Technological Options to Address Global Climate Change

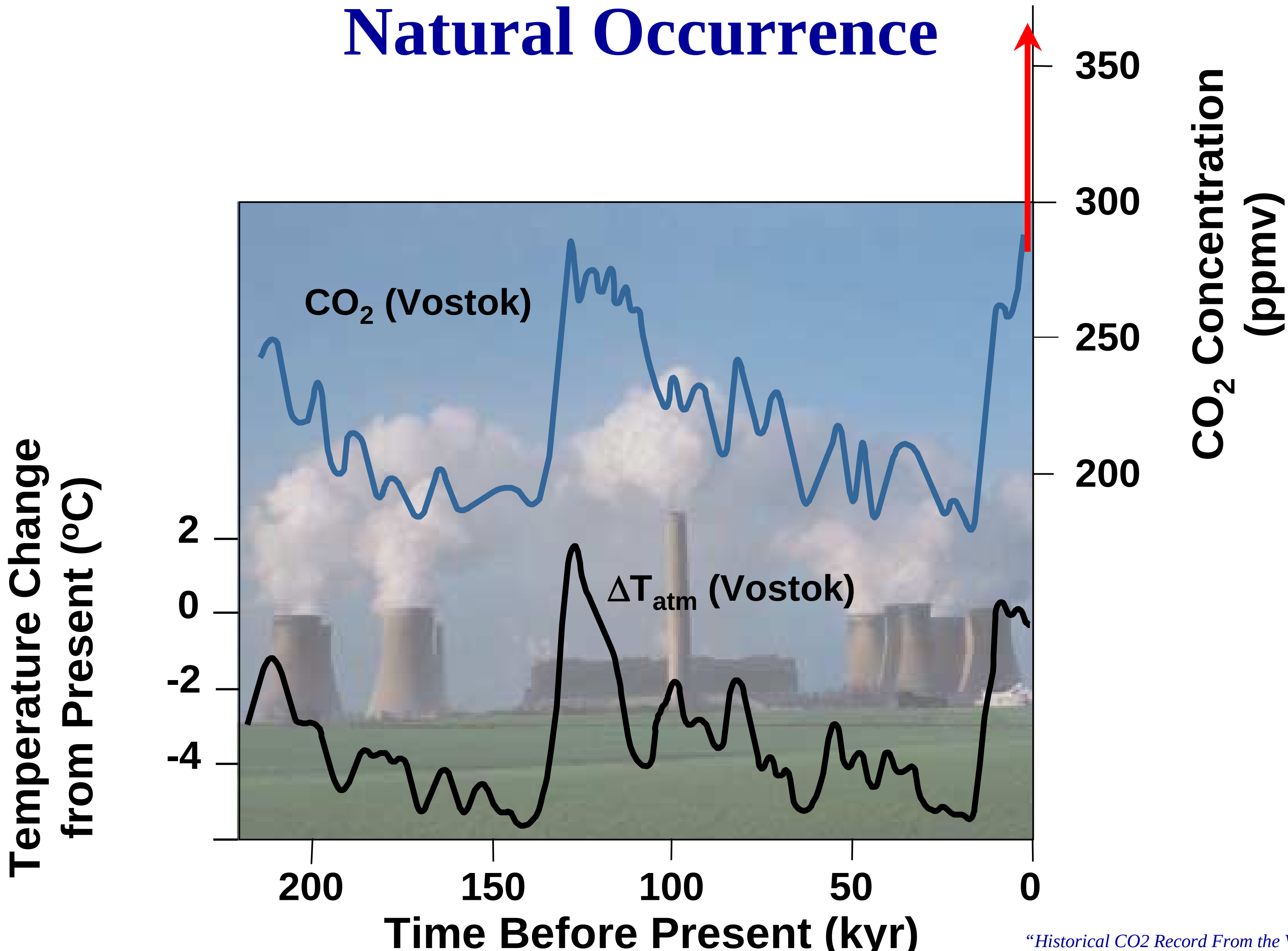
First National Conference on Carbon Sequestration

May 14-17, 2001

Rita A. Bajura, Director
National Energy Technology Laboratory

The Climate Change Debate

CO_2 Concentrations Beyond Range of Natural Occurrence



"Historical CO2 Record From the Vostok Ice Core"
J.M. Barnolo et al, August 1999
www.cdiac.esd.ornl.gov/ftp/trends/co2/vostok.icecore.co2

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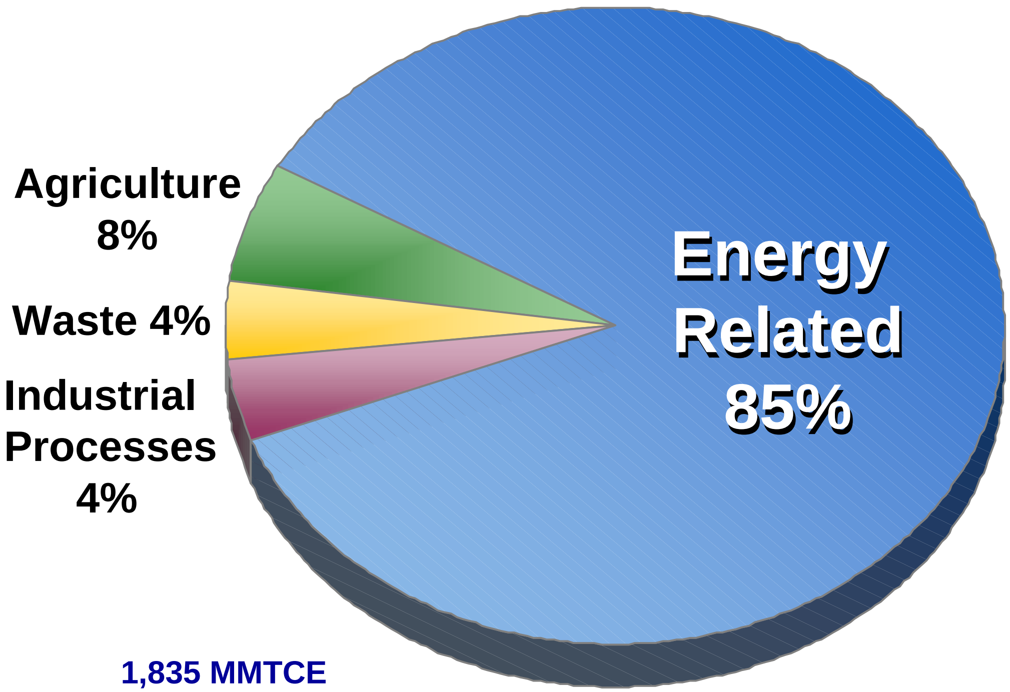
Energy Is Major Contributor

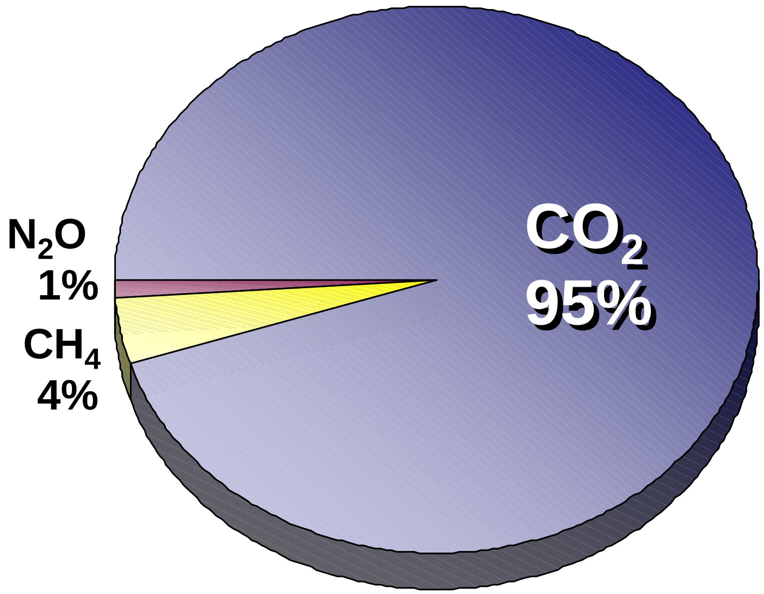
U.S. Anthropogenic Greenhouse Gas Emissions

85% of Emissions Energy Related

CO_2 Dominates Energy-Related Emissions



1,835 MMTCE

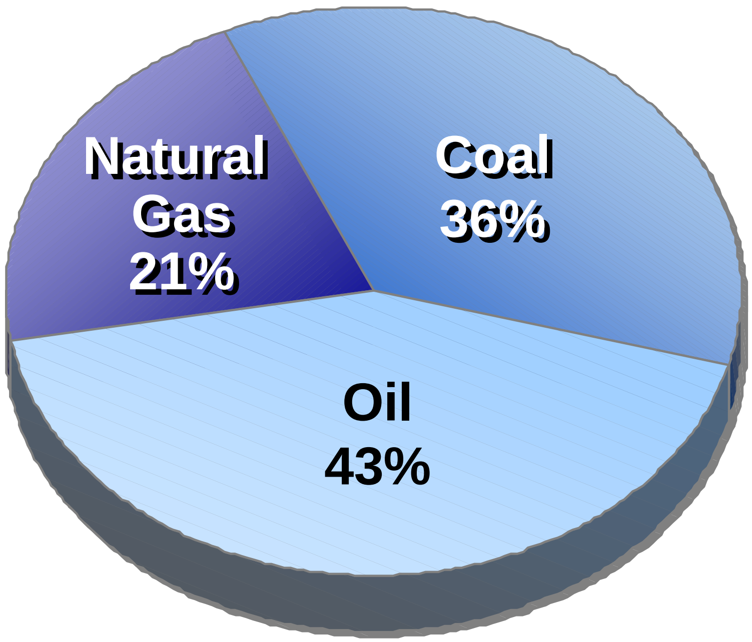


1,555 MMTCE

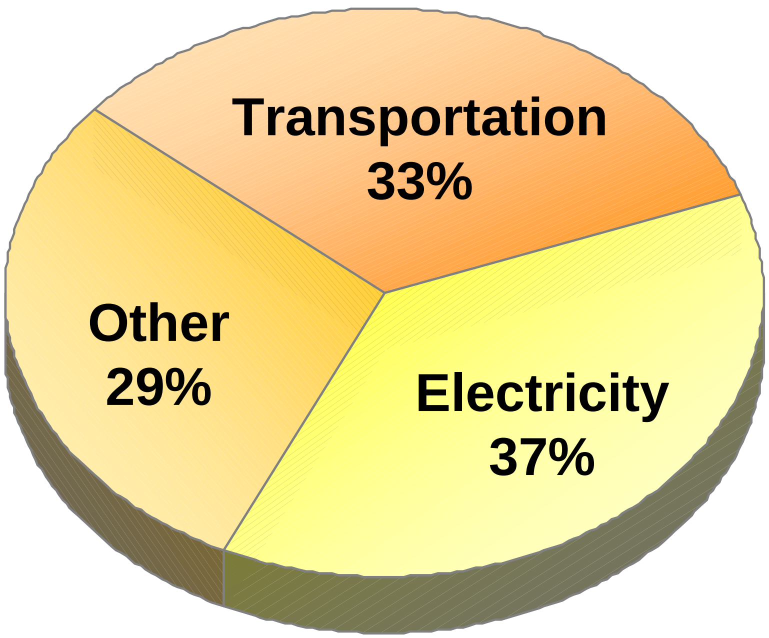
"Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1998," U.S. EPA, April 2000

