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Potential for Advanced Carbon Capture and Sequestration Technologies in a Climate Constrained World

SH Kim
JA Edmonds

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Abstract

This study assesses the potential of advanced power plant carbon capture and sequestration technologies for the stabilization of atmospheric CO_2 concentration. Although the current cost of power plant carbon capture and sequestration technology is high, the availability of advanced carbon capture and sequestration technologies could have a significant role in reducing the impact of climate change. Mitigating carbon emissions while continuing to utilize fossil fuels for electricity generation limits drastic changes to the global energy system. The ability to use abundant and cheap fossil fuels without contributing to climate change prevents large reductions in energy consumption and the substitution to more expensive sources of energy. Our analysis shows that significant cost savings could be achieved in stabilizing the atmospheric concentration of CO_2 with advanced carbon capture and sequestration technologies over the next century.

Executive Summary

Introduction

The prospect of eliminating carbon dioxide (CO_2) emissions to the atmosphere while minimizing changes to the current fossil energy system presents an opportunity to lower the economic cost of carbon emissions control policies. Such a strategy could be possible through the development of technologies to capture CO_2 from fossil power plants and to dispose of the captured CO_2 in appropriate geological formations and oceans. Based on this motivation, we investigated the potential of advanced carbon capture and sequestration technologies proposed by the United States Department of Energy, Office of Fossil Energy (FE) in conjunction with their Vision 21 technologies.[1]

Using Pacific Northwest National Laboratory's MiniCAM model, we assessed the impact of advanced capture and sequestration technologies on the global energy system by comparing a world in which the atmospheric CO_2 concentration is stabilized by the end of the 21st century and a world in which there is no effort to reduce carbon emissions. In addition, under the carbon-constrained scenarios, we determined the penetration of the advanced CO_2 capture technologies, the reduction in CO_2 emissions from these technologies, and their ability to reduce the cost of stabilizing atmospheric CO_2 concentrations over the next century.

The State of the Art

The current cost of CO_2 capture and sequestration from stationary power plants is high and ranges from 121 to 337 dollars per tone of carbon ($/tC) depending on the specific type of power plant.[2] The Office of Fossil Energy is conducting research on advanced carbon capture and sequestration technologies to increase the efficiency of power plants and to lower the cost of carbon capture and sequestration. Specific program goals are to improve the fuel efficiency of advanced coal power plants to 60 percent and natural gas combined cycled plants to 70 percent by 2015, and to reduce the net cost of carbon sequestration to 10 $/tC or lower in the near future.[1]

We have simulated the advanced carbon capture and sequestration technologies of the Vision 21 Program in our modeling and have assumed that fuel efficiencies reach the above levels and that the net carbon capture and sequestration cost falls from 50 $/tC in 2015 to 10$/tC by 2035 with 90% effectiveness of CO_2 capture.

Stabilizing the Atmosphere *With* FE's Advanced Carbon Capture and Sequestration Technologies

The adoption of FE's Vision 21 advanced carbon capture and sequestration technologies has a dramatic impact on the global energy system under all atmospheric CO_2 concentration constraints studied (750, 650, 550, and 450 ppmv). These technologies enable the consumption of electricity to be maintained at reference levels or even higher while limiting the emission of CO_2. Carbon emissions control policies that raise the cost of fossil fuels combined with the availability of carbon capture and sequestration technologies promote a transition to a world that relies more and more on electricity for its energy services. Moreover, higher efficiencies of these advanced power technologies, higher fossil fuel prices due to carbon control policies and greater movement towards electrification leads to a world in which less primary energy is consumed. Lastly, the availability of advanced carbon capture technologies and the ability to rely on abundant fossil fuels achieve stabilization of atmospheric CO_2 concentration at significantly lower costs.

The global generation of electricity for all atmospheric CO_2 concentration stabilization scenarios is maintained at or surpasses the reference level generation. In the reference case, global electricity generation grows nine-fold from 35 exajoules (EJ) in 1990 to 319 EJ by 2095. With advanced capture technologies, global electricity generation is 8, 9 and 11 percent greater than the reference case for atmospheric CO_2 concentration cases of 750, 650 and 550 ppmv, respectively, by the end of the 21st century. Electricity generation for the more stringent 450 ppmv case falls below the reference level by 18 percent by the end of the next century due to the severity of the emissions constraint. The switch to capture technologies occurs after 2020 and nearly all of the CO_2 emitted from electricity generation is captured and sequestered by 2065. Regionally, both OECD and non-OECD regions gain from FE's advanced capture and sequestration technologies, but these technologies have a greater impact on non-OECD countries because of their greater capacity for electrification.

Advanced capture and sequestration technologies enable continued reliance on fossil fuels, and coal and natural gas remain the major sources of electricity in the next century. However, continued reliance on fossil fuels does not imply that the future world remains the same. Fixing the cost of carbon control on electricity generation while increasing the price of fossil fuels encourages greater use of electricity for energy services in the end-use sectors of the economy. As the carbon constraint becomes tighter, more and more of the energy services in the residential, commercial and industrial sectors rely on electricity. Hence, the generation of electricity can surpass reference levels as indicated above. The implications of this transition are the potential of improved local air quality and greater overall energy efficiency, in addition to the control of carbon emissions.

Although the availability of FE's advanced capture technologies under carbon constraints results in large increases in the global generation of electricity, global primary energy consumption falls from the reference case. Reference case primary energy consumption exceeds 1200 EJ by 2095 from 355 EJ in 1990. Power plant fuel efficiency improvements, energy conservation from higher fossil fuel prices and substitution from direct fuel use to electricity in the end-use sectors of the economy result in lower primary energy consumption levels. Global primary energy consumption for the 750, 650, 550, and 450 ppmv cases are 18, 18, 25, and 52 percent lower than the reference case, respectively, by the end of the 21st century.

The Cost of Atmospheric Carbon Concentration Stabilization

The most significant contribution of FE's advanced capture technologies are the dramatically lower carbon taxes necessary to stabilize atmospheric CO_2 concentrations. These technologies reduce the carbon taxes necessary to stabilize CO_2 concentrations to 750, 650 and 550 ppmv levels by more than 70 percent relative to scenarios without such technologies. By 2035, capture technologies have already begun to have an impact and carbon taxes for the 750, 650, 550 and 450 ppmv cases are 19, 32, 57, and 177 $/tC, respectively. By 2095, carbon taxes for 750 and 650 ppmv cases are even less at 14 $/tC and 21 $/tC, respectively. The carbon tax for the 550 ppmv case rises to 89 $/tC, and in the most extreme case of the 450 ppmv scenario, the carbon tax increases to 811 $/tC by 2095.

Rising carbon taxes in the more stringent 450 and 550 ppmv cases, even with the availability of FE's advanced capture technologies, reflect the rising cost of substitution to electricity in all end-use sectors of the global economy and in particular, the transportation sector.

The lower carbon tax levels over the next century mean that the difference in having or not having available FE's advanced capture technologies ranges from hundreds of billions to trillions of dollars for the world depending on the concentration desired. The value of these technologies is comprised of both the improvements to plant efficiency and the availability of the capture technology. However, higher plant efficiencies alone, without the capture technology, are not sufficient to lower the stabilization costs as concentration constraints become more stringent. The value of capture technologies, therefore, is much greater when lower atmospheric carbon concentrations are desired.

Carbon Storage Reservoir

Comparison of the cumulative emissions mitigation in the concentration stabilization scenarios to the global estimates of carbon storage reservoir by Herzog et al. indicates that there is sufficient capacity for carbon storage to meet the most stringent concentration ceiling imposed.[3] However, it does not seem likely that depleted oil and gas reservoirs or coal seams alone are sufficient to meet the world's carbon storage needs. Storage to meet more stringent concentration constraints, such as the 450 ppmv case, will necessitate CO_2 disposal in saline aquifers and oceans. In the 450 ppmv case, the cumulative carbon emissions mitigation from the year 2000 to the end of the next century amounts to 850 billion tonnes of carbon.

Conclusions

This analysis shows the tremendous potential of advanced capture and sequestration technologies for the stabilization of atmospheric CO_2 concentrations. The difference to the world of having available such technologies is significant and warrants greater investigation. Because the global energy system relies on fossil fuels for the majority of its needs, use of carbon capture and sequestration technologies lowers the cost of stabilizing atmospheric concentrations of carbon emissions. Concentration stabilization is achieved while preventing drastic changes to the global fossil energy system where reductions to energy consumption and substitution to more expensive sources of energy are limited.

More specifically, the availability of carbon capture and sequestration technologies enables greater consumption of electricity under all carbon constraints studied. Capture technologies under carbon penalties promote greater use of electricity by encouraging substitution from the direct use of fossil fuels to electricity in the end-use sectors. In addition, primary energy consumption is greater for all concentration cases with the availability of capture technologies than without, but lower than the reference case due to efficiency improvements, higher fuel prices, and electrification.

With capture and sequestration technologies, stabilization of the atmospheric CO_2 concentration is possible at significantly lower costs. Carbon taxes and the total cost over the next century fall significantly for all concentration cases with the availability of capture and sequestration technologies. The cost savings from such technologies range from hundreds of billions to trillions of dollars over the next century depending on the concentration target. In the 550 ppmv case, the present value of total cost savings from FE's advanced capture technologies is $215 billion (1996 US$) for the US and $1,741 billion (1996 US$) for the world. Assuming a discount rate of 5 %, the annualized savings are $11 billion for the US and $88 billion for the world over the next century. To put these values in perspective, the total federal R&D budget for energy in the United States in 1997 was $2.2 billion (1996 US$).[4]

Capture and sequestration technologies have real potential to reduce the cost of carbon emissions control; however, more R&D is required to bring down the current cost to levels targeted in FE's Vision 21 Program. Additionally, greater understanding of the environmental safety and limitations of carbon storage in all reservoirs is necessary.

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1. Introduction

The Framework Convention on Climate Change (FCCC),[1] signed by more than 155 nations, has as its ultimate objective, "...*stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system*." The treaty and five subsequent conferences of the parties to the convention, however, did not address some key questions. At what concentration should greenhouse gases be stabilized? How is this to be accomplished? And how much will this cost? These are not entirely unrelated questions.

It is not surprising that technology plays a large role in constructing the answers. In this analysis we attempt to develop some information that can help to shed light on one potentially relevant opportunity – power plant carbon capture and sequestration technology. We begin by discussing the motivation for capture and sequestration technologies and the current state of the art for such technologies. Next, we describe the approach in assessing the impact of capture and sequestration technologies. A model description is provided and the reference global energy system along with its assumptions is described. We impose on this reference scenario hypothetical atmospheric carbon concentration constraints and examine the role of advanced carbon capture and sequestration technologies in achieving those constraints. More specifically, we assess the impact of capture and sequestration technologies on the global energy system by comparing a carbon constrained world to a world in which there is no effort to reduce greenhouse gas emissions. Lastly, we assess the value of these technologies for reducing the cost of stabilizing atmospheric carbon concentrations over the next century.

1.1 Motivation for Considering Carbon Capture and Sequestration

Fossil fuel is the backbone of the world's energy system and is likely to remain so for the foreseeable future. Methods to reduce carbon emissions by moving away from fossil fuels through either conservation or non-carbon energy technologies could require substantial changes to the current energy system and result in significant economic costs. Therefore, the prospect of minimizing changes to the current fossil energy system while eliminating the emission of carbon to the atmosphere is desirable and could present an opportunity to lower the economic cost of carbon emissions control. Such a strategy could be possible through the development of carbon capture and sequestration technologies. These technologies refer to the capture of carbon dioxide from fossil-fueled electric power plants and the subsequent disposal of the captured carbon dioxide in appropriate geological formations and oceans. Based on this motivation, we investigated the impact of advanced carbon capture and sequestration technologies proposed by the Office of Fossil Energy in conjunction with their Vision 21 technologies.[2]

2. The State of the Art

2.1 The Present State of Technology for Carbon Capture and Sequestration

The present state of carbon capture and sequestration technology is focused on the capture of carbon dioxide (CO_2) from the flue gas of fossil-fuel electric power plants and the disposal of the captured CO_2 in various geological formations. Great attention has been placed recently on the technology for CO_2 capture from stationary power plants, and several technologies exist today to capture CO_2 from flue gases. Capturing CO_2 from power plants is not a new idea and has its origins as sources of CO_2 for enhanced oil recovery[3] and for agricultural CO_2 fertilization in greenhouse applications.[4]

According to Herzog et al., the current cost of CO_2 capture from coal and natural gas power plants is 66 to 282 dollars per tonne of carbon ($/tC) avoided depending on the specific type of power plant.[5] The additional capital, fuel, operations, and maintenance costs of CO_2 capture add 1 to 3 cents per kWhr to the electricity cost of base plants. Part of the cost of CO_2 capture is due to energy requirements of the capture process that result in net power losses. Such energy penalties can range from 13 to 37 percent depending on the plant type. Current capture technologies, however, can remove 75 to 90 percent of the CO_2 emitted from the combustion of fossil fuels.

Although the current cost and technical feasibility of the capture technologies are well understood, the cost and environmental impacts of CO_2 disposal have not been fully evaluated. The practice of injecting CO_2 into oil wells for enhanced recovery is mature and provides the basis for the feasibility of CO_2 storage in geological formations. Enhanced oil recovery provides some information on the cost of CO_2 disposal, but does not represent the true cost of long-term CO_2 disposal as the process was not intended to counter the impact of climate change. Storage of CO_2 through enhanced oil recovery has not been adequately evaluated in terms of its ability to sequester carbon for long periods of time, or for related unintended adverse environmental impacts.

Current demonstration of CO_2 sequestration for the sole purpose of combating climate change lies with Statoil, a Norwegian oil company. Induced by a Norwegian carbon tax of 50 dollars per tonne of CO_2 (183 $/tC), the first commercial CO_2 capture and sequestration facility started operation in September 1996 by Statoil. CO_2 from a natural gas field is sequestered into a sandstone aquifer one kilometer beneath the North Sea. The CO_2 is injected from a floating rig at a rate of 20,000 tonnes per week which corresponds to the rate of CO_2 produced from a 140 MWe coal-fired power plant. According to Herzog, the cost of Statoil's sequestration operation alone is 15 dollars per tonne of CO_2 (55 $/tC). Other than the experiences discussed above, there are no large-scale commercial carbon capture and sequestration technologies currently deployed.

Combining the above capture costs and Statoil's sequestration cost, the total cost of CO_2 capture and sequestration ranges from 121 to 337 $/tC. Unless there are carbon control policies like the Norwegian carbon tax, such high CO_2 capture and sequestration costs are not likely to provide incentives for the deployment of these technologies. Thus, lowering the cost of capture and sequestration technologies could provide greater incentives for both the deployment of capture and sequestration technologies as well as the implementation of carbon control policies.

2.2 The Potential for Advanced Carbon Capture and Sequestration Technologies

The United States Department of Energy (DOE), Office of Fossil Energy (FE) is conducting research on ways to stabilize levels of atmospheric carbon concentrations through the Vision 21 Program.[2] In addition, DOE's Office of Fossil Energy and Office of Science have prepared a draft "state-of-the-science" report on carbon sequestration. The goals of the program include reducing the carbon content of fuels, improving the efficiency of energy use, and developing advanced carbon capture and sequestration technologies. Of the many methods and processes included in the program for CO_2 capture and sequestration, development of advanced capture technologies for stationary power plants is an important part.

In this regard, the Vision 21 Program seeks to produce advanced fossil-based energy systems that cost less, use less fuel, and emit near zero levels of CO_2 and criteria pollutants to the atmosphere. Specific program goals are to improve the fuel efficiency of advanced coal power plants to 60 percent and natural gas combined cycled plants to 70 percent by 2015, and to reduce the net cost of carbon sequestration to 10 $/tC or lower in the near future.

We have investigated the impact of advanced carbon capture and sequestration technologies that simulate the technologies of the Vision 21 Program. Power plant fuel efficiencies reach the above levels and the assumed net carbon capture and sequestration cost falls from 50 $/tC in 2015 to 10$/tC by 2035 with 90% effectiveness of CO_2 capture. The 50 $/tC is equivalent to a 25% penalty each on the capital cost and efficiency of coal power plants and a 16% penalty each on the capital cost and efficiency of natural gas power plants. By 2035, the cost of 10$/tC is equivalent to a 5% penalty on the capital cost and efficiency of coal power plants and 3 % penalty on the capital cost and efficiency of natural gas power plants.

3. Modeling Carbon Capture and Sequestration in a Global Energy System

3.1 MiniCAM

The Pacific Northwest National Laboratory's MiniCAM model is employed in this analysis to simulate interactions of population, economy, energy, agriculture, land-use, greenhouse gas emissions, and atmospheric dispositions. The MiniCAM is a partial equilibrium model of the world that is focused on agriculture and energy sectors to project the emission of greenhouse gases from energy consumption and land-use changes. The current version is updated from the MiniCAM model described in Edmonds et al.[6] and Edmonds et al.[7] The energy component of the MiniCAM has its origins in the Edmonds and Reilly Model (ERB).[8] The energy module has been extended and upgraded on numerous occasions. The most recent enhancements are documented in Edmonds et al.[9] and Kinzey et al.[10]

The energy module incorporates demographics, energy resources, supply technologies, end-use demand, and technical change to project energy consumption and emissions levels. Technologies in the MiniCAM are described by fuel costs and non-fuel costs, the latter including operations and maintenance costs and payments to capital. The electricity supply sector incorporates both carbon-based and carbon-free generation technologies, and competition exists among all available generation technologies.

