly pure CO_2 vented per scf H_2 produced. Twenty four sources of less than 0.02 MMTC/yr were omitted. EIA web site, RefCap01, survey 820;

In 2000, refinery SMRs emitted 3.8 MMTC based on a total 26.42 Qbtu of Petroleum transportation fuel (AEO 2002 Table A2), or 0.144 MMTC/Qbtu. AEO 2002 reference case project for petroleum transportation fuels in 2020 is 38.11 Qbtu. Using an average emissions rate of 0.16 MMmtC/Qbtu (based on low-sulfur diesel and heavier crudes), 6 MMTC of CO_2 emissions estimated for year 2020.

Ethanol Production:

This section provides the detailed data on assumptions for calculating CO_2 emissions for each selected industrial source.

Type of CO_2 Vent	Number Vents in 2000	Emissions in 2000 (MMTC)	Emissions Projected 2020 (MMTC)
Ethanol manufacturer	34	1	4

The Renewable Fuels Association web site states that 1.63 billion gallons of ethanol were produced from 69 facilities in 2001. Using a conversion factor of 3 kg CO_2 per gallon of ethanol (from a study by the Kansas Geological Survey CO_2 is produced in equimolar amounts with ethanol during fermentation of the corn.), 1.3 MMTC were calculated to be emitted. Omitting 35 sources with less than 0.02 MMmtC/yr of emissions, leads to 34 point sources with 1.2 MMTC of CO_2 emissions.

The AEO 2002 projects ethanol use to double from 0.14 Qbtu in 2000 to 0.28 Qbtu in 2020. It is assumed that an MTBE phase out, which is not considered in the AEO 2002 NEMS runs, causes an additional 0.14 Qbtu of ethanol production. This leads to an estimate of 4 MMTC of CO_2 emissions in 2020.

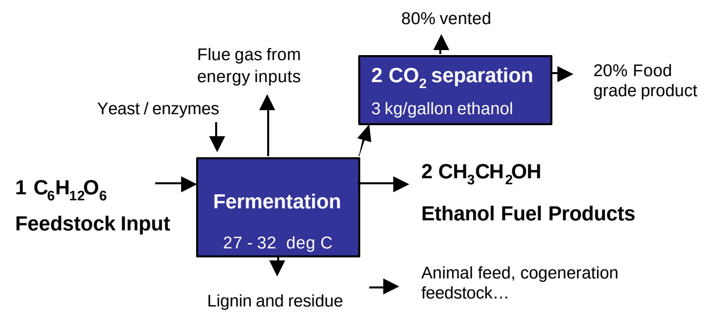


Figure 3 Ethanol production schematic

The states of Iowa, Illinois, Nebraska, Minnesota, South Dakota and North Dakota produce 86% of U.S. ethanol.[vi] The industry markets roughly 20% of their CO_2 emissions as liquid food-grade CO_2.

Helium Production:

Type of CO_2 Vent	Number Vents in 2000	Emissions in 2000 (MMTC)	Emissions Projected 2020 (MMTC)
Helium production	1	-	9

All the CO_2 is assumes to be from the Ridgeway Petroleum project in St. Johns AZ, estimated to be implemented in 2004.

Advanced Coal-Fired Power Generation:

Type of CO_2 Vent	Number Vents in 2000	Emissions in 2000 (MMTC)	Emissions Projected 2020 (MMTC)
Advanced coal-fired power generation	-	-	0 to 40

EIA projects 31.2 GW of coal-fired capacity additions between 2005 and 2020 (AEO 2002, Table A9). If one assumes all of it is either IGCC or oxygen combustion, with a heat rate of 7,500 Btu/kWh, and a capacity factor of 75%, the CO_2 emissions factor is 25.76 MMTC / Qbtu coal (EIA Emissions of GHGs in the U.S. 2000, Table B1). The calculation is then: 31.2 x10^6 kW * (8,760 * 0.75) hrs/yr * 7,500 Btu/kWh * 25.7 x10^{-15} MMTC/Btu = 39.5 MMTC/yr.

References

Industry	Source
SMR at Refineries	EIA refcap01, survey 820, date 0101
Ethanol Fermentation	Renewable Fuels Association, Last Updated: April 2002, and Kansas Geological Survey, Co-generation, Ethanol Production and CO_2 Enhanced Oil Recovery Model for Environmentally and Economically Sound Linked Energy Systems, Open-file Report 2002-6
Ammonia Plants	Background Report AP-42 SECTION 5.2 Synthetic Ammonia, US EPA, 1993. Page 3
Cement Clinker	Emission Factor Documentation for AP-42 Section 11.6 Portland Cement Manufacturing 1994
Coke/ Coal Gasifiers	Advanced Resources International/SFA Pacific
Natural gas processing	Advanced Resources International/EIA Natural Gas Annual 1998
Helium extraction	Advanced Resources International/Ridgeway Petroleum Corporation

Global Warming Potentials, U.S. Sources of CO_2 Emissions and Sinks (Tg CO_2 Eq.)