All Fossil-Based Sources and Uses Contribute
1999 U.S. CO_2 Emissions From Energy

Fuel Sources

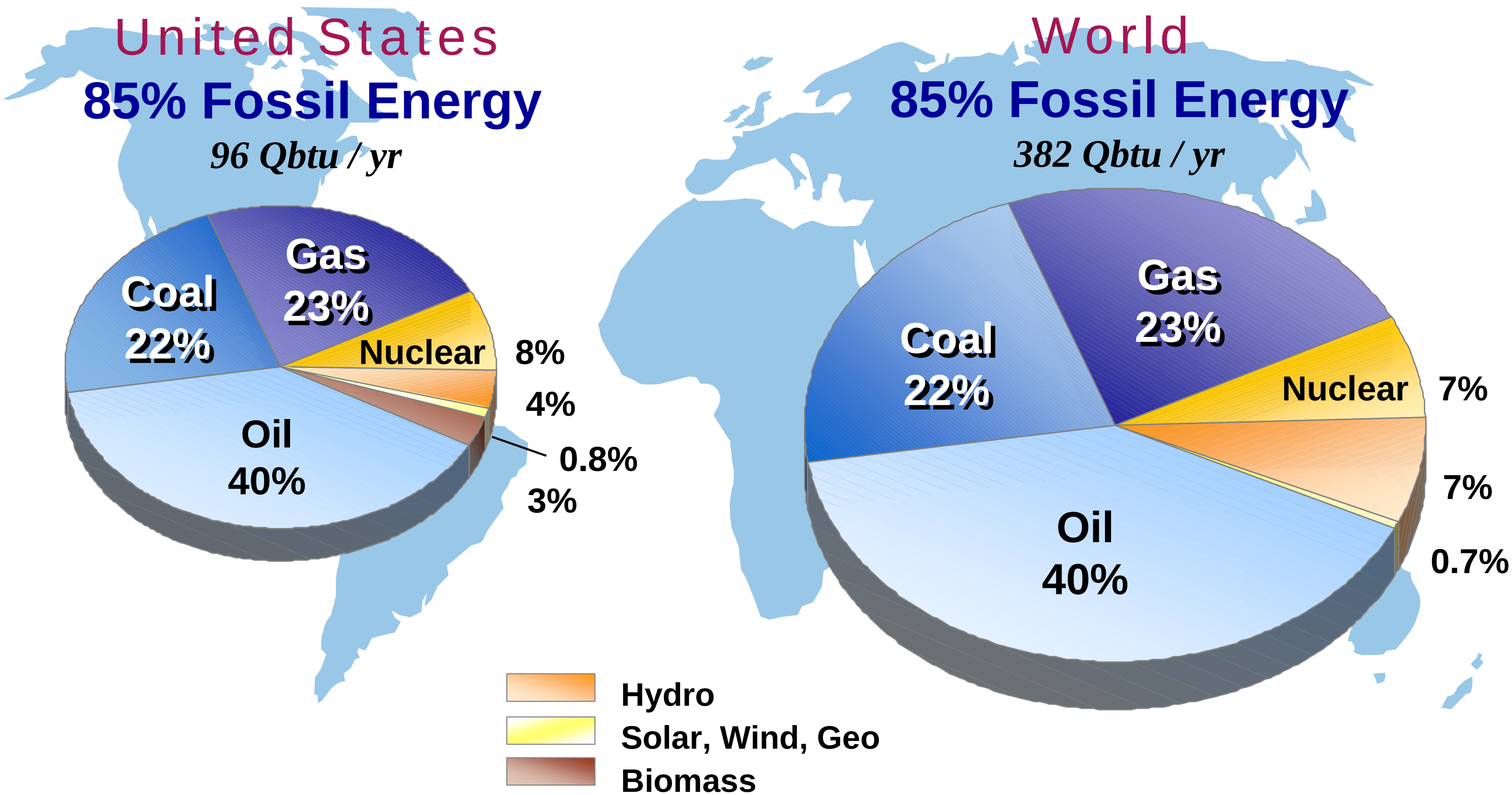


End Uses



AEO 2001, Table A19

U.S. and World Economies Based on Fossil Fuels



World data from International Energy Annual 1999 (February 2001)
U.S. data from Renewable Energy Annual 2000 (March 2001)
World data does not include non-grid-connected biomass

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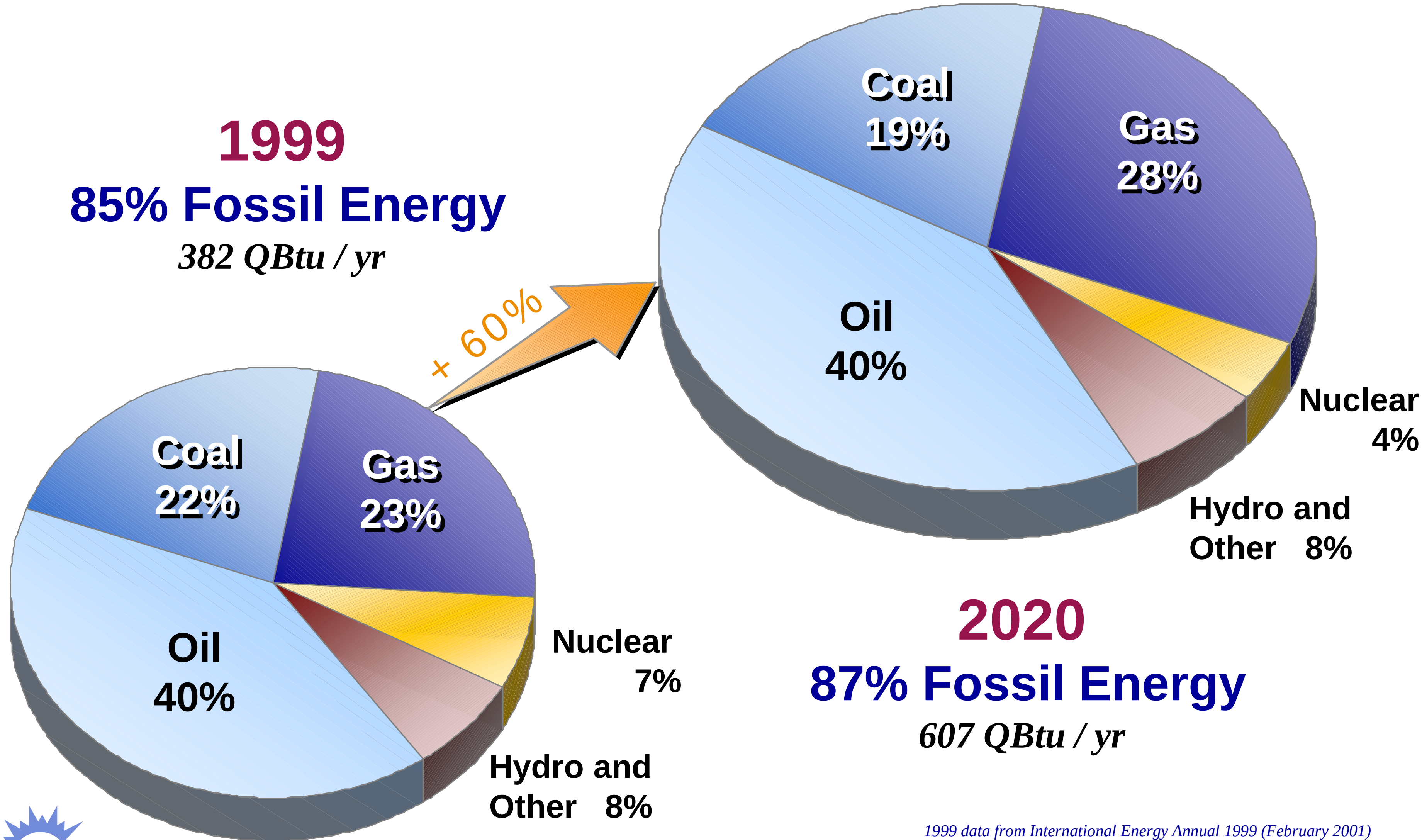
Fossil Fuels Will Continue as Key to World Economy

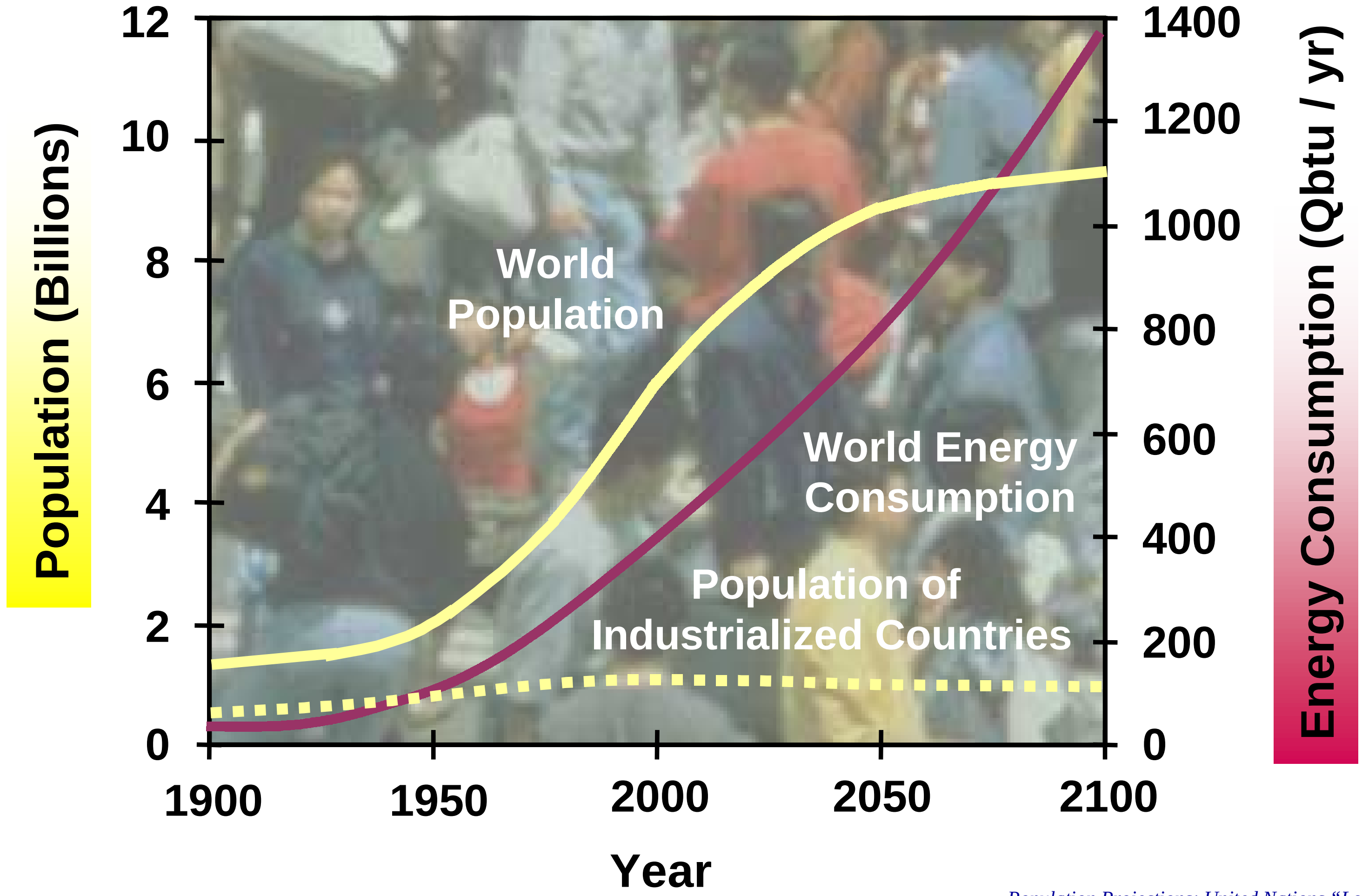
1999
85% Fossil Energy
382 QBtu / yr



2020
87% Fossil Energy
607 QBtu / yr

1999 data from International Energy Annual 1999 (February 2001)
2020 data from International Energy Outlook 2001 (March 2001)