The agriculture land-use component of the model projects agriculture and forest product outputs and tracks the demand for managed and unmanaged land. The agriculture land-use module supplies biomass products for energy, while the energy module determines the level of demand for biomass energy.

The MiniCAM model is designed for the assessment of various climate change policies and technology strategies for the globe on a long time scale. The model runs in 15 year time steps from 1990 to 2095 and includes 14 regions. The model is capable of incorporating carbon taxes, carbon permit trading, and carbon constraints in conjunction with numerous fossil and non-fossil based technology options for the globe. Thus, the MiniCAM is an appropriate tool for the assessment of carbon capture and sequestration technologies and the impact of carbon mitigation policies.

3.2 The Reference Global Energy System

The reference scenario assumes a transition from the present conventional oil and gas based world to a future world dominated by coal. This scenario is the standard vision of the future defined by the Intergovernmental Panel on Climate Change (IPCC) in 1992.[11] All scenarios of the future are virtually unanimous in their anticipation of reductions in energy intensity during the course of the next century.[11] This reduction in intensity is likely to result from changes in the composition and efficiency of future activities. Power generating facilities in the future, for example, can be anticipated to be more efficient than at present. While models generally treat such technological change as if it materialized by magic, in the real world it is energy R&D that provides the technological catalyst.

The relationship between R&D and technological change has proved difficult for researchers to predict.[a] This analysis does not attempt to develop a cause-and-effect

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[a] Some authors have examined the effect of induced technological change on the timing of emissions mitigation. See for example, Goulder and Schneider,[12] Nordhaus,[13] and Grubb.[14] This literature breaks induced technological change into two types: learning-by-doing and induced R&D. The general conclusions reached by these researchers is that the presence of induced technological change tends to move mitigation activities from the near-term to the far-term when an optimal global tax policy is implemented. The presence of learning-by-doing has an ambiguous effect on the timing of emissions abatement. Whether this effect shifts mitigation to the near-term or far-term depends on the particular parameterization chosen.

representation for R&D and energy technology. Rather, we will consider changes in the global energy system that might be anticipated under alternative regimes to stabilize the atmosphere. We examine the changes in the energy system to indicate areas in which technical performance will be at a premium.

This approach compares a reference energy system over time to an alternative policy path. We have in this analysis developed a reference scenario for the interaction of global population, economy, energy, and agriculture that evolves against a background of continued productivity improvement in energy production, transformation and end-use.

3.3 Reference Case Assumptions

There are many assumptions in any modeling effort. Below we describe some of the more pertinent assumptions within MiniCAM concerning population and economic drivers, oil, gas and coal resources, electric power technologies, and technical change.

3.3.1 Population and Economic Drivers

The reference scenario is intended to reflect in large measure a continuation of many present trends. We assume that global population will eventually stabilize at approximately eleven billion people.

Economic growth is assumed to proceed in a heterogeneous manner. We assume that rapidly developing regions will continue to close the per capita income gap with developed nations and approach parity with the presently developed world over the course of the next century. Those presently growing less rapidly are assumed to begin the process of more rapid development some time during the next century.

These assumptions reflect an underlying theory of heterogeneous economic growth and development, with per capita income in developed regions continuing to grow steadily, but slowly, and various developing regions joining the developed group through accelerated economic growth over sustained periods. We assume that some developing nations make the transition before others. That is, economic growth transitions occur in "waves." The order of the waves cannot be known *a priori.* Rapid economic growth is assumed to continue in China and South and East Asia, while other regions initiate the "catch-up" process subsequently. Other orders than those assumed here are, of course, also plausible.[b]

3.3.2 Oil, Gas and Coal Resources

Primary energy forms—oil, gas, and coal—are modeled as resource-constrained technologies. Each of these energy forms has a set of resources that can be exploited. Resources are graded, and less-expensive grades are developed before more-expensive

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[b] One could, for example, assume that the 1998 economic crisis in Asia leads to long-term, economic stagnation in that region such as occurred in Argentina.

grades. It is also assumed that the cost of production for each resource grade declines at an average annual rate of 0.5% per year for all regions. Although the extraction cost of each grade of fuel is determined exogenously, all primary and secondary fuel prices are determined endogenously by the model.

In the reference case, unconventional oil and gas resources, including methane hydrates (clathrates) are available at $50 per barrel with technological progress reducing costs after 2005 by 0.5% per year. Resource estimates are taken from IPCC,[15] Rogner,[16] and Edmonds and Reilly.[8]

3.3.3 Electric Power Generation

A full set of options for the generation of electricity is represented in the model. Electricity generation from petroleum, natural gas, coal, biomass, solar, nuclear, and hydro is included, as well as generation from power plants with carbon capture and sequestration technologies. Plants with carbon capture and sequestration technologies compete with all other energy forms in the generation of electricity. In determining the role of carbon capture and sequestration technologies in the market for electric power, the cost of fossil fuels matters as much as the cost of capture and sequestration technologies. In a carbon constrained world, for example, the cost of a combined cycle gas turbine increases by one cent per kWh for every $100 per tonne of carbon tax levied on the input fuel, natural gas. Capture and sequestration technologies can take advantage of a carbon penalty on its fossil fuel and non-fossil competitors only if the cost of electricity generation from capture and sequestration technologies is within the resulting higher cost of generation from fossil fuels. Moreover, carbon capture and sequestration will compete not only with traditional fossil technologies, but with continually improving renewable and nuclear energy technologies.

Fossil fuel electric power generation is assumed to improve continuously between 2000 and 2095. In the reference case, the average natural gas combined cycle plant efficiency is assumed to reach a maximum of 52 percent while the average coal plant efficiency is assumed to reach a maximum of 42 percent by the year 2010. Because the MiniCAM model runs in 15 year time steps, these efficiencies are achieved in the model's next evaluation period, 2020. Non-carbon-based (or carbon neutral) electricity generation sources are solar, nuclear, hydro-electric and biomass-derived power. The electricity generation cost of solar technology is assumed to decline rapidly from 52 cents per kilowatt-hour (cents/kWh) in 1997 to 14 cents/kWh by 2020 and to remain at 7 cents/kWh after 2050. We assume that nuclear power remains an option throughout the world, and the resource cost of nuclear fuels is assumed to decline at an average annual rate of 0.5 percent per year. Hydro-electric power is resource limited and is modeled by a logistic penetration function given in Edmonds and Reilly.[8] The biomass technology for electricity generation is assumed to be a direct-combustion boiler/steam turbine technology and the biomass fuel price is generated internally from the agriculture-land use component of the model.

Although we have not modeled wind energy specifically, the category of solar energy is inclusive of both solar photovoltaic and wind energy, as well as other resource constrained renewable technologies. The use of the logit structure to describe technology shares in the MiniCAM provides for a distribution of technology costs and does not specify a particular technology but rather a mode of energy service. However, since the above solar cost is representative of solar photovoltaic systems rather than wind energy, a more detailed study is necessary to understand the specific impact of wind energy.

3.3.4 End-use Energy Efficiency Improvement

In addition to energy efficiency improvements in the energy supply sectors described above, there are assumptions of energy efficiency improvements in the end-use sectors. This is generally referred to as the Autonomous End-use Efficiency Improvement (AEEI). AEEI assumptions used in this analysis vary across region and time. OECD countries have AEEI assumptions of 0.5 percent per year from 2020 to the end of the next century for all end-use sectors, whereas that for developing and transitional economies have higher initial rates of AEEI that decline to OECD levels by the end of the next century. For example, in China, the AEEI is 3.5 percent per year in 2020, 1.5 percent per year in 2050 and 0.5 percent per year by 2080.

3.4 Hypothetical Carbon Concentration Ceilings

The United States and the global community have not yet agreed on the appropriate policy for the control of greenhouse gas emissions. The Kyoto protocol focuses on the near-term target of stabilizing emissions, but provides little direction on the long-term goal of concentration stabilization. The climate change issue is a long-term century scale problem due to the nature of the carbon cycle. This analysis is concerned with the stabilization of atmospheric carbon concentration and how we might achieve such a result more cost effectively through carbon capture and sequestration technologies.

Since there is yet inconclusive understanding of what is a safe greenhouse gas concentration level as called for in the FCCC, we have looked at a range of concentrations. The literature on the relationship between anthropogenic emissions and CO_2 concentrations in the atmosphere is relatively mature,[15] and numerous models have quantified the relationship. While it may be possible, with a given model, to predict the future concentration of CO_2 from a trajectory of emissions, the inverse problem has no unique solution. Several alternative trajectories have been created, including IPCC[11] and Wigley et al.[17] The specific choice of trajectory will depend on the concentration ceiling deemed desirable, the policy instruments employed to insure that the ceiling is maintained, and the suite of technologies available to provide energy services to future growing economies.

Current projections of energy use exhibit continued growth in fossil fuel emissions. This growth is inconsistent with eventual stabilization of CO_2 concentrations. Because we do not know whether or at what level concentrations will eventually be stabilized or what constitutes a safe level, we explore constraints of 450, 550, 650, and 750 parts per million by volume (ppmv) in addition to the unconstrained reference case. In this analysis we use the trajectories of Wigley et al. (WRE) as they reflect a relatively low cost emissions control path. Reference case emissions and the emissions trajectories that result in the target concentration levels are shown in Figure 1.

[Figure 1]

We compute the cost of achieving each of these alternative objectives under a specific policy regime. This policy regime assumes a coalition of all of the world's nations to mitigate emissions, though there may be compensating transfers of income among nations. At any point in time we impose on all economic agents in the model, in all regions, a common carbon tax[c] to be included in all economic decision making. This strategy minimizes the global cost of emissions mitigation at each and every point in time.[d] The costs of achieving stable carbon concentrations could be significantly greater if expensive emissions mitigation policies are undertaken too early in the 21st century, if significant portions of the world remain outside the coalition[e], or if barriers are erected to impede large-scale trading.

3.4.1 Emissions from Land-use Change

According to the IPCC there are net emissions from changes in land-use.[21] The WRE emissions trajectory includes all sources of emissions. We have accounted for the emissions from fossil fuel combustion as well as from land-use change in our modeling. According to the IPCC, net emissions from changes in tropical land-use amounts to about 1.6 gigatonnes of carbon per year (GtC/yr).[21] Assumptions associated with income growth and agricultural productivity lead to a decline in net emissions from land-use change over time from 1.5 GtC/yr in the year 2005 to 0.6 GtC/yr in 2095. The carbon cycle model used to construct the WRE emissions scenarios from concentration targets have already incorporated terrestrial and ocean sinks so we do not make any assumptions concerning changes to these systems.

4. Projection of the Reference Global Energy System

4.1 Primary Energy Consumption by Fuel

Global primary energy consumption grows tremendously in the next century. The total global primary energy consumption exceeds 1,200 exajoules (EJ) per year in the reference case by 2095. This is a near four-fold increase in the global primary energy

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[c] The carbon tax is the premium associated with net carbon emissions that should be employed in all internal planning by energy producers and users to satisfy the associated carbon constraint.

[d] This is not precisely the minimum possible cost that could ever be encountered. That cost entails allowing the carbon tax to rise at the rate of interest plus the rate of carbon removal from the atmosphere by the natural system.[18] The WRE trajectories provide a path that is similar in cost, however.

[e] Manne and Richels[19] have shown that deviation from a cost-effective path can multiply the cost of complying with an atmospheric concentration ceiling, such as 550 ppmv. Richels et al.[20] showed that if significant regions remain outside an emissions control regime, costs escalate.

consumption from the 1990 level of 355 EJ. Figure 2 shows the global energy system in the reference case where fossil fuels remain the primary source of the world's energy consumption.

In the reference case, the transition from conventional oil and gas to coal is accompanied by an increase in the price of liquids and gases during the first half of the 21st century. The price increase leads to pressures on future energy demand by end-use applications, but also to increasing use of carbon-intense coal for primary energy. Up to 56 percent of the total global energy consumption is from coal by the end of the next century. The next largest primary energy source is natural gas which makes up 24 percent of the global total by 2095, followed by crude oil which contributes only 6 percent to the total by 2095. Crude oil consumption peaks in 2050 and falls in the second half of the 21st century. Other sources of primary energy, such as from biomass, solar, nuclear, and hydro, all rise with time. However, they are limited in their total contribution due to higher costs and/or constrained resources. Contribution of these energy resources amount to 14 percent of the total global primary energy consumption in 2095.

[Figure 2]

4.2 Primary Energy Consumption by Region

Although the majority of the world's energy is consumed by the present industrialized countries, over time developing countries surpass the industrialized countries as the major consumer of energy. OECD countries' share of the global primary energy consumption falls from over 50 percent in 1990 to less than 30 percent in 2095. The rapid economic and energy consumption growth of non-OECD countries in the next century results in the reallocation of the world's energy resources such that greater than 70 percent of the world's energy is consumed by non-OECD countries.

An example of the contrast is evident in the primary energy consumption growth of the United States and China. The US primary energy consumption in 1990 is 84 EJ whereas that for China is 31 EJ. By 2095, the US consumption doubles to 161 EJ. China's consumption, on the other hand, grows eleven-fold to 341 EJ by the same time period. See Figures 3 and 4 for primary energy consumption by fuel in the US and China.

For the US, the shares of primary energy consumption by fuel reflect in large part the global shares. Coal is the major source of primary energy, followed by natural gas and then crude oil. By 2095, the share of primary energy from coal, natural gas and crude oil are 59, 26 and 6 percent, respectively. The current dominance of crude oil for primary energy declines in the middle of the next century while consumption of natural gas and coal, in particular, rise with time.

[Figure 3]

In China, the emphasis on coal is even greater than in most regions of the world. In 1990, 73 percent of the total primary energy is from coal. By 2095, coal's share of primary energy grows to 78 percent. Although the use of natural gas grows and contributes to 10 percent of the total primary energy by the end of the next century, the declining consumption of crude oil from the middle of the next century encourages additional use of coal.

[Figure 4]

4.3 Electricity Generation by Fuel

As dramatic as the growth of primary energy consumption, the world's demand for electricity is even more remarkable. There is a nine-fold increase in the global generation of electricity from 1990 to 2095 as shown by Figure 5. Of the 35 EJ of electricity generation in 1990, 65 percent of it is generated from fossil fuels. By 2095, the total generation of electricity is 319 EJ and the share of electricity from fossil fuels grows to 76 percent. Coal and natural gas are the main fossil fuel sources for electricity. Coal contributes to 47 percent of the generation and natural gas contributes to 27 percent by the end of the century. Generation from natural gas plants, however, increases at a faster rate than coal plants in the next 50 years due to rapidly increasing efficiencies. However, as gas resources diminish and prices rise, the share of generation from gas falls. Electricity from oil remains a minor and decreasing part of the total.

Electricity from non-fossil technologies, such as nuclear, hydro and solar, increases in physical generation but becomes a smaller fraction of the total generation by the end of the next century. The declining shares of generation from these technologies do not imply a diminishing role, but rather an indication of the dramatic overall growth in the demand for electricity. In physical units, generation from nuclear rises from 6 EJ in 1990 to 24 EJ by 2095. Generation from solar grows from virtually nothing in 1990 to 21 EJ by 2095. Hydro-electricity expands from 6 to 30 EJ in the same time frame.

[Figure 5]

4.4 Electricity Generation by Region

As reflected in the primary energy consumption by region, the growth in the demand for electricity is driven by non-OECD countries. In 1990, 60 percent or 21 EJ of the global electricity generated is from OECD countries. By 2095, the share drops to 25 percent or 80 EJ of the total. Conversely, non-OECD's demand for electricity grows from 14 EJ to 240 EJ from 1990 to 2095. This growth represents an increase in the global share from 40 percent to 75 percent.

In OECD countries, the US is the largest consumer of electricity with consumption growing to 38 EJ or 48 percent of the total OECD consumption by the end of the next century. The use of natural gas for electricity generation grows in the US, but coal remains the main source of electricity. Coal's share of electricity generation is 52 percent in 1990 and 54 percent in 2095. The share of electricity from natural gas increases from 9 percent 1990 to 30 percent by 2095. Electricity from nuclear, however, falls in the US over the next century and generation from solar and hydro see only modest growth. See Figure 6 for US electricity generation growth by fuel. The electricity generation costs from coal and natural gas plants are the lowest in comparison to other modes of generation and contribute to the growing role of coal and natural gas as the most important fuels for electricity generation. A comparison of US electricity generation cost by fuel type is shown in Table 1.