Global Warming Potentials (100 Year Time Horizon)

Gas	GWP
Carbon dioxide (CO_2)	1
Methane (CH_4)*	23
Nitrous oxide (N_2O)	296
HFC-23	12,00
HFC-32	550
HFC-125	3,400
HFC-134a	1,300
HFC-143a	4,300
HFC-152a	120
HFC-227ea	3,500
HFC-236fa	9,400
HFC-4310mee	1,500
CF_4	5,700
C_2F_6	11,900
C_4F_{10}	8,600
C_6F_{14}	9,000
SF_6	22,200

U.S. Sources of CO_2 Emissions and Sinks (Tg CO_2 Eq.)

Source or Sink	1990	2000
Fossil Fuel Combustion	4,779.8	5,623.3
Electricity Generation	1,858.9	2,352.5
Transportation	1,471.8	1,789.5
Industrial	871.6	1 829.2
Residential	332.1	374.8
Commercial	217.3	239.3
U.S. Territories	28.1	38.0
Iron and Steel Production	85.4	65.7
Cement Manufacture	33.3	41.1
Indirect CO_2 From CH_4 Oxidation	30.9	26.3
Waste Combustion	14.1	22.5
Ammonia Manufacture	18.5	18.0
Lime Manufacture	11.2	13.3
Limestone and Dolomite Use	5.2	9.2
Natural Gas Flaring	5.5	6.1
Aluminum Production	6.3	5.4
Soda Ash Manufacture and Consumption	4.1	4.2
Titanium Dioxide Production	1.3	2.0
Ferroalloys	2.0	1.7
Carbon Dioxide Consumption	0.8	1.4
Land-Use Change and Forestry (Sink)[a]	(1,097.7)	(902.5)
International Bunker Fuels[b]	113.9	100.2
Total	**4,998.5**	**5,840.0**
Net Emissions (Sources and Sinks)	**3,900.8**	**4,937.5**

CO_2 emissions and Conversion Factors in MMTC per year

Source Type	2001 U.S Production	Units	CO_2 Conversion Factor	
SMR at Refineries	3,243	MMSCFD H2	0.0045	MMmtC/yr / MMSCFD H2
Ethanol Fermentation	1.63	Billion gallons Ethanol per year	3	kg CO_2 /gallon ethanol
Ammonia Plants	15,014	Thousand mt ammonia per year	0.97	mt CO_2 / mt NH3
Cement Clinker	83,692	Thousand tons cement per year	0.5	mt CO_2 per mt cement

Calculations:

Carbon Emissions Calculation:

SMR at Refineries

$$\frac{3{,}243\ \text{MMscf}\ H_2}{\text{Day}}\ \Big|\ \frac{0.26\ \text{scf}\ CO_2}{\text{Scf H2}}\ \Big|\ \frac{0.1235\ \text{lb}\ CO_2}{\text{Scf}\ CO_2}\ \Big|\ \frac{1\ \text{mt}}{2200\ \text{lbs}}\ \Big|\ \frac{365\ \text{d}}{\text{year}}\ \Big|\ \frac{12\ \text{C}}{44\ CO_2} = \frac{4.7\ \text{MMTC}}{\text{yr}}$$

Ethanol Fermentation

$$\frac{1.63\ \text{B gallons}}{\text{Year}}\ \Big|\ \frac{3\ \text{kg}\ CO_2}{\text{gallon}}\ \Big|\ \frac{1\ \text{mt}}{1000\ \text{kg}}\ \Big|\ \frac{12\ \text{C}}{44\ CO_2} = \frac{1.3\ \text{MMTC}}{\text{yr}}$$

Ammonia Plants

$$\frac{15{,}014\ \text{thousand tons}}{\text{Year}}\ \Big|\ \frac{0.97\ \text{kg}\ CO_2}{\text{Kg NH3}}\ \Big|\ \frac{12\ \text{C}}{44\ CO_2} = \frac{4.4\ \text{MMTC}}{\text{yr}}$$

Cement Clinker

$$\frac{83{,}692\ \text{thousand tons}}{\text{Year}}\ \Big|\ \frac{0.5\ \text{kg}\ CO_2}{\text{Kg cement}}\ \Big|\ \frac{12\ \text{C}}{44\ CO_2} = \frac{11\ \text{MMTC}}{\text{yr}}$$