World Energy Demand Growing Dramatically



Population Projections: United Nations "Long-Range World Population Projections: Based on the 1998 Revision"

Energy Projections: "Global Energy Perspectives" ITASA / WEC

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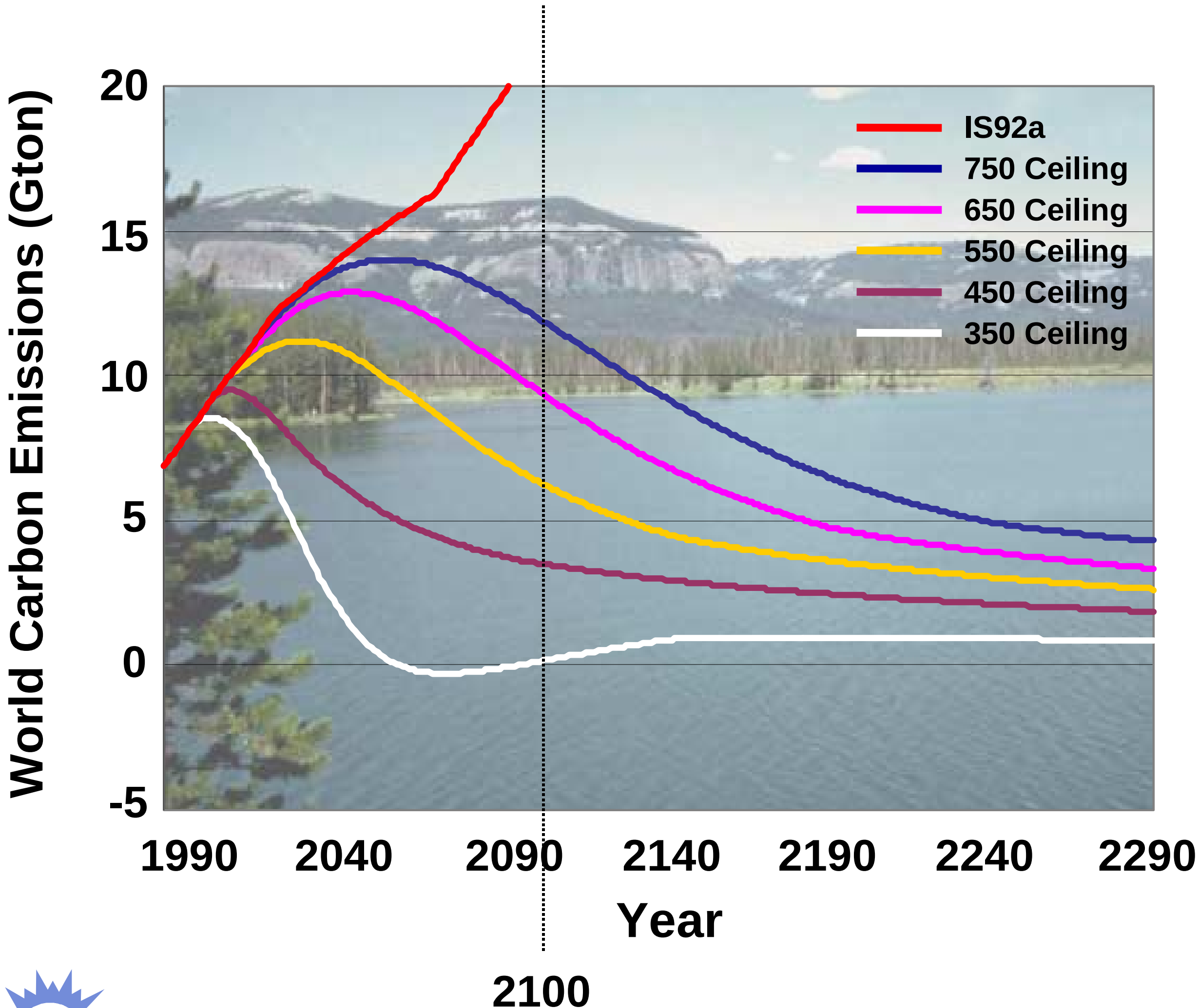
Scenarios to Stabilize CO_2 Concentrations



550 ppmv pathway requires 60% reduction from 1990 levels by 2100

Wigley, T.M.L., Richels, R., and Edmonds, J.A. ***Nature 379****, 240-243 (1996)*

Technological Carbon Management Options

Reduce Carbon Intensity	Improve Efficiency	Sequester Carbon
• Renewables • Nuclear • Fuel Switching	• Demand Side • Supply Side	• Capture & Storage • Enhance Natural Processes

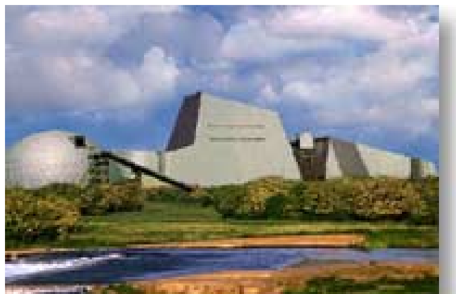
All options needed to:

- **Supply energy demand**
- **Address environmental objectives**

Approaches to Sequester Carbon

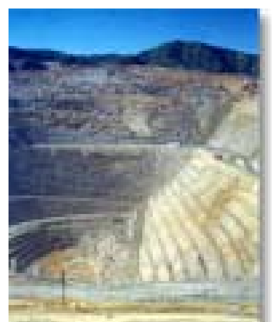
Capture and Storage

Unmineable Coal Seams



Deep Ocean Injection

Depleted Oil / Gas Wells, Saline Reservoirs



Mineral Carbonation

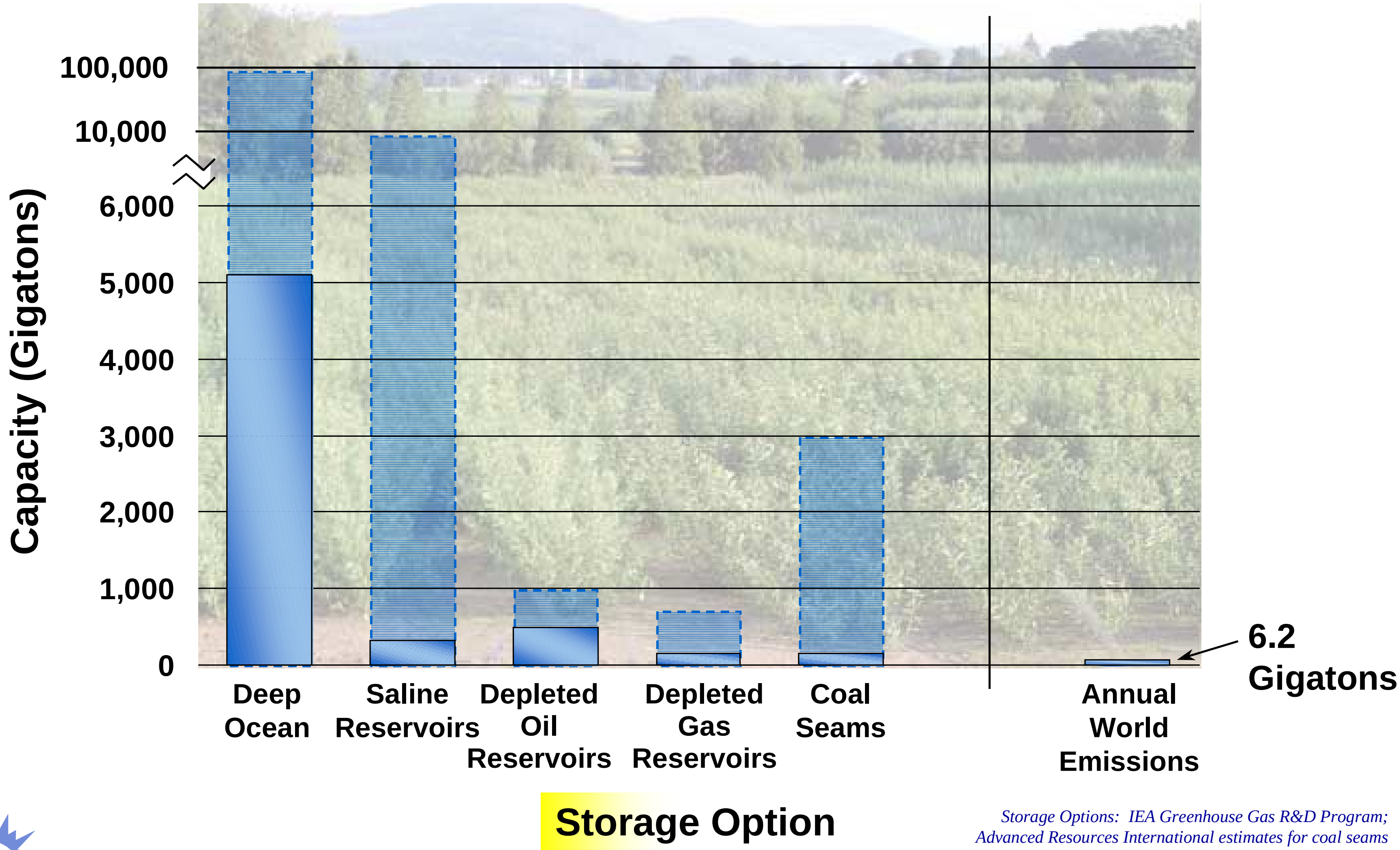
Enhance Natural Processes

Forestation

Iron or Nitrogen Fertilization of Ocean

Enhanced Photosynthesis

Large Potential Worldwide Storage Capacity



Storage Options: IEA Greenhouse Gas R&D Program; Advanced Resources International estimates for coal seams
World Emissions: International Energy Outlook 2000, Table A10

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Requirements for Sequestration

- **Environmentally acceptable**
  - No legacy for future generations
  - Respect existing ecosystems
- **Safe**
  - No sudden large-scale CO_2 discharges
- **Verifiable**
  - Ability to verify amount of CO_2 sequestered
- **Economically viable**

DOE's Sequestration Program

Office of Fossil Energy

- **Separation and capture**
- **Terrestrial ecosystems**
- **Geologic sequestration**
- **Ocean sequestration**
- **Conversion and reuse**
- **Modeling and assessments**