[Figure 6]

Table 1. Cost of Electricity by Fuel in the US (1996 Cents/kWh)

Year	Oil	Natural Gas	Coal	Nuclear	Solar	Hydro	Biomass
2005	5.7	4.5	4.8	6.8	33.5	3.8	6.9
2050	5.8	3.3	2.9	6.8	7.8	3.8	6.3
2095	7.3	3.3	2.9	6.7	7.0	3.8	6.5

Of the non-OECD countries, China becomes the largest consumer of electricity over time. By 2095, China consumes 75 EJ of electricity or 31 percent of all non-OECD electricity generation. As shown in Figure 7, coal remains the single most important source of fuel for electricity generation in China even though all other forms of electricity generation increase with time. The share of electricity from coal is 72 percent in 1990 and 57 percent by 2095. The next largest share of electricity generation is from natural gas which grows to 19 percent of the total by 2095. Electricity from nuclear, solar and hydro also play growing roles but their contribution is limited to less than 8 percent each.

[Figure 7]

4.5 Carbon Emissions by Fuel

Inevitably, with the growing use of fossil fuels, carbon emissions reach unprecedented levels. Global CO_2 emissions in 2095 reach 24 billion metric tons of carbon (BtC) in this scenario. See Figure 8. This is a four-fold increase from the 1990 CO_2 emissions level of 6 BtC. Not surprisingly, coal combustion contributes the most to CO_2 emissions. 64 percent of total CO_2 emissions are released from coal in 2095 and the rest are from natural gas and crude oil emitted in relatively equal shares. CO_2 emissions from natural gas is 19 percent of the total, whereas that from crude oil is 18 percent. The contribution of oil, gas and coal to CO_2 emissions in the end of the next century represents a change from the current sources of CO_2 emissions. In 1990, the major share of global CO_2 emissions came from crude oil followed by coal and then natural gas. The shares were 43, 39 and 17 percent for oil, coal and gas, respectively. The shift in contributions to CO_2 emissions reflects the diminishing role of crude oil for primary energy and the growing importance of natural gas and coal.

[Figure 8]

4.6 Carbon Emissions by Region

The far reaching implication of the growing use of fossil fuels in developing and transitional economies is the shift in the contribution of global CO_2 emissions from OECD to non-OECD countries. Although CO_2 emissions from OECD countries expand from 2.9 to 6.2 BtC from 1990 to 2095, OECD's share of the total global CO_2 emission falls from 48 to 26 percent. Further into the next century, non-OECD countries play a larger role in the overall growth of carbon emissions. CO_2 emissions from non-OECD countries grow five-fold from the 1990 level of 3.2 BtC to the 2095 level of 17 BtC. By 2095, non-OECD countries emit 74 percent of the total global CO_2 emissions.

US and China are the single largest emitters of CO_2 within OECD and non-OECD countries, respectively. US emissions grow from 1.4 BtC in 1990 to 3.4 BtC by 2095 as shown in Figure 9. China's emissions are initially much lower level than in the US but China's emissions surpass US emissions by a factor of two by 2095. CO_2 emissions for China increase from 0.7 BtC in 1990 to 6.6 BtC in 2095 as shown in Figure 10.

[Figure 9]

[Figure 10]

5. Stabilizing the Atmosphere

The reference case result presented above is a scenario in which there are no efforts to reduce greenhouse gas emissions. In this section, we present results of policies to stabilize atmospheric carbon concentrations that could arise from increasing concerns for climate change.

The imposition of the WRE carbon emission constraints, discussed above, clearly alters the reference global energy system. These changes are initially relatively modest, but over time the world's energy system undergoes dramatic changes as it relies heavily on energy conservation and carbon-free energy forms. We first examine the impacts of carbon constraints without the availability of advanced carbon capture and sequestration technologies that are part of FE's Vision 21 technologies. We then discuss a future in which FE's advanced carbon capture and sequestration technologies are available and examine their role under a carbon-constrained world. Results for the range of carbon concentrations are provided. However, detailed comparisons across fuels and regions are provided for the 550 ppmv case only, as it represents the middle range of the concentration extremes studied.

5.1 World *Without* FE's Advanced Carbon Capture and Sequestration Technologies

5.1.1 Primary Energy Consumption by Fuel

All concentration cases result in significant reductions to the global consumption of primary energy. The severity of reductions occurs in the latter half of the next century, as the emissions constraints become more stringent. By 2095, reductions in primary energy consumption are 26, 30, 33, and 44 percent of the reference level for 750, 650, 550, and 450 ppmv cases, respectively. Moreover, as the CO_2 concentration constraint tightens from 750 ppmv to 450 ppmv, the change in global energy system becomes increasingly pronounced as reflected in the severity of energy consumption reductions. To achieve the lower concentration targets more and more reduction must take place earlier in time.

The pattern of these changes for the globe to meet the 550 ppmv constraint is shown in Figure 11. The global energy system moves away from using fossil fuels and moves toward conservation and use of non-carbon technologies, such as solar, nuclear and biomass energy. Consumption of all fossil fuels is reduced but carbon-intense coal is affected more significantly. For the 550 ppmv case, energy conservation from higher overall energy costs results in 413 EJ of global net energy reduction from the reference by 2095. In particular, the carbon penalty results in coal reduction of 688 EJ or 99 % and natural gas reduction of 100 EJ or 33 % from the reference case by 2095, while energy from solar, nuclear and biomass increases to compensate for these reductions. All three energy forms increase in supply by a total of 280 EJ or 243 % in 2095, with biomass, solar and nuclear contributing to 96, 95 and 88 EJ, respectively. Oil consumption falls for most of the next century except towards the end. The carbon penalty on coal discourages the production of synfuels from coal and encourages the use of more expensive crude oil resources at the end of the next century.

[Figure 11]

5.1.2 Primary Energy Consumption by Region

In the 550 ppmv case, non-OECD countries are responsible for majority of the energy reduction since they consume a large portion of the total energy by 2095. Of the 413 EJ of energy reduction in 2095, 79 percent or 328 EJ of the reduction comes from non-OECD countries, whereas 21 percent or 85 EJ of the reduction is from OECD countries. There is a slightly greater share of reduction from OECD than non-OECD countries in the first half of the next century, but the opposite is true in the second half of the next century as the demand for energy grows more rapidly in non-OECD countries. For OECD countries, reduction of primary energy consumption is 10 percent of the reference level in 2020. By 2095, the reduction grows to 27 percent. For non-OECD countries, the reductions are 9 and 35 percent in 2020 and 2095, respectively.

In the US, up to 31 percent of the reference level primary energy consumption is reduced by 2095 from the 550 ppmv carbon constraint. The reduction represents a net conservation of 51 EJ in addition to fuel switching. Coal use is virtually eliminated as 96 percent of the reference level coal consumption is reduced by 2095. Natural gas use is reduced by 21 percent by the same time period. Reductions from these sources are replaced to some degree by biomass, nuclear and solar energy. An additional 29 EJ of energy is generated from biomass, nuclear and solar over the reference level by 2095. Nuclear and solar contribute 10 EJ each and biomass adds 9 EJ. Crude oil consumption falls throughout most of the next century except towards the end when synfuel production from coal is no longer competitive with crude oil due to the carbon penalty. By 2095, 22 EJ of additional crude oil is consumed relative to the reference case. See Figure 12 for the change in US primary energy consumption in the 550 ppmv case relative to the reference.

[Figure 12]

China is affected even more than the US by the carbon constraints. By 2095, up to 48 percent of the reference level primary energy consumption is reduced. The 550 ppmv carbon constraint forces 164 EJ of net energy conservation and substitution away from coal to nuclear, solar and biomass energy. Nuclear and solar increase by 31 EJ each over the reference levels and biomass increases by 25 EJ by 2095. There are substitutions into less carbon-intense natural gas and crude oil as well, but their contributions are mixed. Natural gas plays a larger role in fuel substitution in the first half of the next century but diminished in the second half due to increasing carbon penalties. Crude oil plays a stronger role only in the end of the next century when lack of synfuels from coal encourages the use of expensive crude oil resources. See Figure 13 for the change in China's primary energy consumption in the 550 ppmv case relative to the reference.

[Figure 13]

5.1.3 Electricity Generation by Fuel

All carbon constraints lower the global level of electricity generation from the reference case. As the constraint becomes tighter, less and less electricity is generated. The reduction in electricity generation, however, is not as severe as the reduction in primary energy. Electricity is a more valued form of energy than primary energy and is not affected as significantly. The 750, 650, 550 and 450 ppmv cases result in electricity generation levels that are 13, 14, 14, and 26 percent lower than the reference level by 2095.

In the 550 ppmv case, 14 percent or 46 EJ of electricity generation is reduced from the global reference total by 2095. Moreover, 98 percent of the electricity generation from coal is eliminated by 2095. See Figure 14 for the composition of global electricity generation in the 550 ppmv case. Electricity generation from natural gas and oil increases for some time but is eventually reduced in comparison to the reference case due to higher carbon costs. Up to 9 percent more electricity is generated from natural gas in the middle of the next century before reversing to 27 percent less generation relative to the reference case by 2095. All of the electricity generation loss is compensated for by increasing generation from solar, nuclear and biomass energy, and by conservation. Solar and nuclear make significant inroads into supplying electricity when carbon constraints are applied. Along with natural gas, they are the largest sources of electricity generation. Biomass makes lesser but important contributions to the total generation. By 2095, generation from solar, nuclear and biomass increases by 47, 44 and 34 EJ, respectively. The remainder of the generation loss is attributed to energy conservation.

[Figure 14]

5.1.4 Electricity Generation by Region

The impact of the carbon constraints on electricity generation in OECD and non-OECD countries varies with time. Before 2065, the loss in electricity generation from OECD countries is a greater portion of the global reduction. But after this date, more of the global reduction in electricity generation comes from non-OECD countries. This is reflective of the growing demand for electricity in non-OECD regions in the reference case. In 2050, OECD's share of the total global reduction is 68 percent while that for non-OECD is 32 percent. By 2095, however, non-OECD's share grows to 69 percent while that for OECD is 31 percent.

US electricity generation reduction is the largest source of OECD reduction under the 550 ppmv carbon constraint and comprises nearly 70 percent of the total OECD reduction. US generation falls by 10 EJ to a total of 28 EJ by 2095 as shown in Figure 15. All of the reductions come from decreasing electricity generation from coal power plants. The share of generation from coal is only 6 percent of the total generation by 2095. The share of generation from gas grows to 28 percent in 2095. The generation from gas in physical units is equal to the level in the reference case, however. The shares of generation from nuclear, solar and biomass energy counter the losses from coal and grow to 20, 19 and 12 percent of the total generation, respectively, by 2095. These increases are, however, not enough to maintain generation levels comparable to the reference case levels. The contribution to generation from oil grows slightly but is not a significant part of the total.

[Figure 15]

For China, however, the carbon constraint increases the overall generation of electricity for most of the next century. Only at the very end of the next century is China forced to reduce generation due to the carbon constraint. Unlike the US, China uses significantly more primary energy than electricity in the end-use sectors of the economy. And as carbon penalties are applied, the direct cost of using primary fuels encourages substitution to electricity for energy services. In 2050, there is 12 percent or 5 EJ more electricity generation under the carbon constraint than in the reference case. By 2095, generation drops by 5 percent or 4 EJ from the reference case.

There are, nevertheless, major changes to the electric power sector in China due to the carbon constraints as shown in Figure 16. China's use of coal for electricity falls dramatically to only 1 percent of the total generation by 2095. Nuclear, solar, biomass, and natural gas use for electricity generation all increase. The additional generation from natural gas occurs in the first half of the next century, while in the second half, generation from nuclear, solar and biomass energy contributes to a much greater extent. Nuclear, solar, natural gas, and biomass comprise 30, 29, 20, and 11 percent of the generation, respectively, in 2095.

[Figure 16]

5.1.5 Carbon Emissions By Fuel

Carbon emissions trajectories for each of the concentration scenarios are as shown in Figure 1 (WRE). Under all concentration scenarios, the bulk of emissions mitigation occurs in the second half of the next century and no mitigation is required before the year 2005. See Table 2. Although the required cumulative emissions mitigation is less in the first than the second half of the next century, the mitigation requirements in the first half are more sensitive to the concentration constraints. More and more emissions mitigation must occur in the first half of the next century to meet the lower concentration constraints.

Not only are the total emissions significantly lower in the concentration cases than in the reference case, but the composition of the emitted CO_2 differs sharply as well. In the 550 ppmv case, for example, CO_2 emissions from coal are no longer the main source of emissions. As shown in Figure 17, coal emissions continue to fall from 2020 and are only 3 percent of the total emissions by 2095. Emissions from crude oil and natural gas comprise nearly all of the total CO_2 emission by 2095 with crude oil contributing to 52 percent and natural gas to 45 percent.

Table 2. Cumulative Emission Mitigation for Alternative CO_2 Concentration Constraints—2000 to 2095 (billion tonnes of carbon)

	450 ppmv	*550 ppmv*	*650 ppmv*	*750 ppmv*
2005-2050	207	86	44	26
2050-2095	639	450	315	236

[Figure 17]

5.1.6 Carbon Emissions by Region

As reflected in the reductions in energy consumption, non-OECD countries undertake most of the CO_2 emissions reduction in the next century. In the 550 ppmv case, 78 percent of the emissions reduction comes from non-OECD countries and 22 percent from OECD countries at the end of the 21st century. Of the emissions allowed under the 550 ppmv case, non-OECD countries still emit more than OECD countries. Emissions from non-OECD countries grow from 3.2 to 4.1 BtC from 1990 to 2095 and those from OECD countries decrease from 2.9 to 2.5 BtC within the same time frame.

Under the 550 ppmv constraint, both US and China's CO_2 emissions are far less than in the reference case. US emissions rise to a peak of 1.9 BtC in 2050 and fall, below the 1990 level, to 1.2 BtC by 2095. China's emissions peak much earlier in 2035 at 1.9 BtC and decline to a slightly higher than the 1990 level to 0.8 BtC by 2095. Because the marginal cost of carbon abatement in China is cheaper than in the US, the impact of the carbon constraint is more immediate in China.

5.1.7 Carbon Taxes

The carbon tax applied to all economic agents in all regions increases with time for all concentration scenarios since annual carbon emissions must decline to a greater and greater extent from the reference case to meet the concentration ceilings. As shown in Table 3, carbon taxes start at modest levels, but increase in all cases by the end of the next century. In the year 2020, the carbon taxes required to meet carbon constraints of 750, 650, 550, and 450 ppmv are $39, $46, $59, and $118 (1996 US$), respectively. By 2095, carbon taxes are significantly higher, reaching $147, $193, $319 and $947 for the 750, 650, 550, and 450 ppmv ceilings. Because of the rapid departure of the 450 ppmv trajectory from the reference case and the severity of the constraint, carbon taxes for this scenario are significantly higher than those for the other cases. The wide range of carbon taxes indicates that efforts to stabilize the atmospheric concentration at lower levels will be notably more costly than at higher levels.

Table 3. Carbon Taxes for Concentration Stabilization Scenarios *Without* Carbon Capture and Sequestration Technologies (1996 $ per tonne of carbon)

Concentration	2020	2035	2050	2065	2080	2095
450 ppmv	$ 118	$ 234	$ 373	$ 526	$ 723	$ 947
550 ppmv	$ 59	$ 94	$ 144	$ 190	$ 259	$ 319
650 ppmv	$ 46	$ 57	$ 79	$ 102	$ 155	$ 193
750 ppmv	$ 39	$ 45	$ 57	$ 67	$ 106	$ 147

5.2 World *With* FE's Advanced Carbon Capture and Sequestration Technologies

The adoption of FE's Vision 21 advanced carbon capture and sequestration technologies as an energy option has a dramatic impact on the global energy system under all atmospheric carbon concentration constraints. The ability to capture and sequester CO_2, along with improvements to the efficiencies of fossil-fueled power technologies, prohibits drastic reductions to energy use while minimizing the cost of meeting carbon concentration targets. Because these technologies continue to rely on fossil fuels does not imply that the future world remains the same. Efficiency improvements of these new power technologies and continued ability to use abundant fossil fuels under carbon constraints promote a transition to a world that relies more and more on electricity for its energy services. Also, it is a world in which less primary energy is consumed and a world in which the atmospheric carbon concentration is stabilized at lower costs. The next few sections are focused on energy impacts both from carbon capture and sequestration technologies as well as from power plant efficiency increases. The impact on cost savings is discussed under the sections *Carbon Taxes* and *The Resource Cost of Stabilization*.

5.2.1 Electricity Generation by Fuel

With FE power plant capture and sequestration technologies, changes to the global energy system begin from the electricity sector. Except for the tightest carbon concentration case of 450 ppmv, the global generation of electricity for all concentration scenarios surpasses the reference level generation. By the end of the 21st century, global electricity generation is 8, 9 and 11 percent greater that the reference case for 750, 650 and 550 ppmv cases, respectively.

The 450 ppmv case does not follow this trend, however. Global electricity generation in the 450 ppmv case falls below the reference level by 18 percent by the end of the next century. This is due to the severity of the emissions constraint in the 450 ppmv case. By the end of the 21st century, the global emissions limit for the 450 ppmv case is 3.2 BtC. This represents approximately one half the 1990 emissions or one half the emissions limit for the 550 ppmv case in 2095. Capture technologies encourage greater use of electricity under all carbon constraints, and electricity's share of the total end-use energy demand is the highest for the 450 ppmv case. Nevertheless, limiting emissions a century from now to half of today's emissions raises the cost of end-use energy service such that the overall demand for electricity falls below the reference level.