Advanced Coal-fired

$$\frac{31.2\ \text{x}10^{6}\ \text{kW}}{}\ \Big|\ \frac{7{,}500\ \text{Btu}}{\text{KWh}}\ \Big|\ \frac{25.7\ \text{x}10^{-15}\ \text{MM mt C}}{\text{Btu}}\ \Big|\ \frac{8{,}760 * 0.75\ \text{hrs}}{\text{yr}} = \frac{39.5\ \text{MMmtC}}{\text{yr}}$$

Aluminum Production

$$\frac{3{,}468\ \text{thousand metric tons}}{\text{Year}}\ \Big|\ \frac{1.5\ \text{mt}\ CO_2}{\text{mt AL}}\ \Big|\ \frac{12\ \text{C}}{44\ CO_2} = \frac{1.4\ \text{MMTC}}{\text{yr}}$$

APPENDIX B

COMPARATIVE COST OF GHG EMISSIONS REDUCTION INCENTIVES

Comparative Cost of GHG Emissions Reduction Incentives

Summary of Results. The purpose of this analysis is to interpret the existing Energy Production Act (EPACT) production tax credits for wind and biomass co-firing in terms of cost per ton of carbon emissions reduced. The incentives are limited in duration, ranging from the first three to ten years of the unit's operation. Table B-1 below summarizes the results.

Table B1. Cost of GHG Emissions Reduction Incentives ($/mtC Avoided)

	Average Over First 3 Years**	Average Over First 10 Years**
EPACT Renewable Energy Production Tax Credit, Wind Turbine Power Generation	98-130	98-130
EPACT Renewable Energy Production Tax Credit, Biomass Co-firing*	65-86	NA

**Assume incentive applies only to portion of total electricity generation attributable to biomass.*
***Range in value of the EPACT tax credit depends on whether the facility is privately or publically owned.*

Detailed calculations for each of the incentive cases shown in Table B-1 are provided below.

1. EPACT Renewable Electricity Production Tax Credit, Wind

Scenario: The incentive causes a wind turbine power generation unit to be deployed. Electricity from the wind turbine displaces electricity from a mix of fossil-fired power plants.

Assumptions:
- GHG emissions from a wind turbine are zero.
- GHG emissions from coal mining and transport are ignored.
- Electricity from a wind turbine displaces the following mix of fossil-fired power generation:
  - Natural gas CT – 50%
  - Diesel generator – 20%
  - Natural gas CCCT – 20%
  - Coal steam – 10%
- The analysis does not incorporate the cost of providing backup or spinning reserves to account for wind fluctuations and a 20% to 40% load factor.
- With the EPACT Production Tax Credit, the wind turbine power facility is economically competitive.
- Without the EPACT Production Tax Credit, the wind turbine power facility has negative net revenues of $0.018/kWh.
- The effective corporate tax rate for the wind turbine facility owner is 33%.

Data: EPACT Production Tax Credit of 1.8 cents/kWh is paid on an annual basis for the first ten years the wind turbine is in operation. The heat and CO_2 emission rates for the displaced mix of fuels is shown below:

Fuel Source	Heat Rate (Btu/kWh)	CO_2 Emissions Factor (MMmtC/Qbtu) [1]	CO_2 Emissions Rate (mt/10^6kWh) [2]
Natural Gas peaker	12,000	14.47	173.6
Diesel peaker	12,000	19.95	239.4
Natural Gas CCCT	7,500	14.47	108.5
Coal steam	10,790	25.76	278.0

[1] EIA AEO 2002, national average for 2000 (21.5 Qbtu/1992 BkWh)
[2] EIA, Emissions of GHGs in the U.S. 1999, Table 13.

Calculations:

1. Weighted average emissions factor from displaced generation:

$$(173.6 * 0.5) + (239.4 * 0.2) + (108.5 * 0.2) + (278.0 * 0.1) = 184.2 \text{ mtC}/10^6\text{kWh}$$

2. Cost of Production Tax Credit per mtC avoided:
   a. <u>Before-Tax Basis</u>
   $0.018/kWh * [1 kWh /(0.0001842) mtC] = $97.7/mtC

   b. <u>After-Tax Basis</u>
   ($0.18/kWh * [1 kWh/0.0001842 mtC])
   + ($0.18/kWh * 0.33 * [1 kWh/0.0001842 mtC])
   = $97.7/mtC + $32.2/mtC = $129.9/mtC

Discussion: The analysis uses EIA AEO 2003 data for the overnight capital costs ($1,004/kw) and for the capacity factor (40%). It applies a 15% before tax capital charge. With the EPACT incentive, the wind turbine power generation facility has net costs slightly below a Baseline Pulverized Coal (PC) power plant and is economically competitive.