Research coordination

Office of Science

- **Geologic sequestration**
- **Enhanced carbon sequestration in terrestrial ecosystems (CSiTE)**
- **Ocean carbon sequestration (DOCS)**
- **Sequencing genomes of microorganisms**
- **Advanced chemical and biological processes**

Applied R&D ← → ***Basic Science***

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Agencies Conducting Sequestration-Related Research

USGS
Geologic sequestration research

NASA
Space-based studies of earth as integrated system

EPA
Inventory of greenhouse gases

OSM
Carbon sequestration on abandoned mine sites

USAID
Tropical reforestation in developing countries

NOAA
Atmospheric and oceanic global observations

NSF
Science of CO_2 and N_2 cycles in oceans

USDA
Terrestrial sequestration, soil carbon database, sequestration models

Forest Service
Management practices to increase carbon sequestration

Office of Fossil Energy's Sequestration Program

Number of Projects by Research Area

15	**Separation and capture**
3	**Terrestrial ecosystems**
17	**Geological sequestration**
7	**Ocean sequestration**
9	**Conversion and reuse**
7	**Modeling and assessments**

1995 ← *Exploratory Assessments* — *Laboratory-Scale R&D* — *Technology Validation* → 2010

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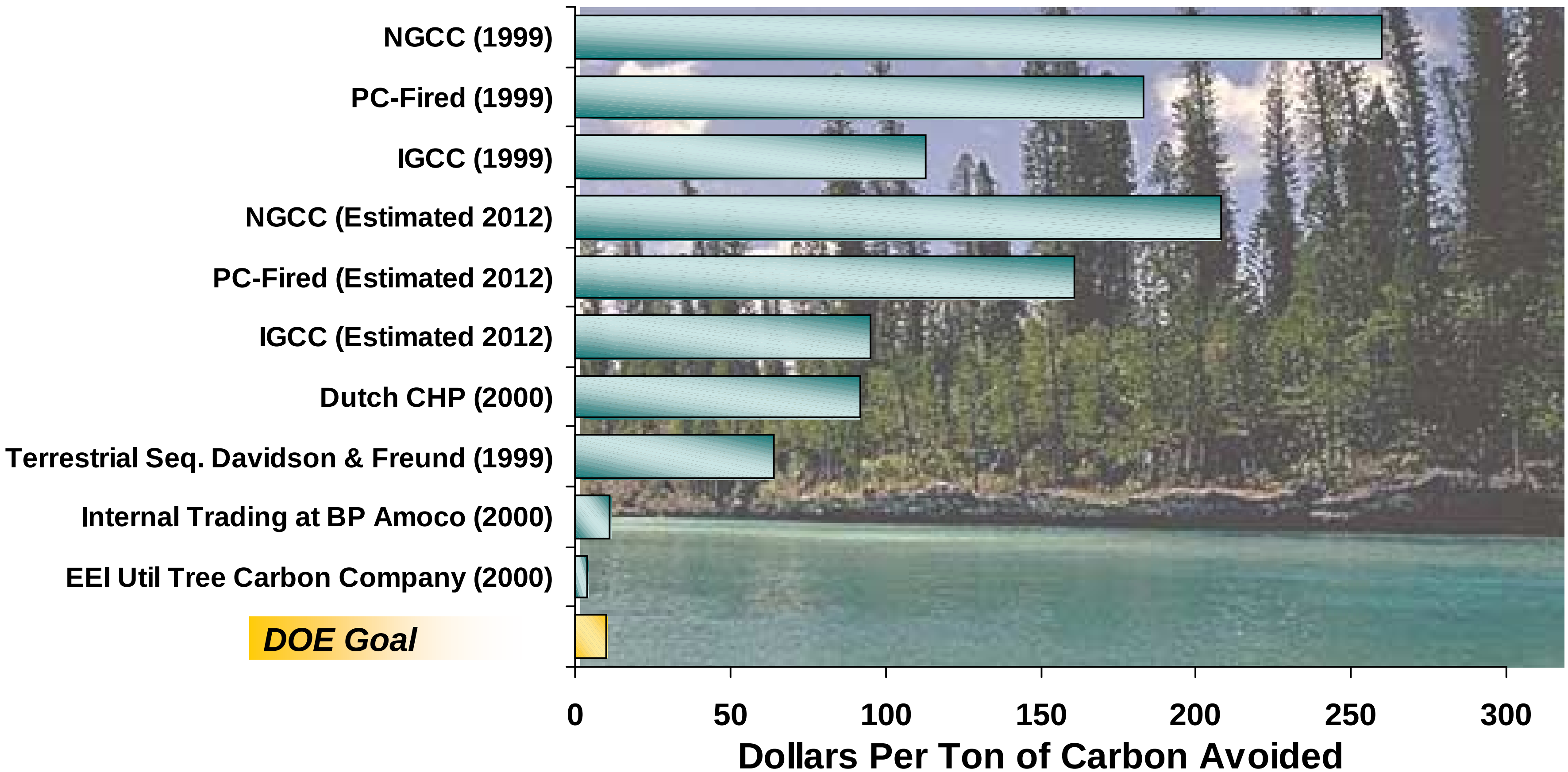
DOE Cost Goal for Sequestration

Net Costs



Long Term Cost Goal Is $10 Per Ton of Carbon Avoided

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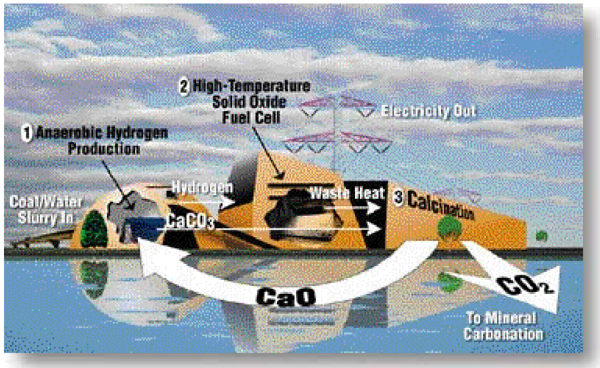
Dollar figures are for year cited & are not adjusted to a constant year dollar

Designs for Carbon Sequestration

Advanced Energy Plants

Coal Gasification With Water Gas Shift to H_2 and CO_2

Pressurized Combustion Using Pure O_2



Coal Gasification With $CaCO_3$ Intermediate to Produce H_2 and CO_2

Producing a Concentrated Stream of CO_2 at High Pressure

- ***Improves Sequestration Economics***
- ***Reduces Energy Penalty***

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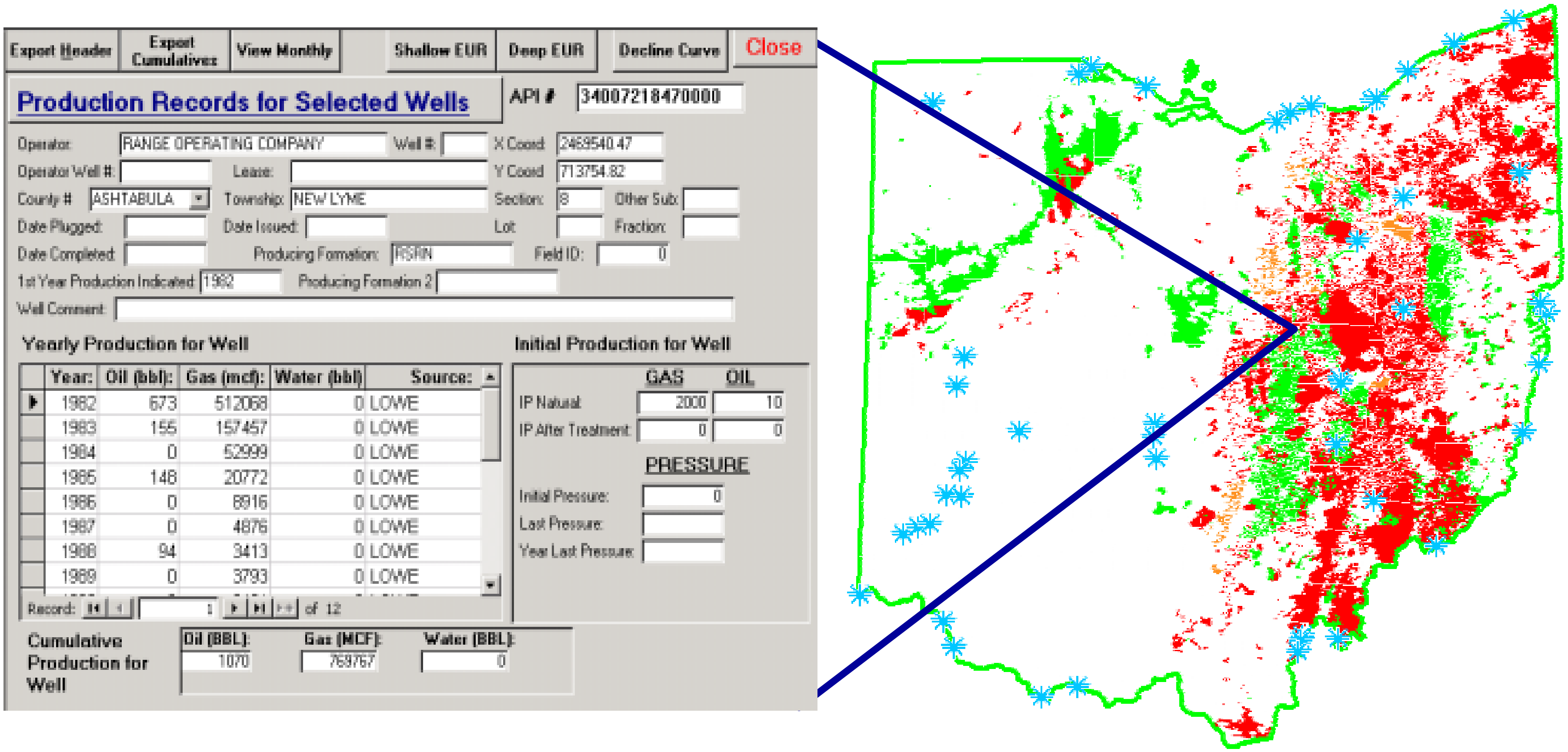
Energy Production ➡ Geological Sinks



Midcontinent **I**nteractive **D**igital **C**arbon **A**tlas and **R**elational Data**B**ase

www.midcarb.org

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Geologic Sequestration in a Depleted Oil Reservoir

First U.S. Depleted Reservoir Storage Project

- **Inject CO_2 and monitor its movement**
- **Location**
  - Oil reservoir near Roswell, New Mexico
- **Partners**
  - Pecos Petroleum
  - Strata Production
  - New Mexico Tech U.
  - Sandia
  - LANL
  - NETL