In the 550 ppmv scenario, FE power plant capture and sequestration technologies promote greater generation of electricity from fossil fuels than in the reference case and coal and natural gas become the major sources of electricity. CO_2 emissions from these fuels, however, are captured and sequestered. See Figure 18 for the composition of global electricity generation with advanced capture technologies in the 550 ppmv case. By 2095, electricity generation from coal and natural gas are 45 and 35 percent of the global total. The remaining shares are 8 percent from hydroelectricity, 6 percent from nuclear, 5 percent from solar, and 1 percent from oil. CO_2 emissions from oil are captured and sequestered as well. The switch to FE capture and sequestration technologies occurs after 2020 and by 2065, nearly all of the electricity generated from fossil fuels utilizes this technology.

Part of the above increase in electricity generation under the carbon constraint is due to higher plant efficiencies of the FE Vision 21 technologies. Higher efficiencies alone play a large role in increasing the generation of electricity in the first half of the next century when carbon emissions constraints are not as severe. Without the availability of capture technologies, however, higher efficiencies alone are not capable of maintaining generation at reference levels in the second half of the next century. As an example, the impact of higher efficiencies is evident in Figure 19 which shows the contributions to electricity generation from higher efficiencies and carbon capture in the 550 ppmv case. In this case, the difference in electricity generation with and without FE capture technologies is nearly all attributed to higher efficiencies in 2020 and 2035. By 2095, however, higher efficiencies contribute to only 18 percent of the difference and capture technologies alone contribute to 82 percent.

[Figure 18]

[Figure 19]

5.2.2 Electricity Generation by Region

Both OECD and non-OECD regions gain from FE capture and sequestration technologies. In the 550 ppmv scenario, OECD countries generate up to 10 percent more electricity than in the reference case by 2095. The availability of FE technologies in non-OECD countries under the 550 ppmv constraint has a slightly greater impact as it enables 12 percent more electricity generation from the reference case over the same time period.

In the US, the 550 ppmv carbon constraint no longer limits the supply of electricity with the availability of FE technologies. With these technologies, electricity generation grows from 9 EJ in 1990 to 41 EJ by 2095 as shown in Figure 20. Generation in 2095 is 6 percent more than in the reference case or 43 percent more than the 550 ppmv case without FE technologies. Compared to the case without FE technologies, 18 percent of the additional generation is due to higher efficiencies alone and 82 percent of the additional generation is due to capture technologies by the end of the next century. See Figure 20.

The composition of electricity generation for the US in the 550 ppmv case with FE capture technologies is shown in Figure 21. Coal and natural gas capture technologies comprise 86 percent of the total generation in 2095 with coal capture contributing to 56 percent and gas capture to 30 percent. Hydroelectricity adds 10 percent to the total and nuclear and solar energy each add 2 percent. FE technologies begin to have an impact after 2020 and by 2095, there is no longer any electricity generation from fossil fuel technologies that do not utilize carbon capture.

[Figure 20]

[Figure 21]

For China, the impact of FE's advanced capture technologies is far greater than in the US. Under the 550 ppmv constraint, these technologies enable China's electricity generation to expand from their 1990 level of 2 EJ to 94 EJ by 2095 as shown in Figure 22. This growth represents significantly higher generation than in the reference case or the 550 ppmv case without FE technologies. In 2095, 25 percent more electricity is generated compared to the reference case and 32 percent more is generated compared to the 550 ppmv case without FE technologies. Contribution to generation from higher efficiencies alone plays a larger role before 2050 but diminishes after this time. Nearly all of the growth in electricity generation by 2095 is attributed to the availability of carbon capture technologies.

Like the US, the majority of electricity generation in China comes from coal and natural gas capture technologies as shown in Figure 23. They comprise 81 percent of the total generation in 2095 with coal capture producing 54 percent and natural gas capture producing 27 percent. China's transition to capture technologies does not occur until after 2035. Nevertheless, by the end of the next century, all electricity generation from fossil fuels utilizes capture technologies.

[Figure 22]

[Figure 23]

5.2.3 Primary Energy Consumption by Fuel

The availability of FE capture technologies under carbon constraints results in large increases in the global generation of electricity. However, fuel efficiency improvements, greater use of electricity for end-use energy services, and conservation from higher fuel prices result in levels of primary energy consumption that are lower than in the reference case. Global primary energy consumption for the 750, 650, 550, and 450 ppmv cases are 18, 18, 25, and 52 percent lower than the reference case, respectively, by the end of the 21st century. These reductions are not as large as those in the concentration cases without FE capture technologies and represent the benefit of controlling carbon emissions through capture technologies.

As indicated by Figure 24, portions of primary energy reduction come from higher plant efficiencies of FE technologies. Under the 550 ppmv constraint and by 2095, 130 EJ or approximately 10 percent of the global reference level consumption is reduced by higher efficiencies alone. In Figure 24, the savings in primary energy consumption from higher efficiencies are represented by the difference in the primary energy consumption between the 550 ppmv case without FE technologies and the 550 ppmv case with higher efficiencies alone. The availability of capture technologies, however, lowers the carbon penalty on fossil fuels and as a result, limits the amount of conservation. In the 550 ppmv case, capture technologies increase the consumption of primary energy by 230 EJ or approximately 19 percent of the reference level consumption. In Figure 24, this increase is represented by the difference in the primary energy consumption between the 550 ppmv case with FE technologies and the 550 ppmv case with higher efficiencies alone. The remaining 310 EJ or 25 percent difference in primary energy consumption from the reference case and the 550 ppmv case with FE technologies is due to conservation from higher fuel prices and greater substitution to electricity for energy services.

Under carbon constraints, large differences exist in the composition of primary energy consumption depending on whether FE capture technologies are available or not. FE technologies enable consumption of primary energy to reflect the shares in the reference case rather than concentration cases without FE technologies. In the 550 ppmv case with FE technologies shown in Figure 25, fossil fuels comprise 86 percent of the total global consumption by 2095. This is the same percentage as in the reference case.

[Figure 24]

[Figure 25]

5.2.4 Primary Energy Consumption by Region

Other than the magnitude of the reductions discussed above, the inclusion of FE capture technologies does not alter the regional contribution to reductions in primary energy consumption by OECD and non-OECD regions under carbon constraints. Moreover, the shares of primary energy consumed by OECD and non-OECD regions reflect those shares in the reference case. As before, OECD's share of the global primary energy consumption falls while non-OECD's share quickly rises.

Both the US and China are able to consume more primary energy under carbon constraints with the availability of FE capture technologies than without. For the US in the 550 ppmv case, there is a 7 percent increase in primary energy consumption over the case without FE capture technologies in 2095. There is, however, a 24 percent reduction in consumption relative the reference case in 2095. Refer to Figure 26 for comparisons of primary energy consumption in the 550 ppmv case. As explained above, reductions from the reference case are attributed to energy efficiency improvements, greater substitution to electricity for energy services and conservation due to higher fuel prices. By the end of the 21st century, 14 EJ or approximately 9 percent of the reference level consumption is reduced from higher efficiencies alone, whereas 27 EJ or 16 percent of the reference level consumption is increased by capture technologies. The remaining 39 EJ or 24 percent reduction from the reference level consumption is from substitution to electricity for energy services and conservation.

[Figure 26]

For China under the 550 ppmv scenario, the availability of FE technologies enables 12 percent greater primary energy consumption than without by 2095. Compared to the reference case, however, primary energy consumption is 36 percent less in 2095. See Figure 27. By the end of the 21st century, higher efficiencies alone reduce 35 EJ or approximately 10 percent of the reference level consumption, whereas capture technologies increase 76 EJ or 22 percent of the reference level consumption. The remaining 123 EJ or 36 percent reduction in consumption from the reference level is from greater use of electricity for energy services and conservation. [Figure 27]

The more noticeable impact of the FE capture technologies on primary energy consumption, however, is the composition of fuels for primary energy in the US and China. As indicated by Figures 28 and 29, both regions are able to utilize large amounts of fossil fuel while still complying with the carbon constraints. For the US in the 550 ppmv case, 91 percent of the total primary energy consumption is from fossil fuels in 2095. Coal, natural gas and crude oil are 47, 28 and 16 percent of this total, respectively. For China in the 550 ppmv case, 83 percent of the total primary energy consumption is from fossil fuels in 2095. The shares of coal, natural gas and crude oil are 64, 18 and 1 percent, respectively. For both the US and China, coal remains the largest source of primary energy.

[Figure 28]

[Figure 29]

5.2.5 Carbon Emissions by Fuel

Compliance with the carbon concentration constraints with FE capture technologies does not affect the WRE emissions path or when the bulk of mitigation must occur. It does, however, affect the sources of the allowed annual carbon emission. The availability of FE power plant capture technologies effectively lowers emissions from the electricity sector to a greater extent. Although some of this reduction comes from higher plant efficiencies of FE technologies, most of the reduction is from capture technologies. Comparison of global carbon emissions in the reference case, reference case with higher plant efficiencies alone and WRE 550 ppmv case, as shown in Figure 30, reveals that higher efficiencies alone cannot achieve the more aggressive emissions reduction necessary to meet the concentration targets.

[Figure 30]

5.2.6 Carbon Emissions by Region

The availability of FE technologies does affect the regional contribution to carbon emissions by OECD and non-OECD regions. Under carbon constraints, OECD countries emit a smaller portion of the global emissions when FE technologies are available than when they are not. OECD countries contribute more to the reduction because there is greater reliance on electricity for energy services in the OECD than non-OECD countries. This regional impact of FE technologies diminishes after the middle of the next century as the use of electricity grows in non-OECD countries. In absolute quantities, however, non-OECD countries continue to reduce more emissions than OECD countries throughout all time periods.

The regional impacts of FE capture technologies are evident in the 550 ppmv case for the US and China. In the US, there is an additional 680 million tonnes of carbon (MtC) emissions reduction in 2050 with FE technologies than without. This represents 24 percent of the reference emissions in 2050. By 2095, the additional reduction diminishes to 120 MtC which is 3.5 percent of the reference emission in 2095. Greater reductions from the US means that other countries like China can emit more without affecting the global total. That is the case for China with FE capture technologies. China emits up to 600 MtC more in 2050 relative to the 550 ppmv case without FE technologies. By 2095, an additional 200 MtC is emitted. These additional emissions are 16 and 3 percent of the reference emissions in 2050 and 2095, respectively

5.2.7 Carbon Taxes

The most significant contribution of FE capture technologies is the dramatically lower carbon taxes necessary to stabilize atmospheric carbon concentrations. FE's advanced carbon capture and sequestration technologies reduce carbon taxes for the 750, 650 and 550 ppmv concentration cases by more than 70 percent in comparison to the concentration cases without these technologies. In 2035, FE technologies have already begun to have an impact and carbon taxes for the 750, 650, 550 and 450 ppmv cases are \$19, \$32, \$57, and \$177 per tonne of carbon (1996 \$), respectively. By 2095, carbon taxes for 750 and 650 ppmv cases are even less at \$14/tC and \$21/tC. The carbon tax for the 550 ppmv case rises to \$89/tC, and in the most extreme case of the 450 ppmv scenario, the carbon tax increases to \$811/tC by 2095. See Table 4 for carbon taxes for all concentration cases with FE technologies.

Rising carbon taxes in the more stringent 450 and 550 ppmv cases, even with FE capture technologies, reflect the rising cost of substitution to greater and greater reliance on electricity in all end-use sectors of the global economy and in particular, the transportation sector. Substitution to electricity lowers the demand for oil and thus, the price of oil falls. Carbon taxes, therefore, must be increased further to induce fuel switching from oil to electricity in the transportation sector.

Table 4. Carbon Taxes for Concentration Stabilization Scenarios *With* Carbon Capture and Sequestration Technologies (1996 \$ per tonne of carbon)

Concentration	2020	2035	2050	2065	2080	2095
450 ppmv	\$ 111	\$ 177	\$ 164	\$ 278	\$ 512	\$ 811
550 ppmv	\$ 47	\$ 57	\$ 52	\$ 21	\$ 40	\$ 89
650 ppmv	\$ 34	\$ 32	\$ 16	\$ 12	\$ 16	\$ 21
750 ppmv	\$ 27	\$ 19	\$ 11	\$ 8	\$ 12	\$ 14

6. The Cost of Stabilization

The benefit of FE capture technologies is also measured by calculating the total direct cost of achieving the concentration targets. The direct cost is the deadweight loss to the economy and is equal to the integral under the marginal cost of abatement curve for carbon. The total direct cost is the cost to the global economy of undertaking the annual required mitigation at the carbon taxes presented above. Tables 5 and 6 show the total direct cost (present value discounted at 5 percent) for all the concentration cases without and with FE capture technologies. The difference in having or not having available FE capture technologies ranges from hundreds of billions to trillions of dollars depending on the concentration desired. For the 550 ppmv case, the value of FE capture technologies, as measured by the difference of Tables 5 and 6, is \$215, \$546 and \$1,741 billion for the US, China and the world, respectively.

The value of FE capture technologies is comprised of both the improvement to energy efficiency and the availability of capture technology. Higher plant efficiencies alone have significant value even though higher efficiencies alone are not likely to be capable of stabilizing atmospheric CO_2 concentrations. The direct cost of meeting the concentration targets with higher efficiencies only is shown in Table 7. Comparison of these costs to the direct costs without FE technologies shows that the value of higher efficiencies is greater when concentration constraints are not as severe. However, as concentration constraints become more stringent, the value of capture technologies becomes much greater. For the 750 and 650 ppmv targets, 79 and 65 percent of the value of FE technologies is due to higher efficiencies alone. Whereas, in the 550 and 450 ppmv cases, the value of capture technologies alone comprises 57 and 78 percent of the total value of FE technologies, respectively.

Table 5. Direct Cost of Meeting Concentration Targets *Without* FE Capture Technologies (Billion 1996 $, Present Value Discounted at 5%)

	750 ppmv	650 ppmv	550 ppmv	450 ppmv
US	$ 104	$ 166	$ 359	$ 1,353
China	$ 203	$ 333	$ 725	$ 2,259
World	$ 666	$ 1,093	$ 2,420	$ 8,414

Table 6. Direct Cost of Meeting Concentration Targets *With* FE Capture Technologies (Billion 1996 $, Present Value Discounted at 5%)

	750 ppmv	650 ppmv	550 ppmv	450 ppmv
US	$ 23	$ 44	$ 144	$ 549
China	$ 35	$ 66	$ 179	$ 1,106
World	$ 129	$ 249	$ 679	$ 4,089

Table 7. Direct Cost of Meeting Concentration Targets *With* High Efficiency Technologies Only (Billion 1996 $, Present Value Discounted at 5%)

	750 ppmv	650 ppmv	550 ppmv	450 ppmv
US	$ 32	$ 72	$ 218	$ 1,106
China	$ 79	$ 177	$ 519	$ 2,003
World	$ 241	$ 542	$ 1,664	$ 7,475

7. Need for R&D

As indicated by the difference in the direct cost of meeting concentration targets with and without FE capture technologies, the potential value of these technologies is great. But much more research is required before large-scale deployment of these technologies is possible. The ability to capture CO_2 from power plants and sequester it in geological formations has been proven. However, all of the efforts thus far have been small-scale. Greater investigation of the potential and safety of long-term CO_2 storage in saline aquifers and oceans is necessary. And the cost of capture technologies, as well as the cost of CO_2 transportation and sequestration, must come down.

In limiting atmospheric CO_2 concentrations to 550 ppmv, the value of FE capture technologies, as calculated above, is $215 billion (1996 US$) for the US and $1,741 billion (1996 US$) for the world. Assuming a discount rate of 5 %, the annualized savings are $11 billion for the US and $88 billion for the world over the next century. To put these values in perspective, the total federal R&D budget for energy in the United States in 1997 was only $2.2 billion (1996 US$).[22]

8. Abundant Oil and Gas Reference Scenario

An alternative reference scenario to the standard vision of future based on coal is one in which resources of inexpensive oil and gas do not diminish as new oil and gas resources are found, and the technology to extract these resources continue to improve. Thus, the world based on conventional oil and gas continues into the future. We refer to this scenario as the Oil and Gas Forever (OGF). Although we have created two different reference scenarios in this exercise, we have chosen the one based on coal as the reference for comparison above. However, a discussion of the OGF reference scenario and the differences between the two reference scenarios are provided here.

In the OGF scenarios, the availability of abundant oil and gas leads to lower energy prices and greater overall consumption of primary energy. The global primary energy consumption in the OGF reference case grows to over 1500 EJ by the end of the next century which represents a 260 EJ greater consumption than in the reference case based on coal. Most of the additional energy consumption occurs in the second half of the next century when more abundant oil and gas begin to distinguish the OGF scenario from the scenario based on coal. Electricity generation also responds to lower oil and gas prices and there is 15 percent or 48 EJ more global generation in the OGF scenario than the coal based scenario by the end of the next century. The additional generation of electricity comes mostly from natural gas and replaces the falling generation from coal. Greater overall energy consumption in the OGF scenario leads to higher emissions of carbon as well. By the end of the 21st century, carbon emissions in the OGF reference case reach nearly 26 BtC exceeding the coal based reference case by 2 BtC.