Once the EPACT incentive expires, and even through dispatch costs of wind power are low, the wind turbine power generation facility can no longer meet its capital charge. As such, the unrecovered capital costs for the wind power generation facility would need to be covered by the larger power generation pool or from other incentives or tax credit provisions. Because of this, only the time period of the incentive is included in the economic analysis and for the assumed economic operating life of the wind power generation facility.

When the analysis is conducted on an after-tax basis, the cost per ton of carbon emissions avoided increases by the size of the unsubsidized net revenue loss incurred by the wind power generation facility times the corporate tax rate of the facility owner. This leads to an incentive with a total value (after tax) of about $0.024/kWh, for this example case. (EIA AEO 2003 places the value of the EPACT production tax credit for wind at $0.028/kWh to more accurately represent its after-tax market value.) Assuming an unsubsidized net revenue loss of $0.018 per kWh and a corporate tax rate of 33%, the cost of the EPACT incentive would increase by about $32 per metric ton carbon avoided to an overall total of about $130/mtC.

2. EPACT Renewable Electricity Production Tax Credit, Biomass Co-firing

Scenario: The incentive causes a biomass and coal co-firing system to be deployed at an existing coal-fired power plant. Co-firing with biomass does not influence the units dispatch and therefore electricity from biomass displaces 10% of the coal otherwise used for power generation in this existing coal-fired power generation facility.

Assumptions:

- Net GHG emissions from biomass are zero.
- Biomass co-firing displaces 10% of the fuel requirement.
- GHG emissions from coal mining and transport are ignored.
- With the EPACT Production Tax Credit and low costs for biomass delivered to the plant, the biomass and coal co-firing facility is economically competitive.
- Without the EPACT Production Tax Credit, the biomass co-firing facility has a negative net revenue of $0.018/kWh.
- The effective corporate tax rate for the biomass co-firing facility is 33%.

Data: EPACT Production Tax Credit of 1.8 cents/kWh is paid on an annual basis for the first three years the co-firing system is in operation. The capital costs for the biomass co-firing retrofit and its operation and maintenance (O&M) costs are from work by SFA Pacific.

Calculations:

1. Average emission factor or displaced coal of 278 mtC/10^6 kWh.
2. Cost of Production Tax Credit per mtC avoided:
   a. Before-Tax Basis
      $0.018 $/kWh * [1 kWh /0.000278 mtC] = $64.7/mtC

   b. After-Tax Basis
      ($0.018/kWh * [1 kWh/0.000278 mtC])
      + ($0.018/kWh * 0.33 [1 kWh/0.000278 mtC])
      = $64.7 + $21.4 = $86.1/mtC

Discussion: The analyses uses biomass co-firing plant overnight retrofit costs, including paying for retrofit outage power, of $735/kWh, a low opportunity-type of biomass fuel charge of $13/mt (BDT), and a 15% before tax capital charge. With the EPACT incentive, the biomass co-firing power generation facility has net costs slightly below a Baseline PC power plant and thus is economically competitive.

Once of the EPACT incentives expires, and even though the dispatch costs of biomass co-firing are close to those of a PC plant, the biomass co-firing power generation facility can no longer meet its capital charge. The capital costs for the biomass co-firing facility would need to be covered by the larger power generation pool or from other incentives or tax credit provisions. Moreover, should the biomass fuel charge increase to a more normal $60/mt (BDT), without the EPACT production tax credit the dispatch costs of the facility would become non-competitive. Because of this, only the time period of the incentive is included in the economic analysis and in the assumed economic operating life of the biomass co-firing facility.

The range of costs for carbon emissions avoided is based on the same before tax and after tax implications as discussed for wind power above.

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[i] http://www.epa.gov/epaoswer/other/oil/execsum.pdf, p 13:

[ii] "Chemical Composition of Discovered and Undiscovered Natural Gas in the Lower 48 United States – 1993 update," Gas Research Institute, Washington D.C., 1993.

[iii] Energy Information Administration, Natural Gas 1998: Issues and Trends pp. 67-69. Washington, D.C.

[iv] Energy Information Administration, Natural Gas Annual pp. 1-2, Washington, D.C.

[v] Emission Factor Documentation for AP-42 Section 11.6 Portland Cement Manufacturing, 1994, http://www.epa.gov/ttn/chief/ap42/ch11/bgdocs/b11s06.pdf.

[vi] http://www.ethanolrfa.org/eth_prod_fac.html).