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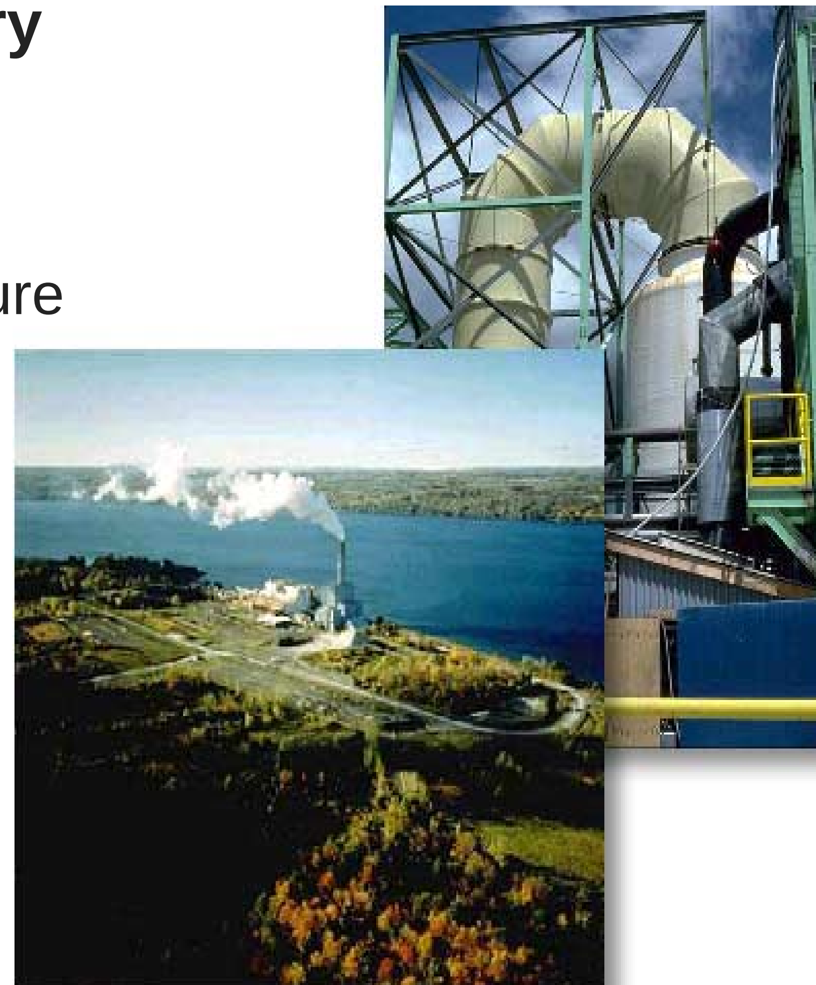
CO_2 Separation from Flue Gas

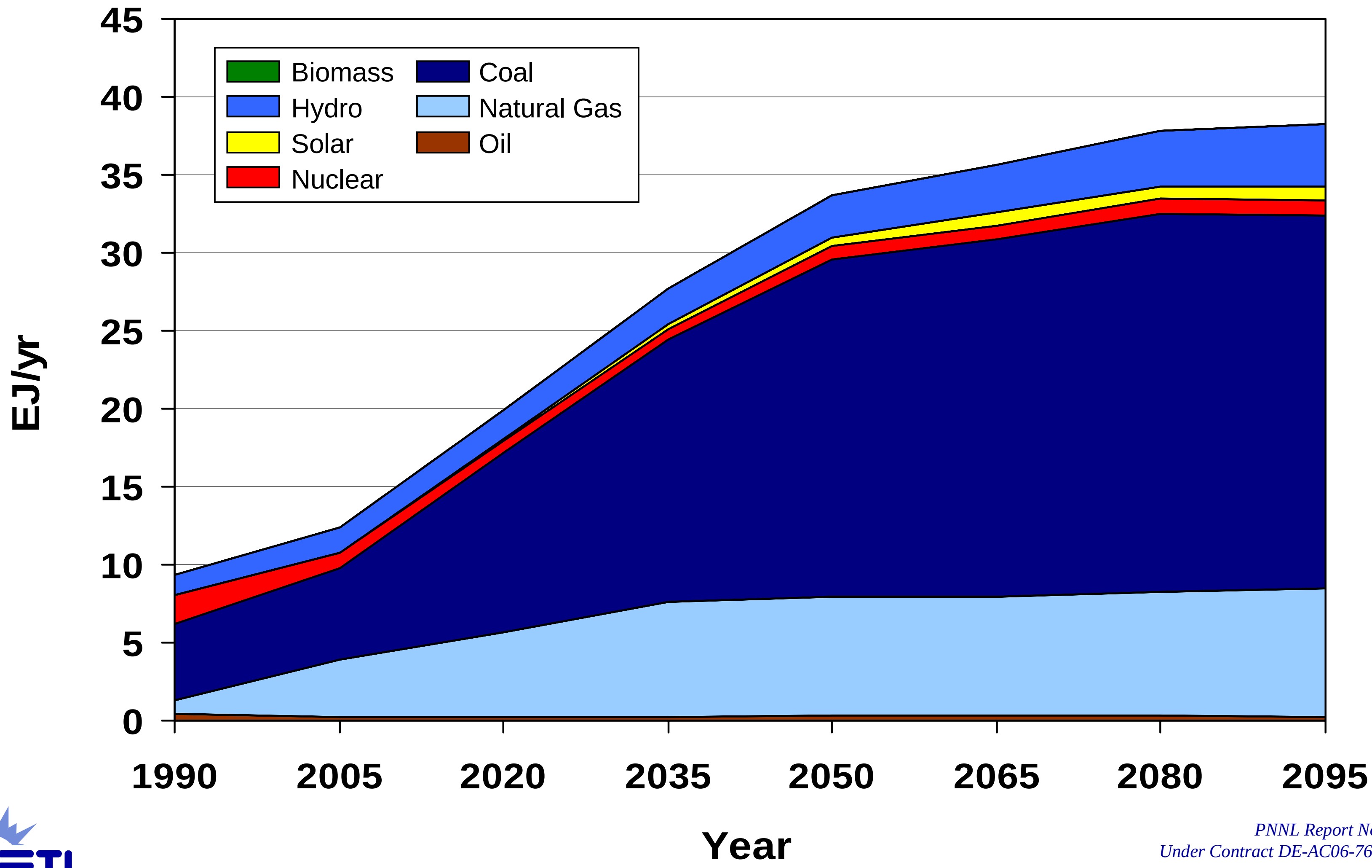
- **Use sodium carbonate, a dry regenerable sorbent**
- **Benefits**
  - Capable of 100% CO_2 capture
  - $15/ton carbon at 25-50% capture
- **Team members**
  - Research Triangle Institute
  - Church and Dwight, Inc.



Terrestrial Sequestration at a Power Plant

- **Amend coal mine spoil land near Paradise Power Plant in KY using FGD solids**
- **Multiple benefits**
  - Sequester carbon
  - Improve soil quality
  - Integrated assessment
- **Partners**
  - TVA
  - EPRI
  - NETL