Higher carbon taxes are necessary to comply with the 450 to 750 ppmv concentration constraints in the OGF scenarios. Lower energy prices and higher carbon emissions require greater penalties on fossil fuels to meet the concentration targets. For this reason, the value of FE capture and sequestration technologies in the OGF scenarios is even greater than in the scenarios based on coal. In the OGF 550 ppmv case, for example, the value of FE capture technologies, as measured by the difference in the cost with and without such technologies, is $279, $616 and $2,033 billion for the US, China and the world, respectively. These values are 30, 13 and 17 percent greater for the US, China and the world than the 550 ppmv scenario based on coal. These results indicate that regardless of whether the world becomes increasingly dependent on coal or whether it continues to rely on oil and gas, the value of FE capture and sequestration technologies is great.

9. The Carbon Reservoirs

In the assessment of carbon capture and sequestration technologies, we have not addressed the capacity for carbon storage. Comparison of the cumulative emissions mitigation in the concentration cases to the estimates of global carbon storage reservoir by Herzog et al. indicates that there is sufficient capacity for carbon storage to meet the most stringent concentration ceiling imposed in this study. Estimates of the global carbon storage reservoirs from Herzog et al. are provided in Table 8.[23] However, it is not clear which type of reservoir would be the most appropriate choice for carbon storage. With the exception of less stringent concentration constraints, it does not seem likely that depleted oil and gas reservoirs are sufficient to meet the world's carbon storage needs. Storage for more stringent concentration constraints will necessitate CO_2 disposal in deep saline aquifers and oceans.

In addition to the reservoirs listed in Table 8, CO_2 sequestration in deep coal seams has the potential of sequestering carbon at a net profit. CO_2 can be injected into coal seams to enhance the recovery of natural gas while sequestering the CO_2. The global estimate of the sequestration potential in coal seams at a net profit range from 5 to 15 billion tonnes of CO_2 and as high as 150 billion tonnes of CO_2 or 41 BtC at moderate to high costs.[24]

Table 8. Estimates of Global Carbon Storage Reservoir (Herzog et al. 1997)

Carbon Storage Reservoir	Low (Billion Tonnes of C)	High (Billion Tonnes of
Deep Ocean	1,391	27,000
Deep Aquifers	87	2,727
Depleted Gas Reservoirs	136	300
Depleted Oil Reservoirs	41	191

10. Limitations of This Study

Carbon free energy options other than power plant capture and sequestration were not addressed explicitly in this analysis. Greater penetration of technologies, such as biomass, solar and wind technologies, as well as other processes of carbon sequestration such as by soil carbon sequestration, reforestation, or marine ecosystem, also have significant potential for reducing greenhouse gas emissions. Each of these technologies and processes, as well as plant capture and sequestration, has its own positive and negative attributes such that the suitability of each technology for a particular global and local region will vary. Biomass energy technology is relatively mature and readily deployable; however, it is not clear whether large quantities of biomass will be available at reasonable costs. The potential of commercial scale biomass energy as a dominant energy form depends on the interactions with other land-use activities. Specifically, commercial biomass energy competes with crops, livestock, and forestry for land resources. Moreover, increasing demand for land results in either direct or indirect pressure to bring less managed ecosystems into the managed category thus affecting greenhouse gas emissions from land-use change.[7]

Wind and solar power technologies have come down in price significantly and are being deployed more and more.[25] However, wind and solar energy are intermittent, limited to areas of strong wind and solar resources, and limited in overall capacity without the addition of costly storage devices.

Depending on the successful development of these technologies, the benefits of power plant carbon capture and sequestration technologies under carbon constraints could vary from the results presented here. However, we feel that the qualitative conclusion of the value of capture technologies is robust across a wide range of sensitivities. As shown by Tables 5 and 6, the cost of stabilizing CO_2 concentrations was reduced significantly by FE capture technologies; however, the cost is not eliminated by these technologies alone. There are additional opportunities for cost reduction and further analysis is necessary to examine the interaction of capture technologies with other carbon free technologies.

11. Conclusions

This analysis shows the tremendous potential of advanced capture and sequestration technologies for the stabilization of atmospheric carbon concentrations. The difference to the world of having available such technologies is significant and warrants greater investigation. Because the global energy system relies on fossil fuels for the majority of its needs, use of carbon capture and sequestration technologies lowers the cost of stabilizing atmospheric concentrations of carbon emissions. Concentration stabilization is achieved while preventing drastic changes to the global fossil energy system where reductions to energy consumption and substitution to more expensive sources of energy are limited.

More specifically, the availability of carbon capture and sequestration technologies enables greater consumption of electricity, under all carbon constraints studied. Capture technologies under carbon penalties promote greater use of electricity by encouraging substitution from the direct use of primary energy to electricity in the end-use sectors. With the exception of the 450 ppmv concentration case, more electricity is consumed globally in the 550, 650 and 750 ppmv concentration cases than in the unconstrained reference case. In addition, primary energy consumption is greater for all concentration cases with carbon capture and sequestration technologies than without. These technologies allow continued reliance on abundant and inexpensive fossil fuels and counter large increases in the price of energy arising from carbon penalties while meeting atmospheric carbon concentration targets.

With capture and sequestration technologies, stabilization of the atmospheric carbon concentration is possible at significantly lower costs. Carbon taxes and the total direct costs over the next century fall significantly for all concentration cases with the availability of capture and sequestration technologies. The cost savings from such technologies range from hundreds of billions to trillions of dollars for the next century depending on the concentration target.

Capture and sequestration technologies have real potential in limiting the emission of carbon to the atmosphere and achieving concentration stabilization. However, more R&D is required to bring down the cost and to assess the environmental safety and limitations of carbon storage in all reservoirs.

Figures

Figure 1. Carbon Emissions Trajectories Necessary to Achieve Stabilization of Atmospheric Concentrations Over the Next Century (Billion Tonnes of Carbon)

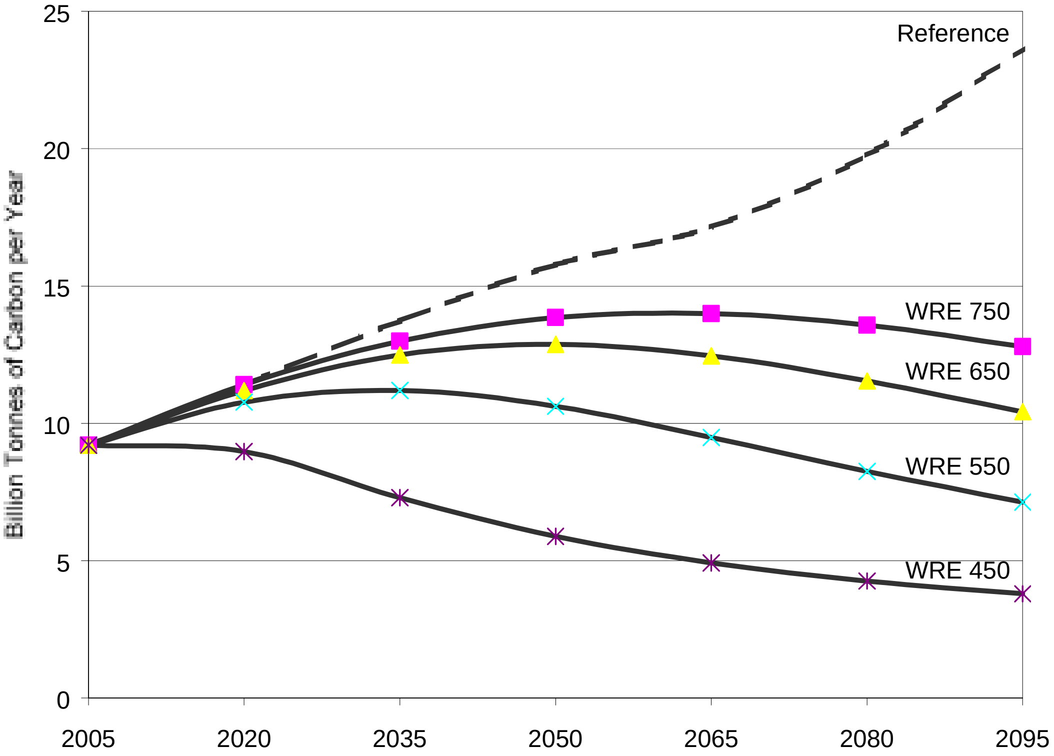


Figure 2. Primary Energy Consumption by Fuel – Global Reference Case (Exajoules per year)

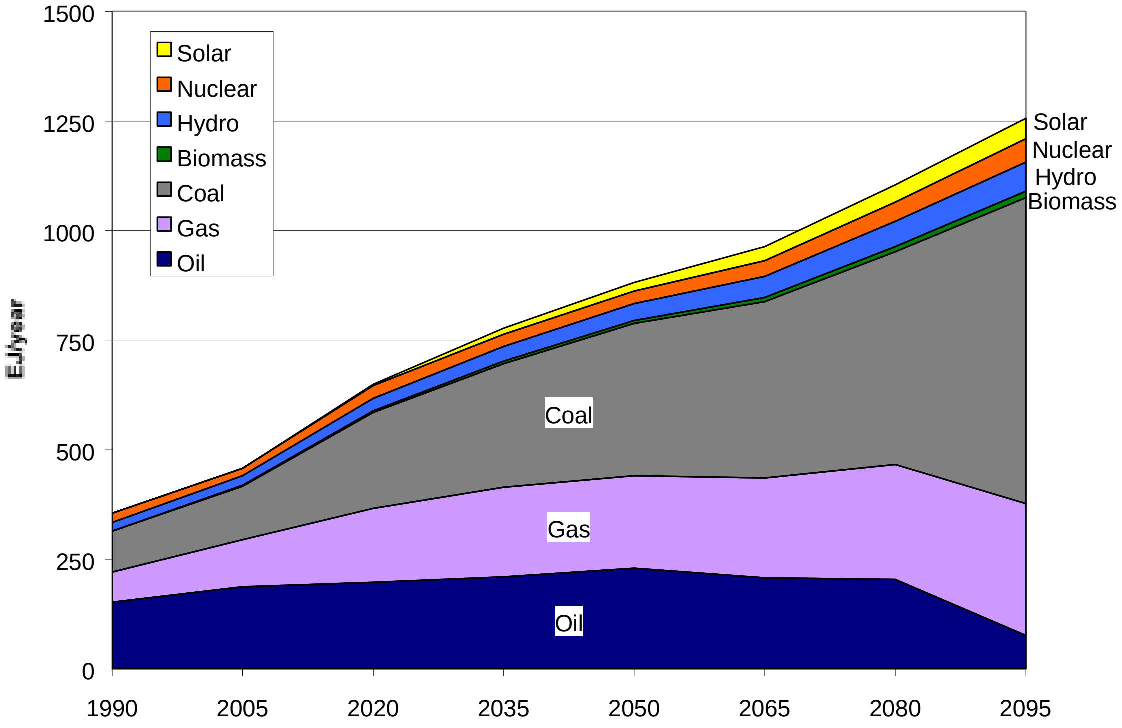


Figure 3. Primary Energy Consumption by Fuel - US Reference Case (Exajoules per year)

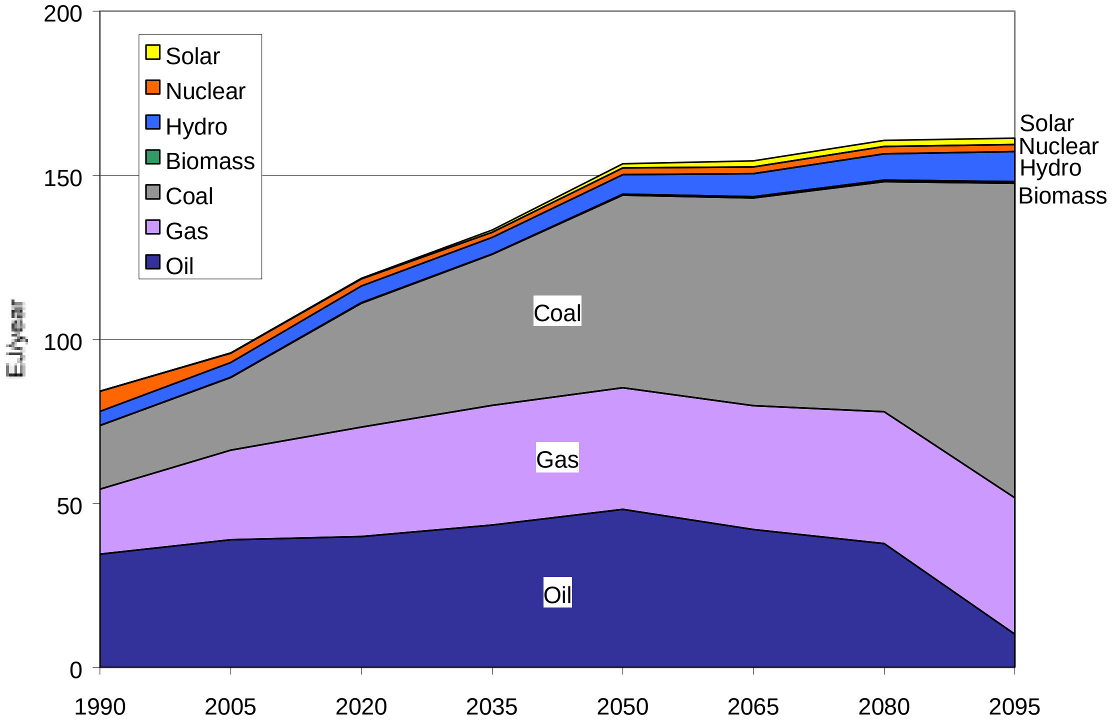


Figure 4. Primary Energy Consumption by Fuel - China Reference Case (Exajoules per year)

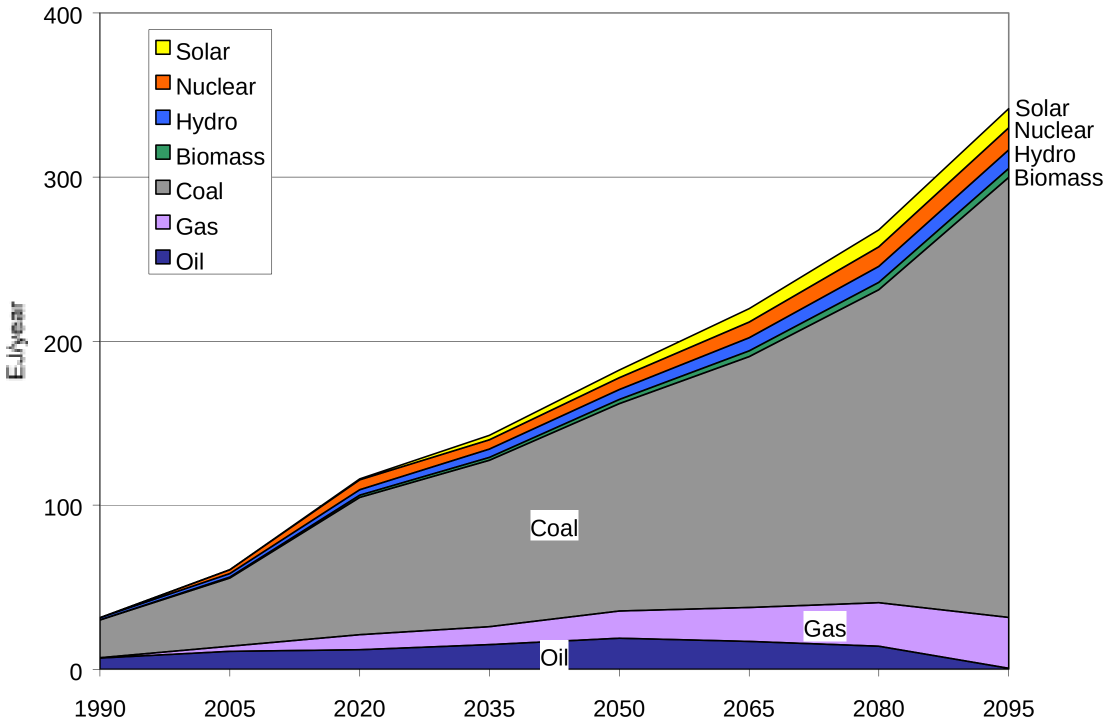


Figure 5. Electricity Generation by Type - Global Reference Case (Exajoules per year)