A Reference Case Scenario
U.S. Electricity Generation

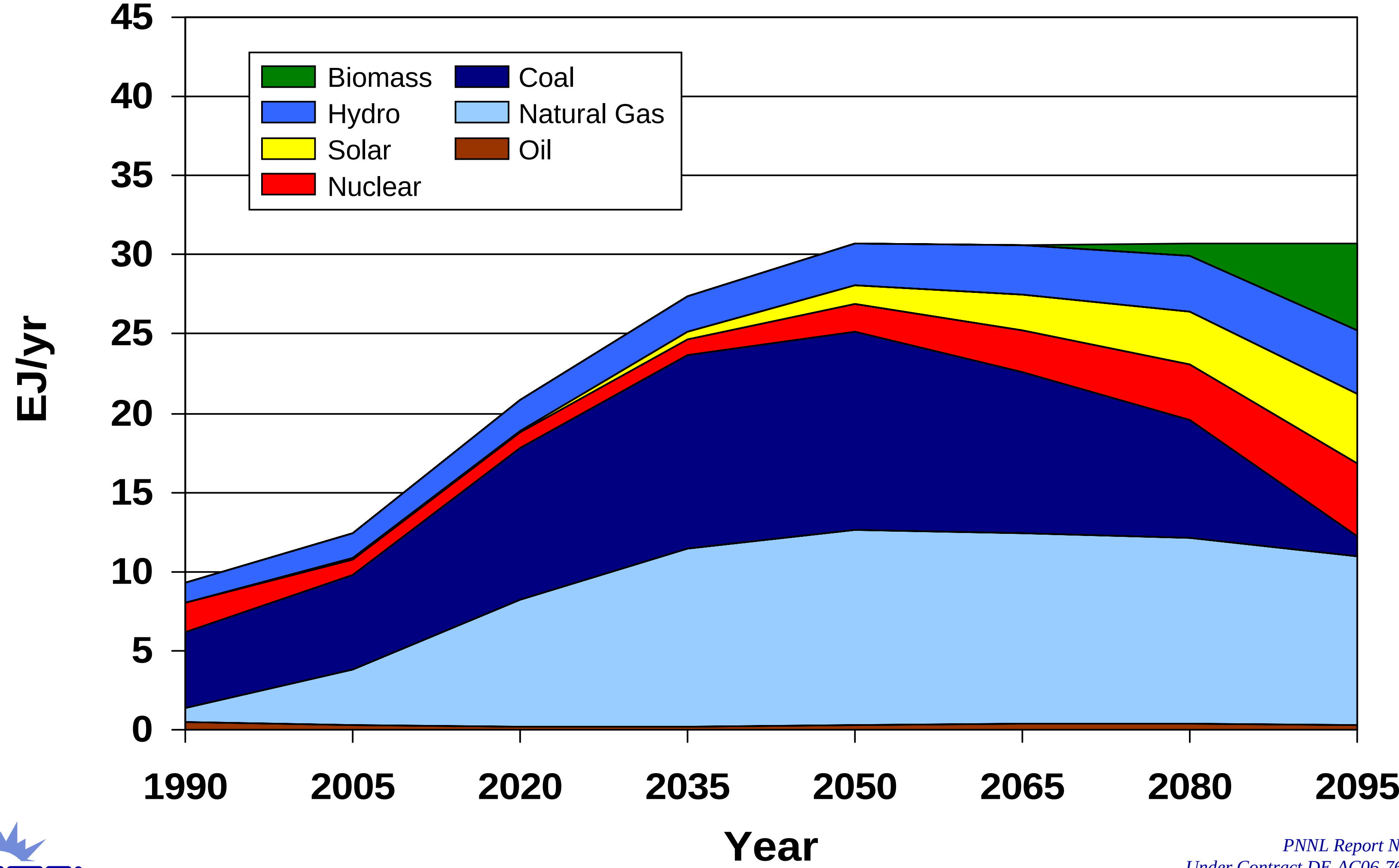


PNNL Report No. 13095;
Under Contract DE-AC06-76RL01830

2K-2854 RAB 4/01

Case Without Carbon Sequestration

U.S. Electricity Generation- 550 ppmv



PNNL Report No. 13095;
Under Contract DE-AC06-76RL01830

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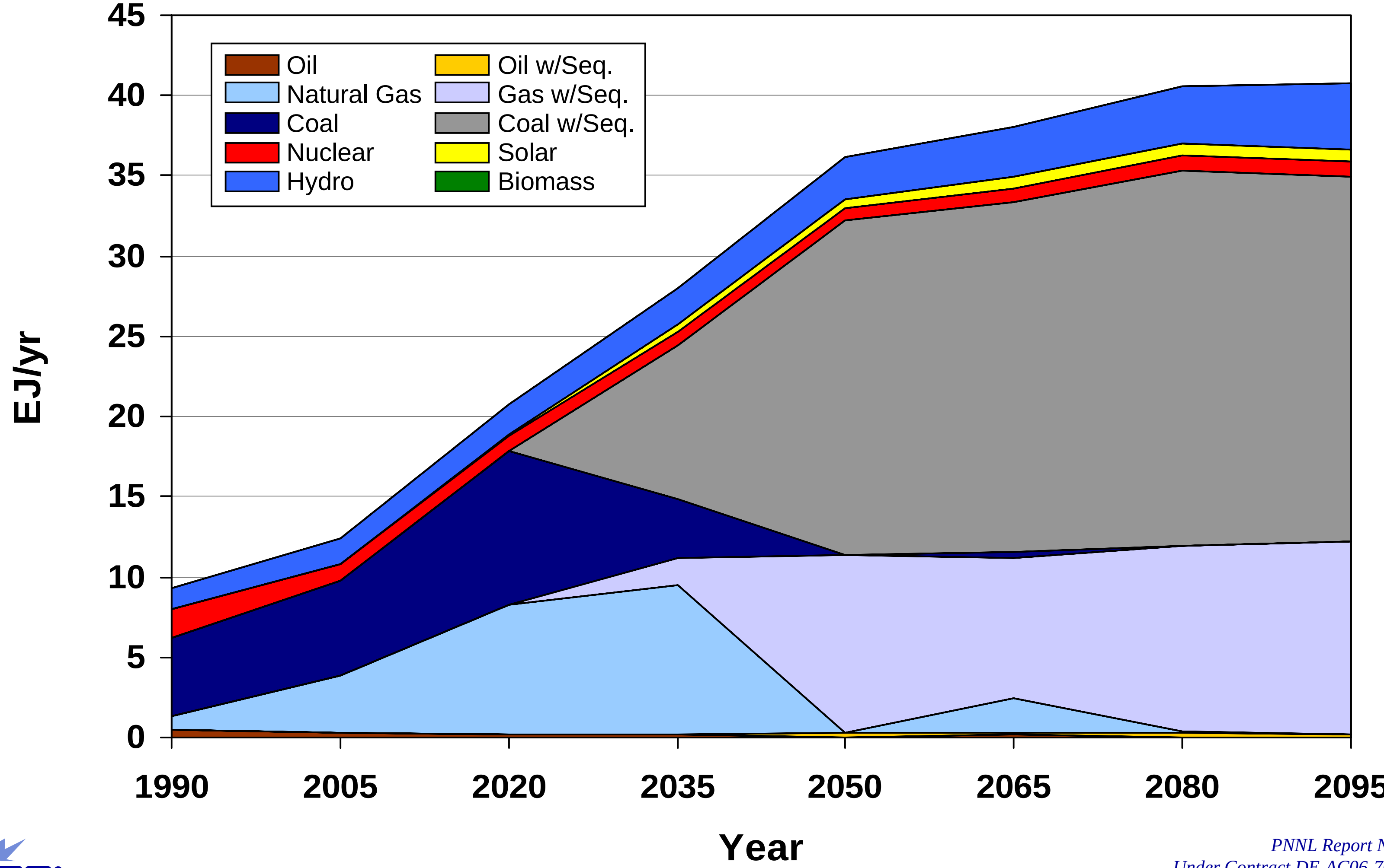
Sequestration / High-Efficiency Generation
U.S. Electricity Generation - 550 ppmv



PNNL Report No. 13095;
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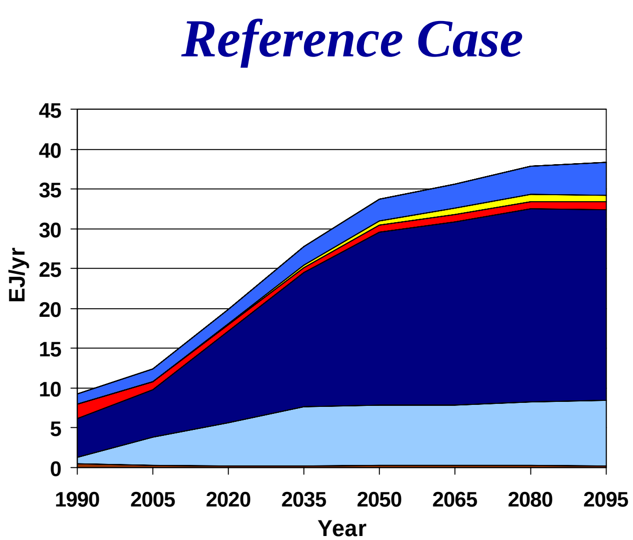
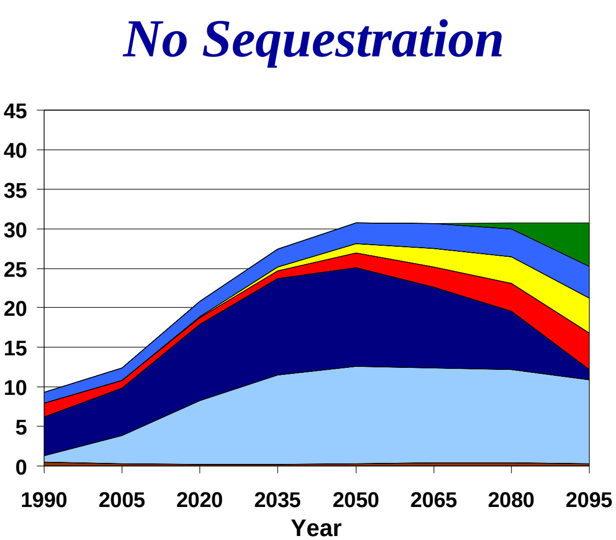
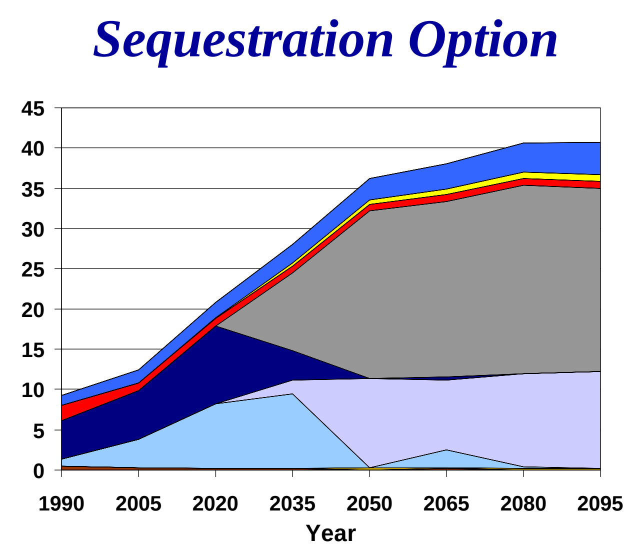
The Benefit of Sequestration







- **Miss environmental target**

- **Meet 550 ppmv target**

- **Meet 550 ppmv target**
- **Save U.S. $215 billion**
- **World Wide Saving ⩾ $1 Trillion**

PNNL Report No. 13095;
Under Contract DE-AC06-76RL01830

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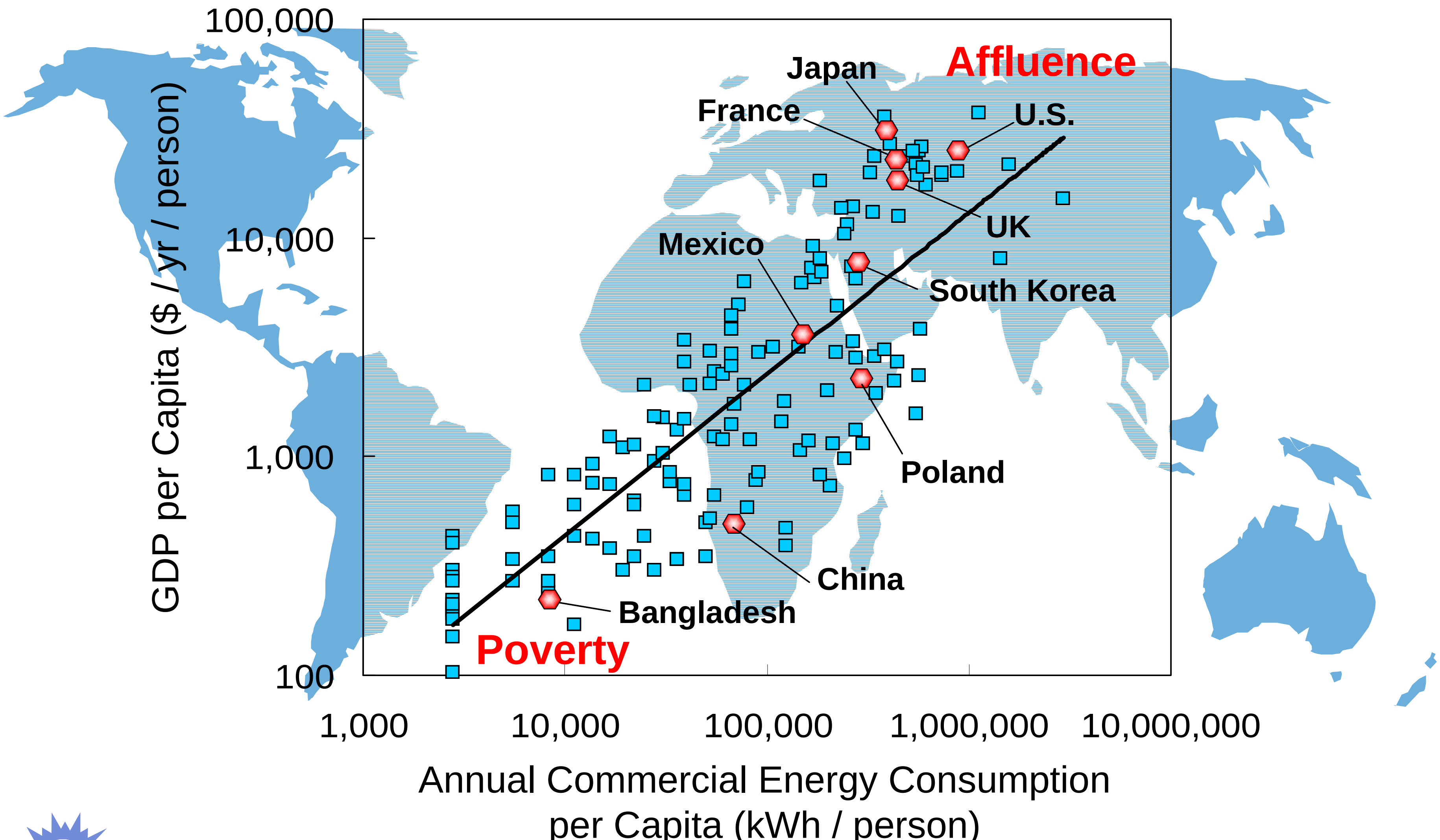
The World Needs Affordable Energy



World Resources Institute Database 1996-1997

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Focus on All Technological Options to Address Climate Change

Reduce Carbon Intensity

Improve Efficiency

Sequester Carbon

Slide 1
Technological Options to Address Global Climate Change

Good morning. Welcome to First National Conference on Carbon Sequestration. My talk this morning will address our technological options to address global climate change. It will be in three parts:

- First, what we know, and what we think we know, about climate change.
- Second, our technological options to manage carbon, and why we need all of them.
- Third, an overview of DOE's carbon sequestration program.

Slide 2
The Climate Change Debate

There is an ongoing debate about climate change. The United States signed and ratified the Framework Convention on Climate Change in 1992. Its objective is to stabilize greenhouse gas concentrations in the atmosphere "at a level that would prevent dangerous anthropogenic interference with the climate system."

Article 2 of the Framework Convention goes on to say that "such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened, and to enable economic development to proceed in a sustainable manner."

The climate-change debate centers on

- what the level to prevent interference is,
- how to achieve stabilization, and
- what the time frame should be.

The devil is in the details. It's tempting to line people up as "believers" and "skeptics," as if these labels define the debate. But this oversimplification masks the tremendous amount of work being done to understand the issues. Feelings run high, but the debate should be decided by the facts. So what <u>do</u> we know?

Slide 3
CO_2 Concentrations Beyond Range of Natural Occurrence

We know that CO_2 concentrations in the atmosphere are higher than they were 150 years ago, at the beginning of the industrial age. This slide shows CO_2 concentrations in the atmosphere (the top line) and change in global temperatures (the bottom line). Concentrations are up 30% — from a pre-industrial-age average of 280 ppm to 365 ppm today (shown here by the red arrow). Concentrations also appear to be higher than at any time over the past 200,000 years. This puts them beyond the range of natural occurrence.

Comparing the upper and lower lines, we can see the close correlation between CO_2 and global temperatures. The cause and effect relationships are not clear. But as we head toward yet higher concentrations of CO_2, it should make us thoughtful about the potential impact of these concentrations on the climate.

Slide 4
Energy is Major Contributor

We know that production and use of fossil fuels are the major contributors to anthropogenic greenhouse gas emissions (emissions from human activities). The large pie chart on the left shows U.S. anthropogenic greenhouse gas emissions broken out by source — 85% of emissions are energy related. The smaller pie chart, on the right, breaks out energy-related greenhouse gas emissions by type of gas — CO_2 dominates at 95%.

It should be noted that anthropogenic emissions are only a small fraction of total global CO_2 emissions — about 3%. Before the industrial age, natural CO_2 emissions were balanced by natural sinks, which removed CO_2. Now, anthropogenic emissions, though relatively small, are changing a pre-existing equilibrium. And as a result, atmospheric concentrations of CO_2 are increasing.

Slide 5
All Fossil-Based Sources and Uses Contribute

We know that all fossil fuels and all end-uses contribute to CO_2 emissions. These pie charts show U.S. CO_2 emissions from energy split out two different ways. The pie chart on the left shows emission split out by fuels — all fossil fuels contribute. The chart on the right shows emissions split out by end-use sector — all end-use sectors contribute.

These two charts suggest it will be more difficult to address CO_2 emissions than, for example, SO_2 emissions. SO_2 emissions are derived primarily from coal use in power plants. CO_2 emissions involve all end-use sectors and all fossil fuels. Sulfur is essentially a trace contaminant in coal. Carbon is the very heart of the chemical structure of fossil fuels.

Slide 6
U.S. and World Economies Based on Fossil Fuels

We know that both the United States and world economies are based on fossil fuels. This slide shows commercial energy sources in the United States and in the world. Both derive about 85% of their energy from fossil fuels. The non-hydro renewables (solar, wind, and geothermal) contribute less than 1% to the United States or world commercial energy supply.

Slide 7
Fossil Fuels Will Continue as Key to World Economy

We are fairly certain that fossil fuels will continue to be the basis of the world's economy for the foreseeable future. DOE's Energy Information Administration (EIA) projects that world energy consumption will increase nearly 60% over the next 20 years, from 382 QBtu to more than 600 QBtu. EIA also projects that fossil fuels will continue to supply 85% of the world's energy in 2020.

Slide 8
World Energy Demand Growing Dramatically

We are also fairly certain that world energy demand will continue to grow dramatically. Accurately predicting future energy demand is difficult, as history has repeatedly shown. Projections depend on the assumptions made for the rate of change in

- population,
- economic development, and
- energy intensity (the ratio of energy consumed per unit of economic activity).

The solid yellow line shows world population, now just over six billion. In its "medium scenario," the UN projects a world population of almost 10 billion by 2100, a 60% increase. Most of this growth will occur in developing countries in Africa, Asia, and Latin America. The population of industrialized countries, shown here by the dashed yellow line, will remain essentially constant — but their consumption of fuel per capita will be much greater than that of the developing countries.

Over the next 100 years, world energy demand (the red line) will increase to support this growing population, and to support growing aspirations for a higher standard of living. The World Energy Council projects that primary energy requirements will increase 2- to 5-fold by 2100. In their "middle course" scenario, shown here, energy use more than triples.

Slide 9
Scenarios to Stabilize CO_2 Concentrations

Finally, we know that massive reductions in CO_2 emissions will be needed to stabilize atmospheric CO_2 concentrations at some small multiple of pre-industrial CO_2 levels.

The curves on this slide show various scenarios for world carbon emissions. The red curve, going off the top of the chart, projects world carbon emissions under an "existing policies" or "business as usual" scenario. This curve is "IS92a" from the IPCC's Second Assessment Report; I'm using this family of curves because no comparable assessment has yet been completed for IPCC's Third Assessment Report.

The scenario shown assumes

- moderate population growth (a world population of 11 billion in 2100),
- moderate economic growth, and
- substantial technological progress, with more than 40% of primary world energy coming from nuclear, solar, hydropower, and biofuels by 2100.

In spite of this, world carbon emissions under this scenario grow from 6 Gtons per year in 1990 to 20 Gtons per year in 2100. The atmospheric CO_2 concentration in 2100 would be more than 700 ppm, and rising.

The lower family of curves is from Wigley, Richels, and Edmonds. The yellow curve, in the middle, shows an emissions pathway that would stabilize atmospheric CO_2 at 550 ppm. This concentration is roughly double the pre-industrial level of CO_2. It's also the lowest level many analysts feel we can practically achieve.

This yellow pathway requires decreasing carbon emissions to 6 Gtons in 2100 (the same as 1990) — a 60% reduction from the existing policy level. Emissions ultimately would need to decrease to a little more than 2 Gtons per year to maintain steady state.

Achieving a global reduction of 60% from 1990 levels by 2100 may be more challenging than we realize. Over the next 100 years, developing countries are likely to increase their energy use eightfold. Thus, it would be extremely difficult for them to return emissions to 1990 levels. Industrialized countries are likely to "only" double their energy use. They may be forced to assume a larger proportionate share of the emission-reduction burden. This level of emission reduction would be a staggering undertaking for the developed nations!

Slide 10
Technological Carbon Management Options

That's what we know. Now, what can we do? We have three technological options to manage CO_2:

- We can reduce carbon intensity. This approach includes using renewable energy, nuclear fuels, or switching to natural gas in place of coal or oil.

- We can improve efficiency — conserve energy. On the demand side, where energy is used, we can improve the efficiency of our buildings, appliances, transportation fleet. On the supply side, where energy is produced, we can use more efficient power plants and refineries.

- We can sequester carbon — either by capture and storage, or by enhancing natural processes to store carbon.

We need all of these options to simultaneously meet the world's growing energy demands and responsibly address climate change.

Slide 11
Approaches to Sequester Carbon

Let's take a closer look then at carbon sequestration, the topic of this conference. This slide shows two approaches to sequester CO_2.

In capture and storage, CO_2 would be collected inside a power plant or other large point source and pumped elsewhere for long term storage. The pictures on the left show some of the storage concepts we are investigating.

- CO_2 could be permanently stored in deep, unmineable coal seams. Methane could also be produced during the injection.
- Potentially, CO_2 could be stored by injecting it deep into the ocean.
- CO_2 can be pumped into depleted oil and gas reservoirs or saline reservoirs for storage.

Processes to enhance natural absorption are shown on the right. This approach captures CO_2 after it has been released to the atmosphere. The approach involves enhancing or accelerating natural absorption processes. It is particularly applicable for smaller sources: houses, cars, and small industries. Possible concepts include forestation, enhanced photosynthesis in algae farms, or iron or nitrogen fertilization of the ocean.

Some sequestration concepts could follow either approach, depending on how they are implemented. An example is mineral carbonation, the reaction of CO_2 with minerals to form geologically stable carbonates, shown here in the center.

Slide 12
Large Potential Worldwide Storage Capacity

Worldwide, the potential storage capacity for CO_2 is hundreds of times our annual emission rate. The bars on the left show estimated worldwide storage capacity for different direct sequestration options. The small bar on the right of this chart shows annual world carbon emissions — 6.2 Gtons.

The ocean is the largest potential storage site for carbon, with some estimates reaching 100,000 Gtons. The potential of deep, saline reservoirs is also very large. Not shown are CO_2 recycle and reuse options, which could also have very large storage capacities. For example, CO_2 could be processed in a cavern with methogenic bacteria to produce methane.

There are gaps in our understanding of the capacity of these storage options. The final capacity will be set by our understanding of the science of sequestration; for example, the potential for changing the chemistry of the ocean. However, we believe that storage capacity is not an issue.

Slide 13
Requirements for Sequestration

For a sequestration method to be a viable public policy option, these are the requirements it must meet:

- It must be environmentally acceptable, that is, it must leave no legacy for future generations and it must respect existing ecosystems.
- It must be safe; there must be no risk of sudden large-scale discharges.
- It must be verifiable; there must be a way to verify the amount of CO_2 that is sequestered.
- It must be economically viable when compared with other options for managing carbon.

DOE’s sequestration program is designed to address all of these requirements.

Slide 14
DOE’s Sequestration Program

DOE’s sequestration program resides in two offices: the Office of Fossil Energy and the Office of Science.

Fossil Energy’s program covers six research areas:

- separation and capture,
- terrestrial ecosystems,
- geologic sequestration,
- ocean sequestration,
- CO_2 conversion and reuse, and
- modeling and assessments.

A key focus of bullets 2, 3, and 4 is integration of sequestration with energy production.

The Office of Science program covers five areas:

- geologic sequestration;
- enhancing carbon sequestration in terrestrial ecosystems (three national labs — Oak Ridge, Pacific Northwest National Lab and Argonne — are working on this in a consortium called CSiTE.);
- ocean carbon sequestration (two Labs — Lawrence Berkeley and Lawrence Livermore — are working on this in a joint center called DOCS);
- sequencing genomes of microorganisms for carbon management; and
- advanced chemical and biological processes.

In general, research in the Fossil Energy program is more applied, with a greater percentage of the research conducted by industry. Research in the Office of Science is more fundamental — basic science — with a greater percentage of the research conducted by national labs.

The two research programs are coordinated — the program was kicked off with a joint R&D roadmap. We make a particular effort to coordinate research in complementary areas through, for example, joint proposal evaluation teams.