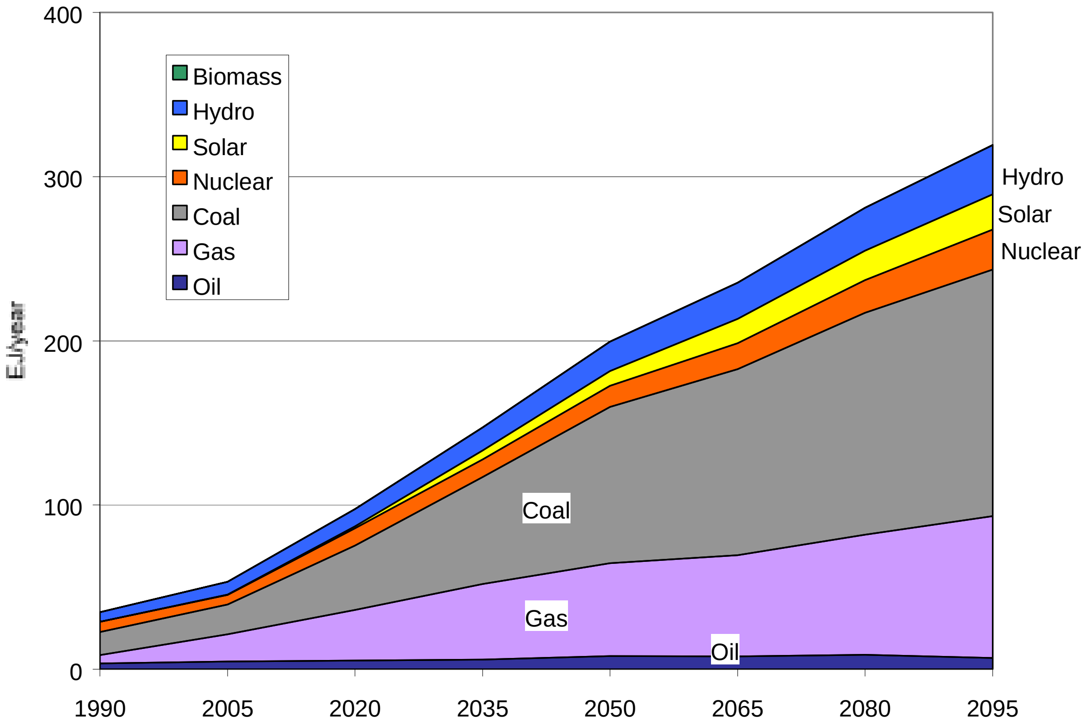


Figure 6. Electricity Generation by Type – US Reference Case (Exajoules per year)

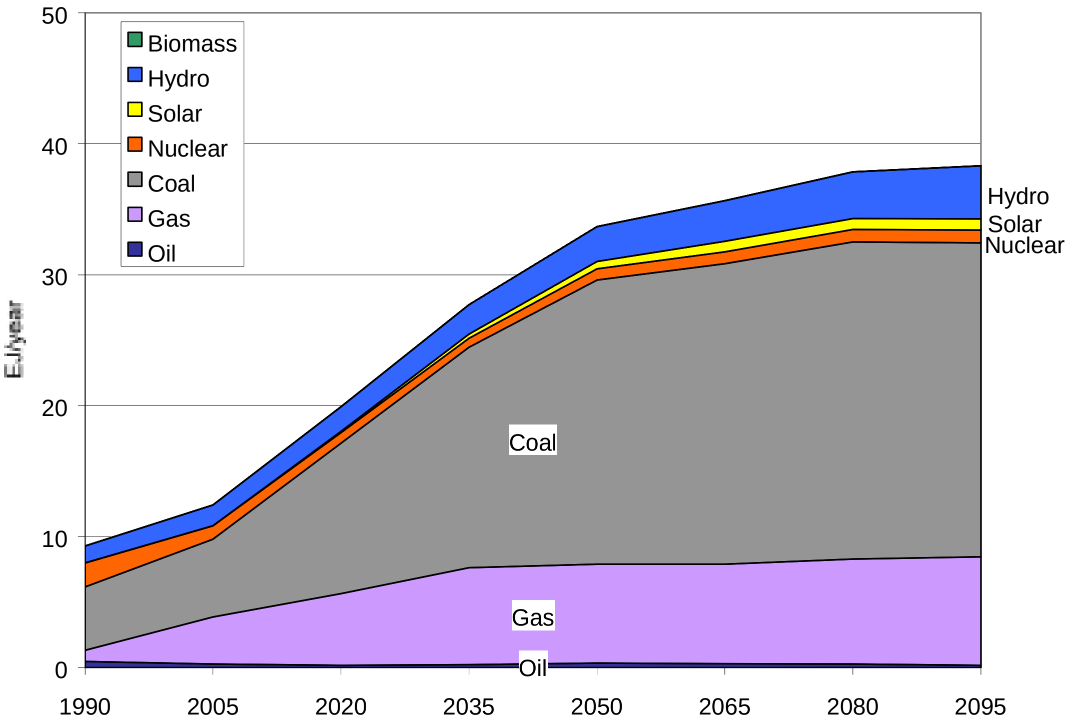


Figure 7. Electricity Generation by Type – China Reference Case (Exajoules per year)

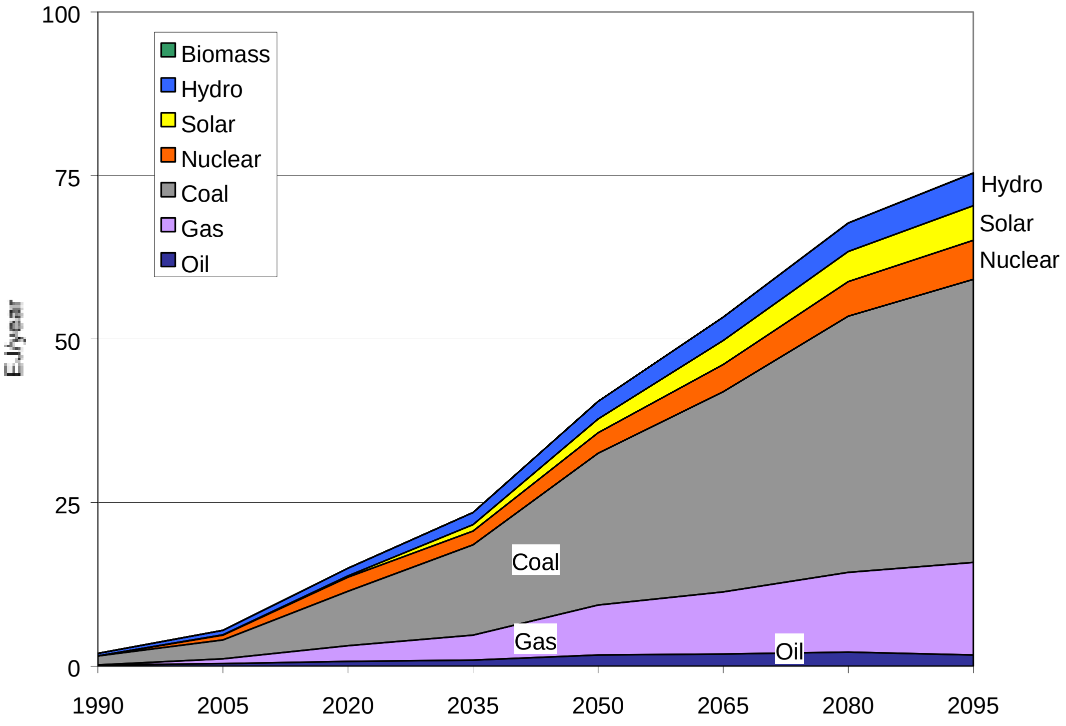


Figure 8. CO$_2$ Emissions by Fuel – Global Reference Case (Billion Tonnes of Carbon)

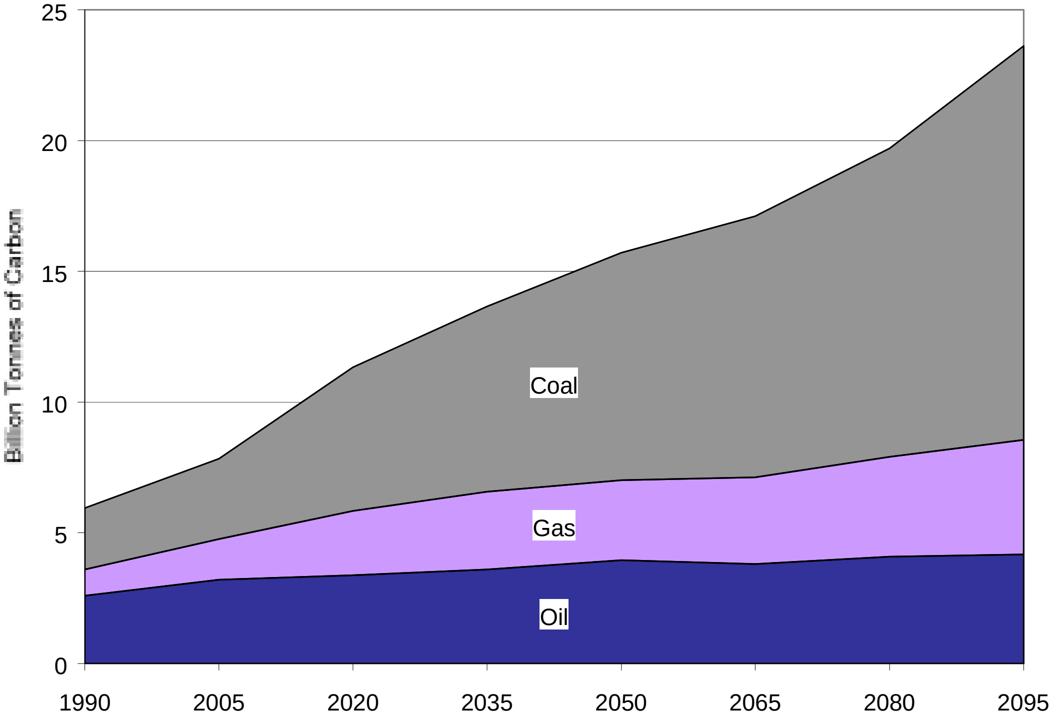


Figure 9. CO$_2$ Emissions by Fuel – US Reference Case (Billion Tonnes of Carbon)

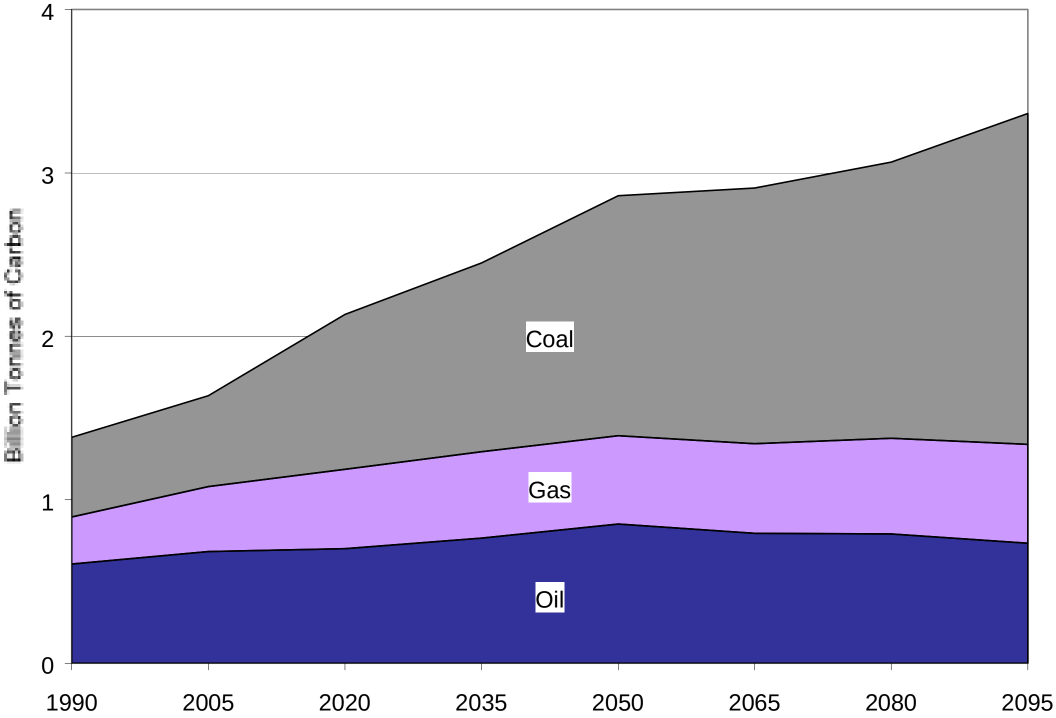


Figure 10. CO_2 Emissions by Fuel – China Reference Case (Billion Tonnes of Carbon)

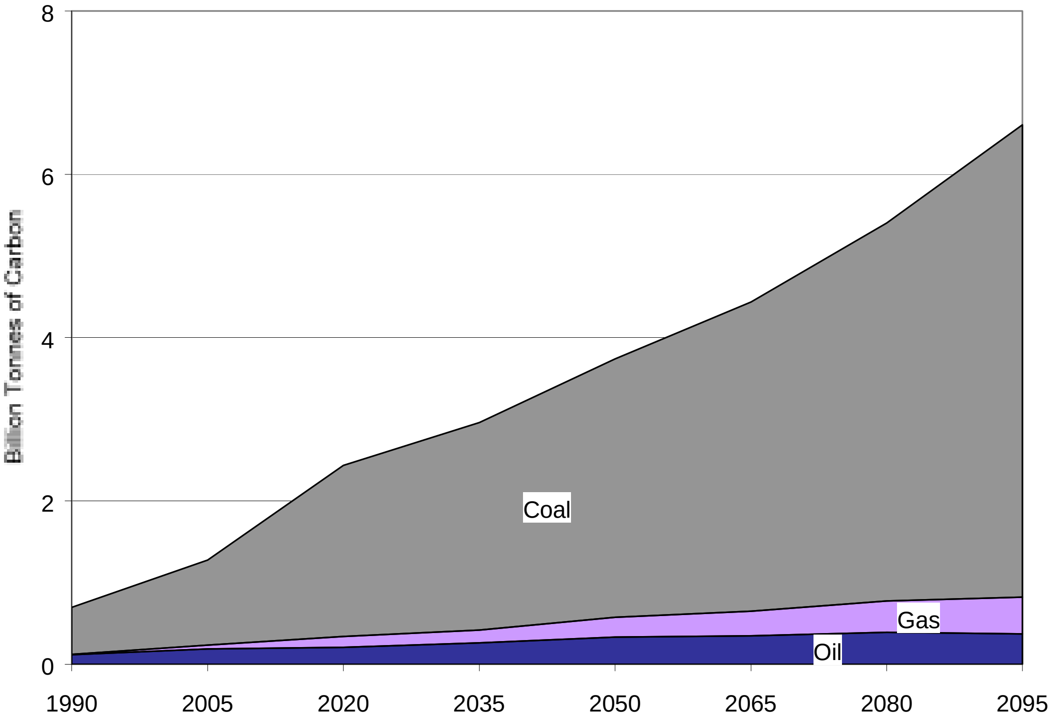


Figure 11. Change in Primary Energy Consumption from Reference - Global 550 ppmv Case *Without* Carbon Capture and Sequestration Technologies (Exajoules per year)

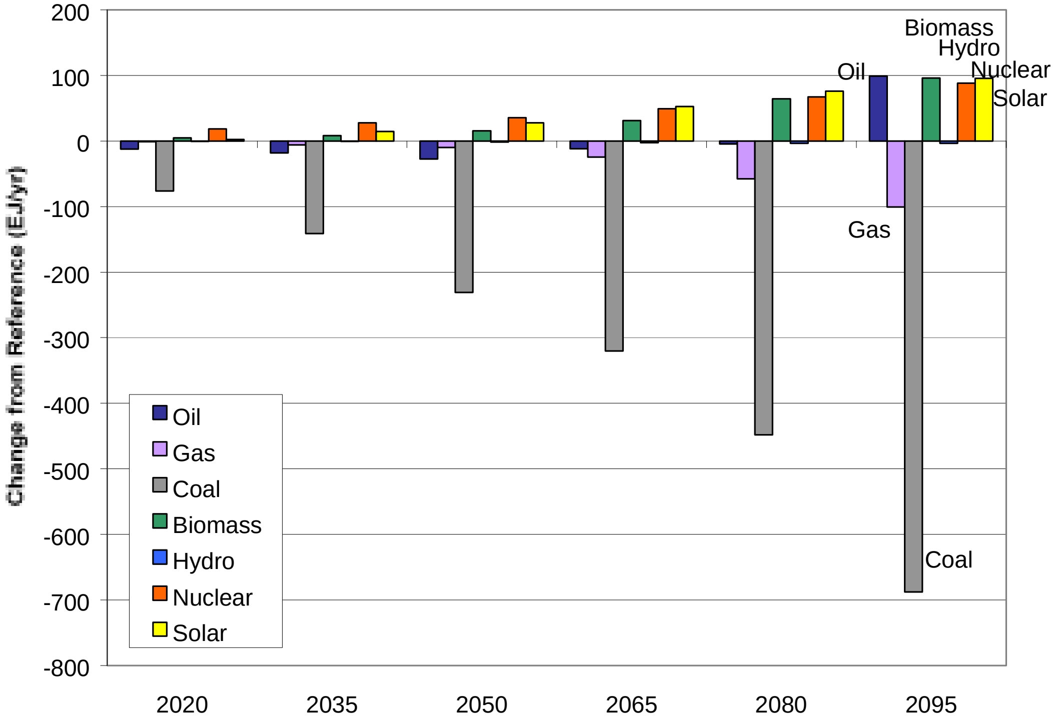


Figure 12. Change in Primary Energy Consumption from Reference – US 550 ppmv Case *Without* Carbon Capture and Sequestration Technologies (Exajoules per year)

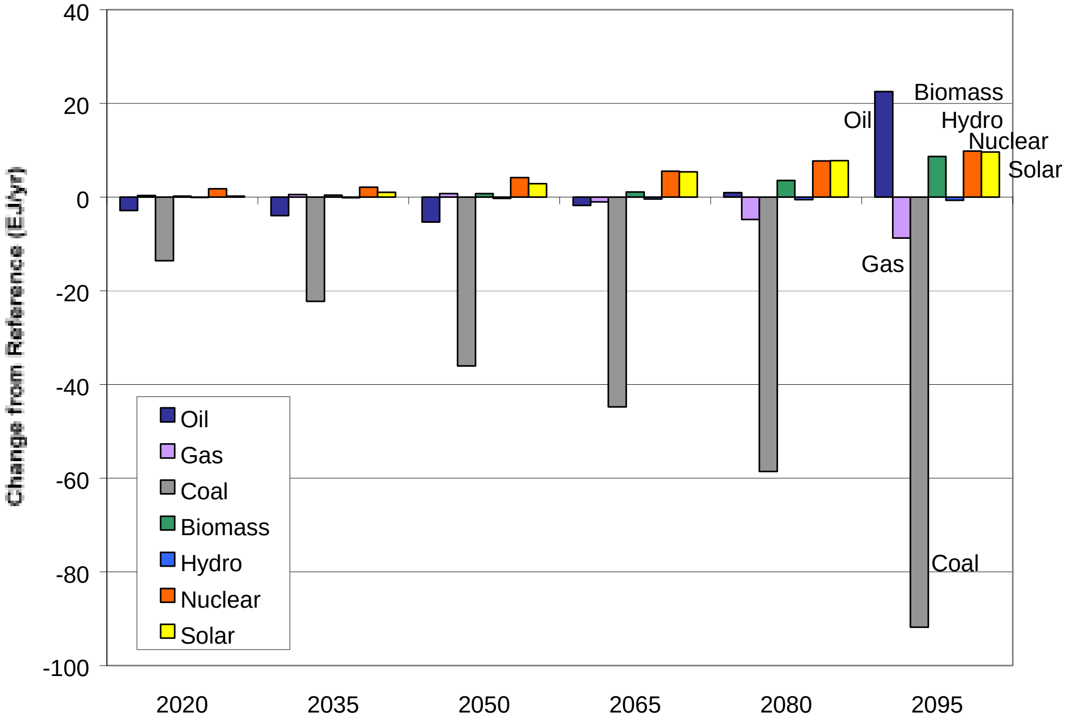


Figure 13. Change in Primary Energy Consumption from Reference – China 550 ppmv Case *Without* Carbon Capture and Sequestration Technologies (Exajoules per year).

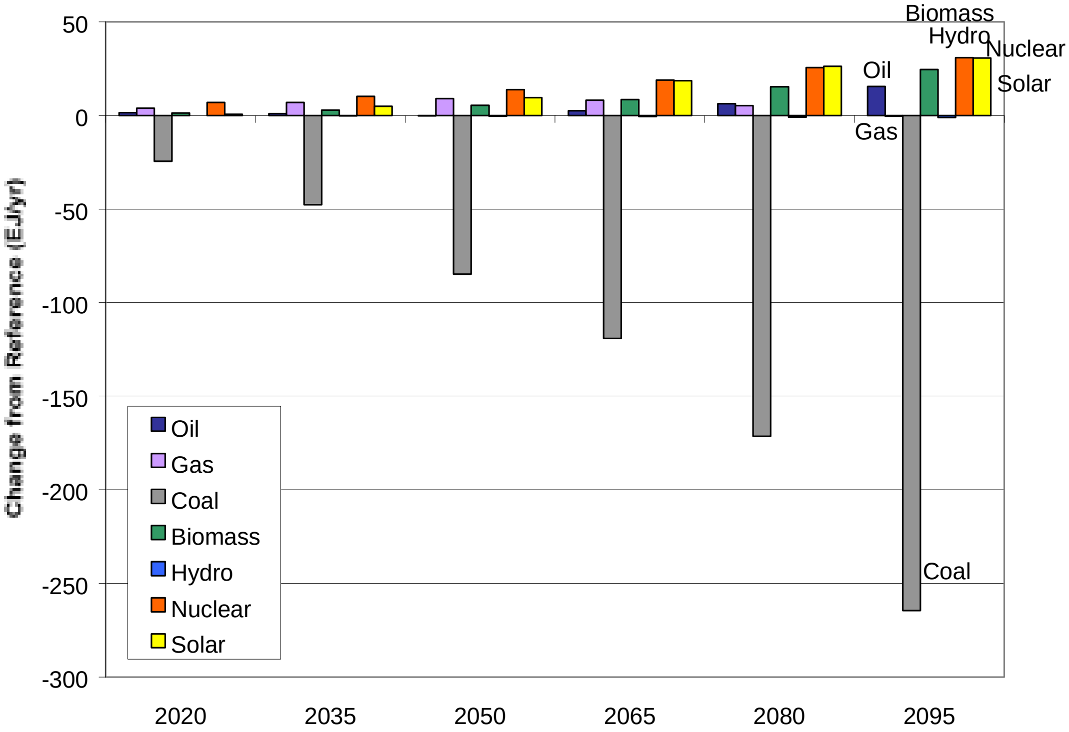


Figure 14. Electricity Generation by Type – Global 550 ppmv Case *Without* Carbon Capture and Sequestration Technologies (Exajoules per year).

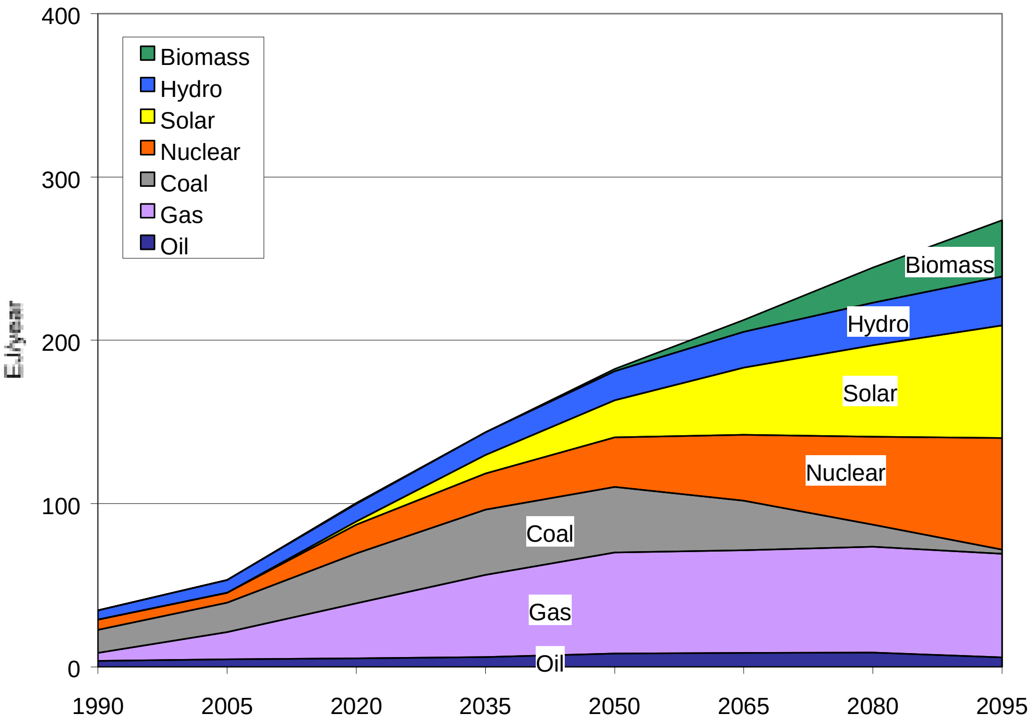


Figure 15. Electricity Generation by Type – US 550 ppmv Case *Without* Carbon Capture and Sequestration Technologies (Exajoules per year).

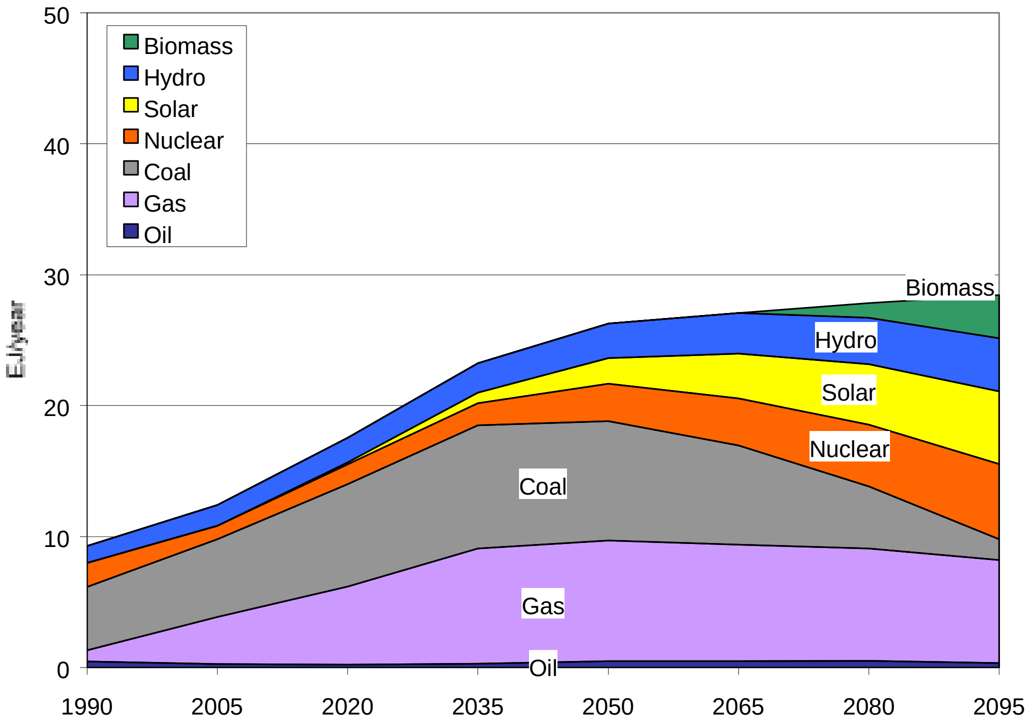


Figure 16. Electricity Generation by Type – China 550 ppmv Case *Without* Carbon Capture and Sequestration Technologies (Exajoules per year).

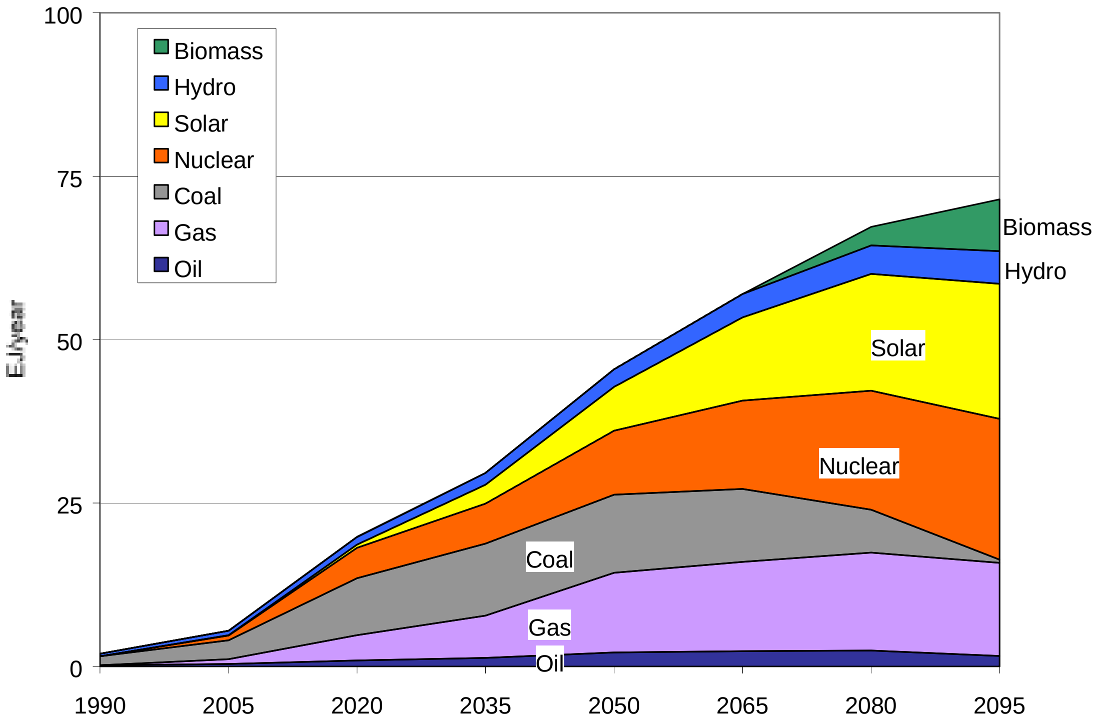


Figure 17. CO_2 Emissions by Fuel – Global 550 ppmv Case *Without* Carbon Capture and Sequestration Technologies (Billion Tonnes of Carbon).

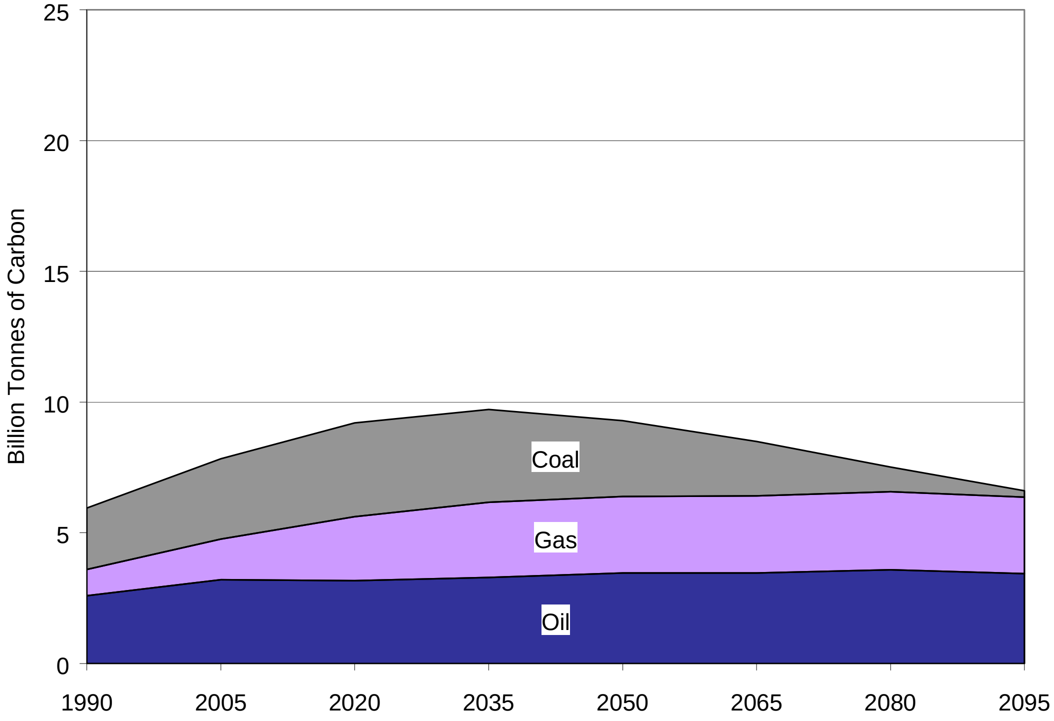


Figure 18. Electricity Generation by Type - Global 550 ppmv Case *With* Carbon Capture and Sequestration Technologies (Exajoules per year)