Slide 15
Agencies Conducting Sequestration-Related Research

While DOE has the lead on carbon-sequestration research, many other U.S. Government agencies conduct sequestration-related activities. Nine of these agencies are listed here along with some of their activities — but the list is not exhaustive. Agencies include:

- NASA — space-based studies of earth as an integrated system.
- EPA — inventory of greenhouse gases and sinks.
- USAID — tropical reforestation in developing countries.
- NSF — science of CO_2 and N_2 cycles in oceans.
- Forest Service — forest management practices to increase carbon sequestration.
- USDA — terrestrial sequestration, soil carbon databases, and sequestration models.
- NOAA — atmospheric and oceanic global observations and modeling.
- OSM — carbon sequestration on abandoned mine sites.
- USGS — geologic sequestration research.

All of these efforts help to improve our understanding of the carbon cycle and how carbon sinks might be enhanced.

Slide 16
Office of Fossil Energy's Sequestration Program

This slide provides more details on the Office of Fossil Energy's carbon sequestration program. We have nearly 60 projects in our six research areas. And our program is growing; we expect to make a number of additional awards very soon. In the past year, we also established a Carbon Sequestration Science Focus Area at NETL.

We are exploring a range of sequestration options because it is too early in the R&D program to know which approaches will meet the requirements of being environmentally acceptable, safe, verifiable, and economically viable. Different regions of the United States may need different approaches. In the east, sequestration in deep saline reservoirs is likely to more cost effective than other approaches. In Texas, the preferred approach may be sequestration in depleted oil wells in the Permian Basin.

The double-headed arrow at the bottom of the slide shows the status of the R&D program in a general sense. We started a few exploratory assessments in 1995. The program was formally established only 2 years ago. Many projects are in the exploratory assessment stage. Some are in the R&D stage. Post 2005, more projects will enter the technology verification stage.

FY 2001 funding for the Office of Fossil Energy program is $19 million. There is a tremendous amount of industrial interest in the program. Industry is cost sharing at the 40% level. The Office of Science program is also funded at roughly $20 million per year.

Slide 17
DOE Cost Goal for Sequestration

A major challenge to the R&D community is to reduce the cost of sequestration. This slide shows recent cost estimates for carbon sequestration from a variety of sources. The top six bars reflect capture and storage of CO_2 from large point sources. Costs range from $100–250 per ton of carbon sequestered. However, these bars reflect today's technologies or, in 2012, minor modifications of today's technologies. The cost using reforestation is generally much lower. However, forest sequestration may be limited in duration.

The yellow bar at the bottom depicts DOE's cost goal of $10 per ton of carbon. The purpose of the Fossil Energy R&D program is to reduce costs to meet the DOE goal. These studies help us understand the cost drivers. For example, the Davidson and Freund study deals with forestation. It showed that the need to monitor and measure the amount of carbon sequestered can add significantly to the cost.

Slide 18
Designs for Carbon Sequestration

One factor that makes direct sequestration expensive is the need to separate CO_2 from the huge volume of gases leaving an energy plant. We can improve the economics of sequestration with new energy plant designs that produce concentrated CO_2 streams at high pressure.

- Future coal gasification plants may have a water gas shift reaction that produces hydrogen for a combustion turbine and a concentrated stream of CO_2 for sequestration.

- An alternative approach would be pressurized combustion using pure oxygen. Compared to atmospheric combustion with air, this would produce much less stack gas with a higher concentration of CO_2.

C Another possibility is to gasify coal in the presence of calcium carbonate to produce hydrogen. Waste heat is used to transform the calcium carbonate back into calcium oxide and a concentrated CO_2 stream.

DOE is laying the groundwork for these power plants of the future as part of our Vision 21 program.

In my next four slides, I want to discuss four representative sequestration projects in our research portfolio. Several of the researchers involved in these projects are in the audience and will discuss the projects in more detail later in the conference— but I want to give you a flavor of Fossil Energy's sequestration program.

Slide 19
Energy Production –> Geological Sinks

The first project is the Midcontinent Interactive Digital Carbon Atlas and Relational Database, called MIDCARB. This is being developed by the University of Kansas and the state geological surveys in five midwestern states: Indiana, Illinois, Kansas, Kentucky, and Ohio.

This slide shows an example of the information that will be available through MIDCARB. The map on the right shows GIS (Geographic Information System) data for oil fields (in green), gas fields (red), and power plants (blue stars) in Ohio.

MIDCARB will be a web-based tool to relate CO_2 sources, such as power plants, with potential sequestration sites, such as depleted oil and gas fields. The data base will also provide information on the cost of compression and transport of CO_2 between the source and the sequestration site. Data on individual oil fields, leases, and wells will also be available.
The goal is to have a practical tool to analyze the feasibility and costs of geologic sequestration.

Slide 20
Geologic Sequestration in Depleted Oil Reservoirs

The second project involves CO_2 sequestration in a depleted oil reservoir. This is the first project of this type in the United States. The demonstration site is the West Pearl Queen field near Roswell, New Mexico. This fall, we will inject at least 2,000 tons of CO_2 into the reservoir over a 1-month period. We will then monitor the advance of the CO_2 plume over the next 3 years.

The objectives of the project are to:

- characterize the reservoir and its capacity to sequester CO_2,
- predict multiphase fluid migration,
- develop improved techniques to remotely monitor reservoirs, and
- measure CO_2-reservoir interactions.

The project team includes members from industry, academia, and national labs.

Slide 21
CO_2 Separation from Flue Gas

The third project is CO_2 separation from flue gas. This is currently a laboratory-scale project. It operates at stack gas temperatures and uses sodium carbonate, a dry regenerable sorbent, to separate the CO_2. The sorbent is capable of 100% CO_2 capture. A particularly attractive feature of this process is its projected low cost at modest capture levels of 25–50%. A $15 per ton capture cost is projected. The principal investigator is Research Triangle Institute.

Slide 22
Terrestrial Sequestration at a Power Plant

The last project I'd like to highlight is a terrestrial sequestration project. The project is located near a coal-fired power plant, the Paradise Plant in Paradise, Kentucky. TVA (Tennessee Valley Authority) plans to use solid byproducts from a flue gas desulfurization process to amend 250 acres of coal-mine spoil land. Following this, a mix of hardwood trees will be planted on the soil. Sequestration will occur through carbon uptake by the trees and in the soil, which currently has low carbon levels.

The project will have multiple benefits. It will sequester carbon, improved soil quality, and assess the integration of energy production with sequestration. In addition to TVA, the other partners on this project are EPRI and NETL.

Earlier in my talk, I said we need all technological CO_2 management options to responsibly address climate change.

- We need technologies to reduce the carbon intensity of our fuels.
- We need technologies to improve efficiency.
- We need technologies to sequester carbon.

Some ask, why do we need carbon sequestration? Can we responsibly address climate change with just two options? In the next four slides, I'd like to make the case why we need all three options.

Slide 23
A Reference Case Scenario

The case for sequestration becomes clear when we take a longer term view, a 100-year view, of the energy world, and we consider the dramatic reductions in CO_2 emissions needed to stabilize CO_2 concentrations in the atmosphere.

This graph is the first of four from Kim and Edmonds at Pacific Northwest National Laboratory. The graphs are from a study in which they assessed the potential of sequestration to stabilize atmospheric CO_2. DOE's Office of Fossil Energy funded this study and it is available on their website.

This graph is a reference case scenario for U.S. electricity generation. PNNL also developed global cases, and cases for China. This shows the power generation mix from 1990 to 2095 in a future dominated by coal. In 2095, renewables (blue and yellow) provide 13% of electricity generation, nuclear (red) provides 3%, coal (dark blue) provides 63%, and natural gas (light blue) provides 22%. The top curve, the total amount of electricity needed in the United States over the next 100 years, is the vision of the future defined by the IPCC in 1992. It represents a fourfold increase in electricity demand.

This scenario provides reliable, affordable electricity. However, no efforts are made to reduce greenhouse gases. Thus, the problem with this case is that emission levels far exceed those needed to stabilize atmospheric CO_2 concentrations.

Slide 24
Case Without Carbon Sequestration

If, instead, we need to stabilize atmospheric CO_2 at 550 ppm, there are many ways to do it — although none are cheap or easy. This is one way. This graph shows a scenario for U.S. electricity generation without carbon sequestration.

This scenario limits emissions through conservation and increased use of carbon-free energy forms. This scenario assumes very aggressive deployment of renewable technologies into the marketplace. Electricity prices rise and less electricity is used. Electricity generation declines 20% from the reference case.

Coal (the dark blue wedge) begins to disappear from the energy mix; it fuels only 4% of electricity generation in 2095. In 2095, renewables (green, blue, and yellow) provide 45% of electricity generation, nuclear (red) provides 15%, and natural gas (light blue) provides 35%.

Slide 25
Sequestration/High-Efficiency Generation

Alternatively, we can stabilize atmospheric CO_2 at 550 ppmv using sequestration and high-efficiency power generation. In this scenario, electricity becomes a more important component of our total energy mix. Electricity generation increases slightly from the reference case — by about 6%. Higher efficiency power generation (dark blue and light blue) plays a large role in increasing electricity generation in the first half of the century when carbon emissions constraints are not as severe. Sequestration begins after 2020. By 2095, coal- and natural-gas-technologies with sequestration (the grey and lavender wedges) fuel 86% of total power generation.

Slide 26
The Benefit of Sequestration

In a future carbon-constrained world, the first of the three options shown here may be unacceptable. If we need to stabilize atmospheric CO_2 at 550 ppm, many options are possible but two are shown. We could stabilize without sequestration (middle chart) or we can develop sequestration technologies so we can stabilization with sequestration (right).

Under the assumptions of the PNNL model, the sequestration/high-efficiency option saves the United States $215 billion. Savings to the world economy are more than $1 trillion. Most of these saving occur after 2050. The dollar figures are discounted at 5% per year into their net present value. Thus, these are conservative cost estimates.

These cost savings are very large numbers! To realize these saving, we need to develop carbon sequestration technology and have it as an available option in addition to reducing carbon intensity and improving efficiency.

Slide 27
The World Needs Affordable Energy

I have two final slides.

Climate change is a global problem that will require a global solution. We need to engage all of the world's countries in reducing greenhouse gas emissions. The bulk of the world's future energy growth will occur in developing countries. Yet they didn't cause the problem. They look to the industrialized countries to take the lead in solving it.

I submit that the world needs affordable energy. This log-log graph plots mean energy consumption per capita versus gross domestic product (GDP) per capita for several nations. The result is the trend line shown here. Affluent countries are shown toward the upper right, with higher energy consumption and higher GDPs. Less-developed countries are toward the bottom left, with lower energy consumption and lower GDPs.

Energy consumption and affluence are linked. Recognizing this, we in the research community need to provide options for the cleanest, cheapest energy possible. These options will provide a mechanism for developing countries to move up the trend line to a level of economic well being. When developing countries meet basic human needs, quality-of-life issues, such as environmental protection, can become a priority.

Slide 28

Focus on All Technological Options to Address Climate Change

Climate change is a long-term issue. It has taken 150 years for the atmospheric CO_2 concentration to increase by 30% — the time it took to transition from a pre-industrial society based on wood to an industrial society based on fossil fuels. Changing our current energy system overnight is not feasible; premature retirement of our existing infrastructure is prohibitively expensive. But we need to conduct research now so we have the tools to manage emissions in the long term.

Technology, including sequestration, will play a crucial role in addressing climate change. Technology is not an abstract. It is the means to reconcile our environmental imperative, a non-despoiled earth for future generations, with our economic imperative, an abundant supply of affordable energy for a robust economy.

Thank you.