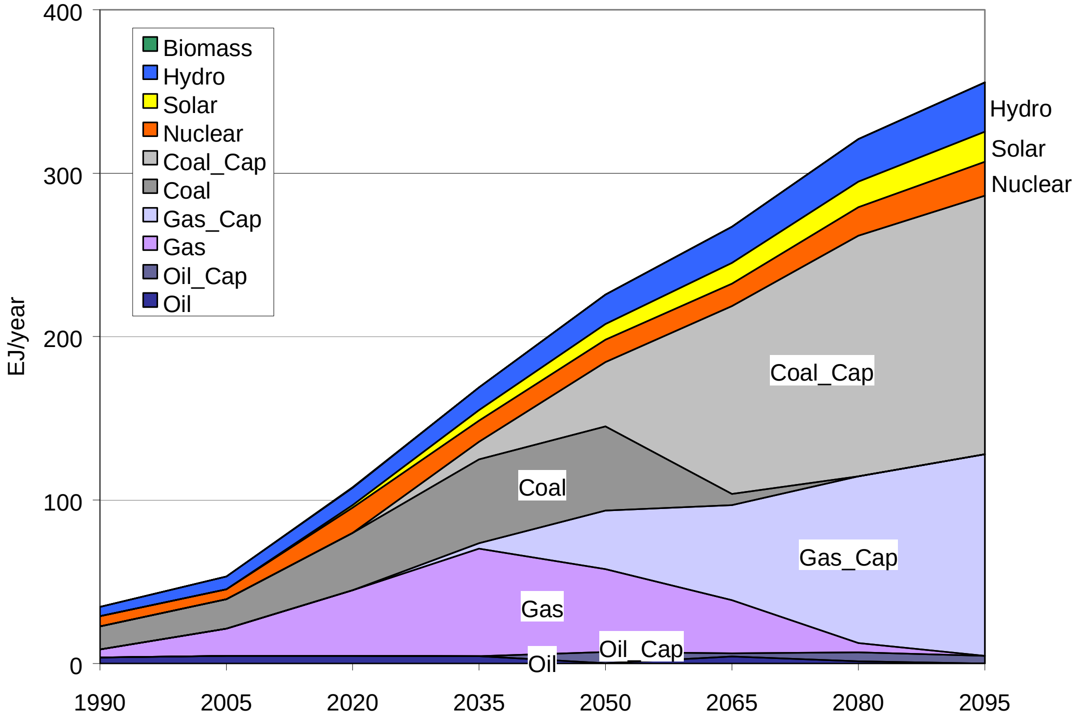


Figure 19. Comparison of Electricity Generation - Global 550 ppmv Case (Exajoules per year)

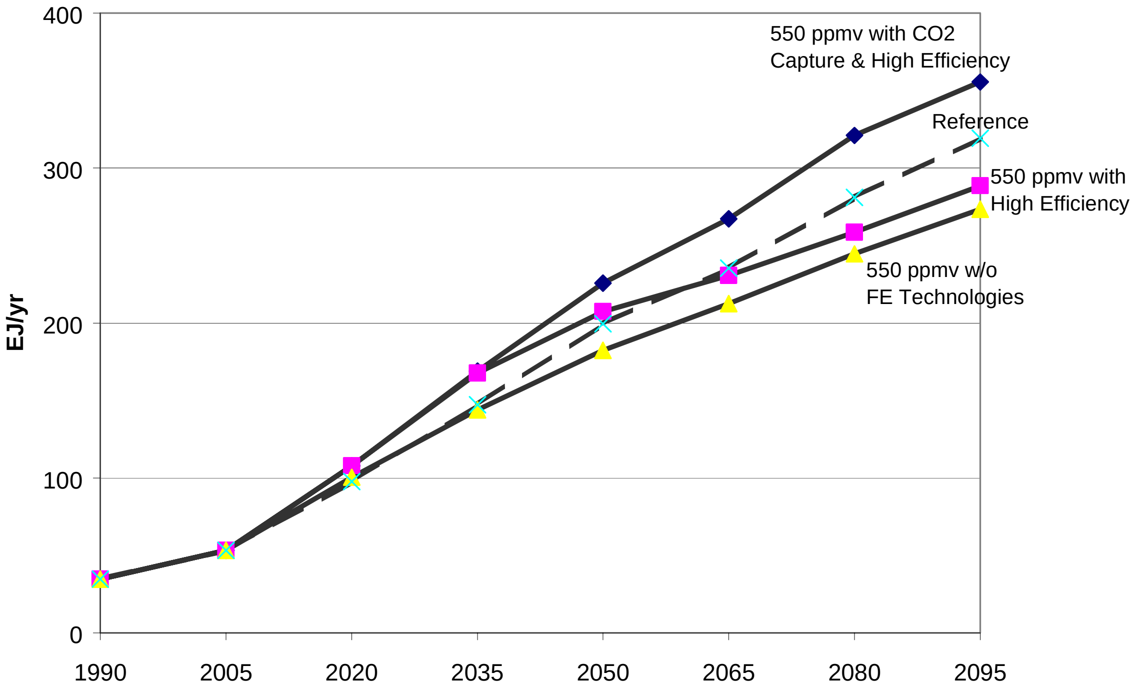


Figure 20. Comparison of Electricity Generation - US 550 ppmv Case (Exajoules per year)

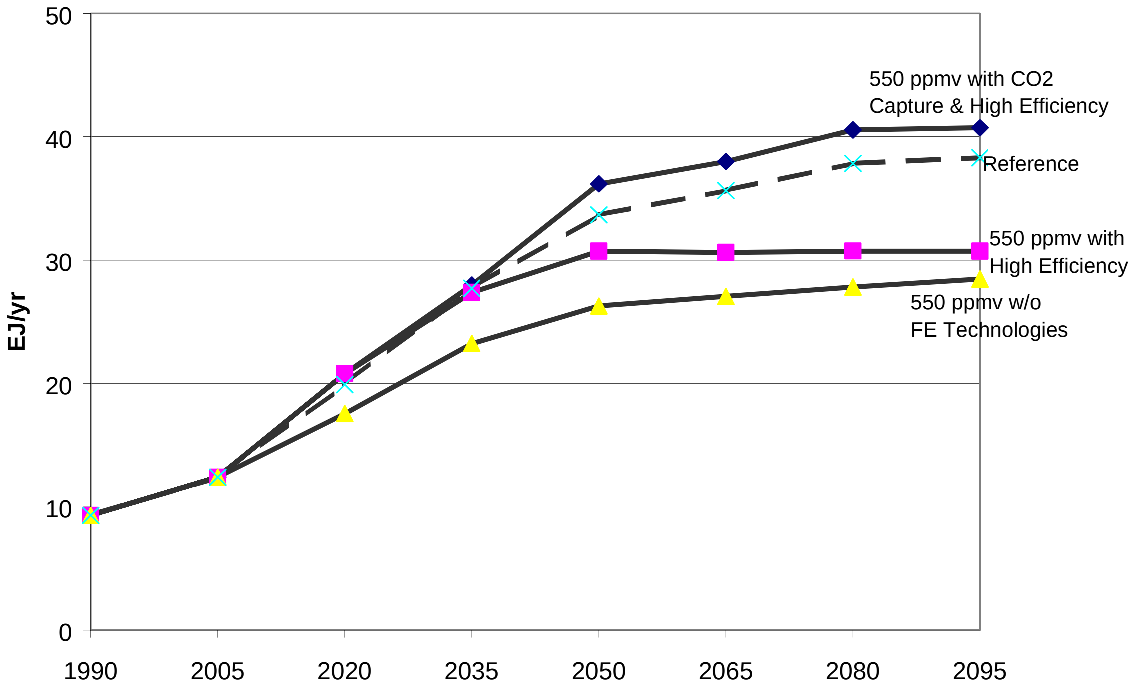


Figure 21. Electricity Generation by Type - US 550 ppmv Case *With* Carbon Capture and Sequestration Technologies (Exajoules per year)

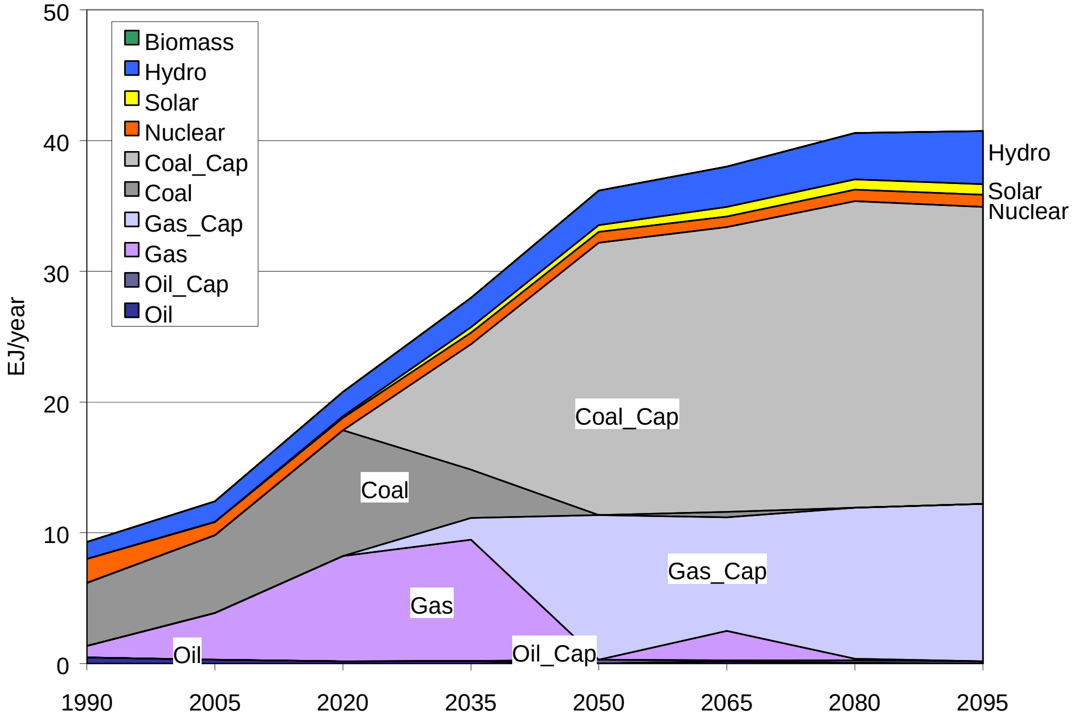


Figure 22. Comparison of Electricity Generation - China 550 ppmv Case (Exajoules per year)

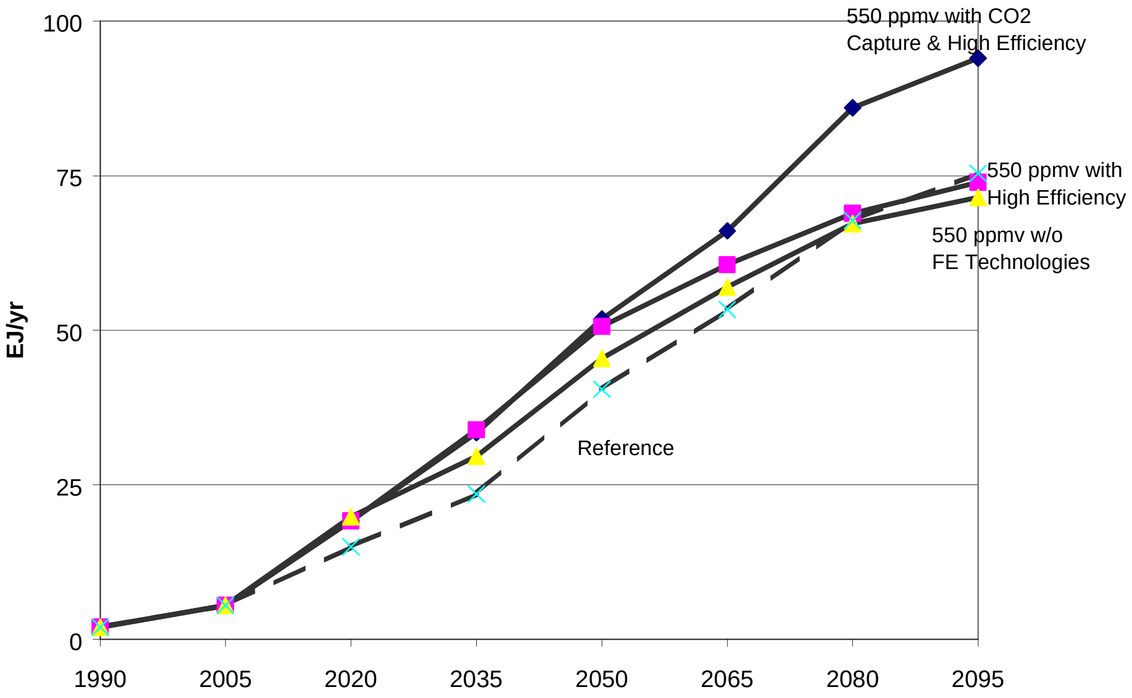


Figure 23. Electricity Generation by Type - China 550 ppmv Case *With* Carbon Capture and Sequestration Technologies (Exajoules per year)

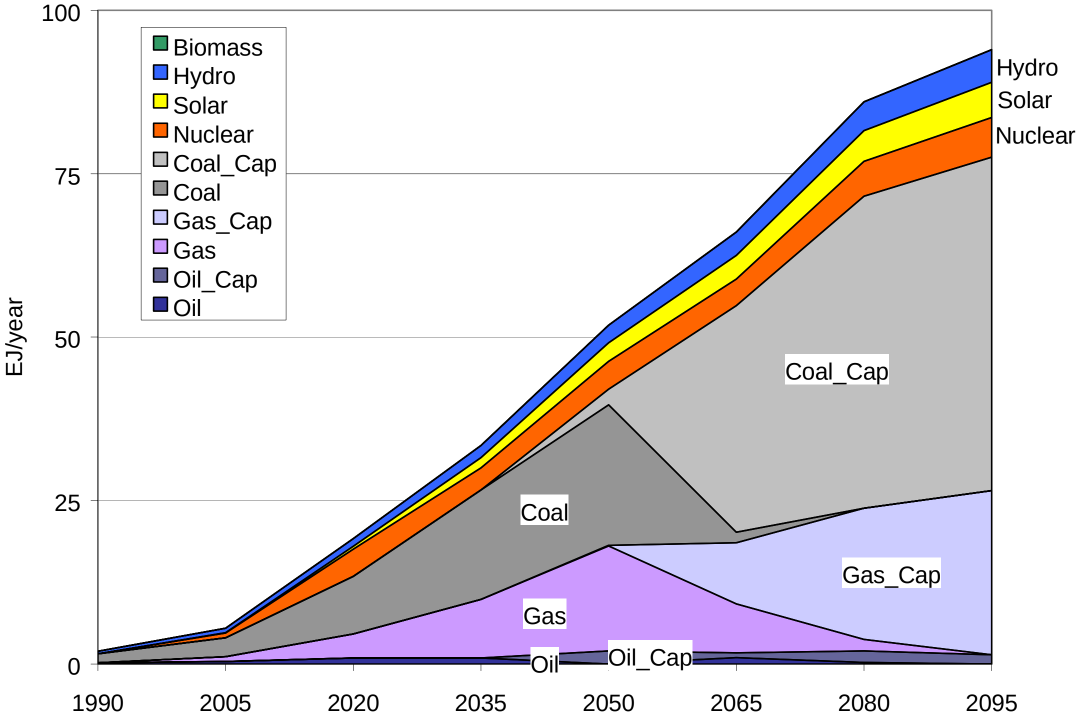


Figure 24. Comparison of Primary Energy Consumption - Global 550 ppmv Case (Exajoules per year)

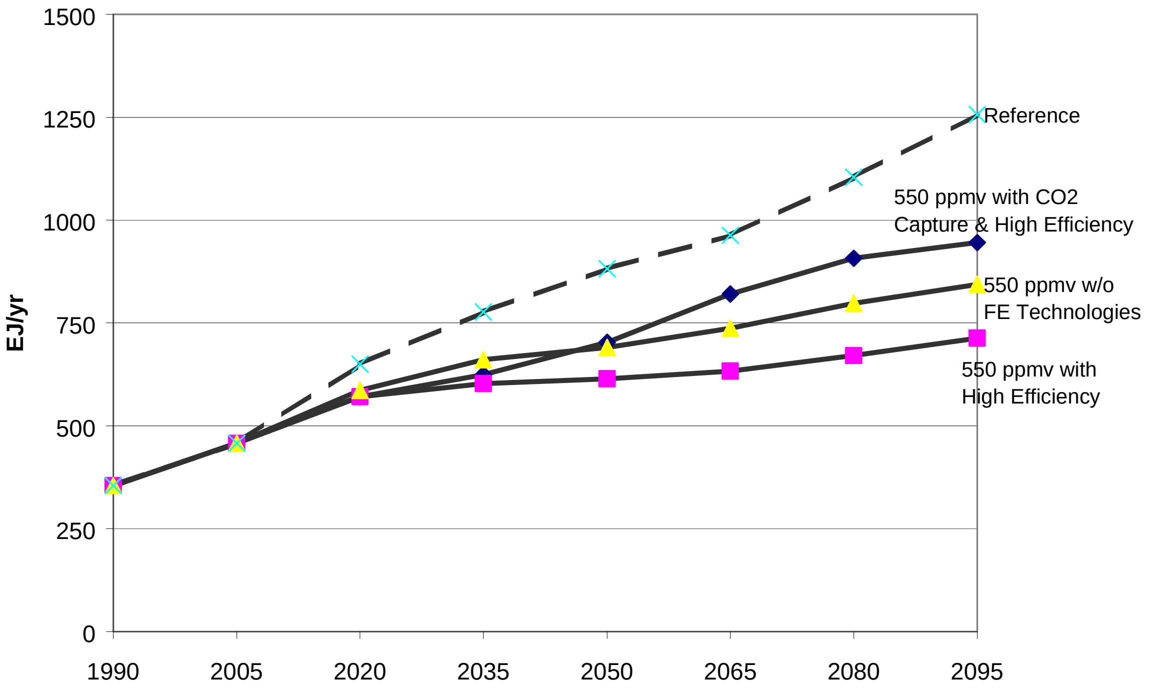


Figure 25. Primary Energy Consumption by Fuel - Global 550 ppmv Case *With* Carbon Capture and Sequestration Technologies (Exajoules per year)

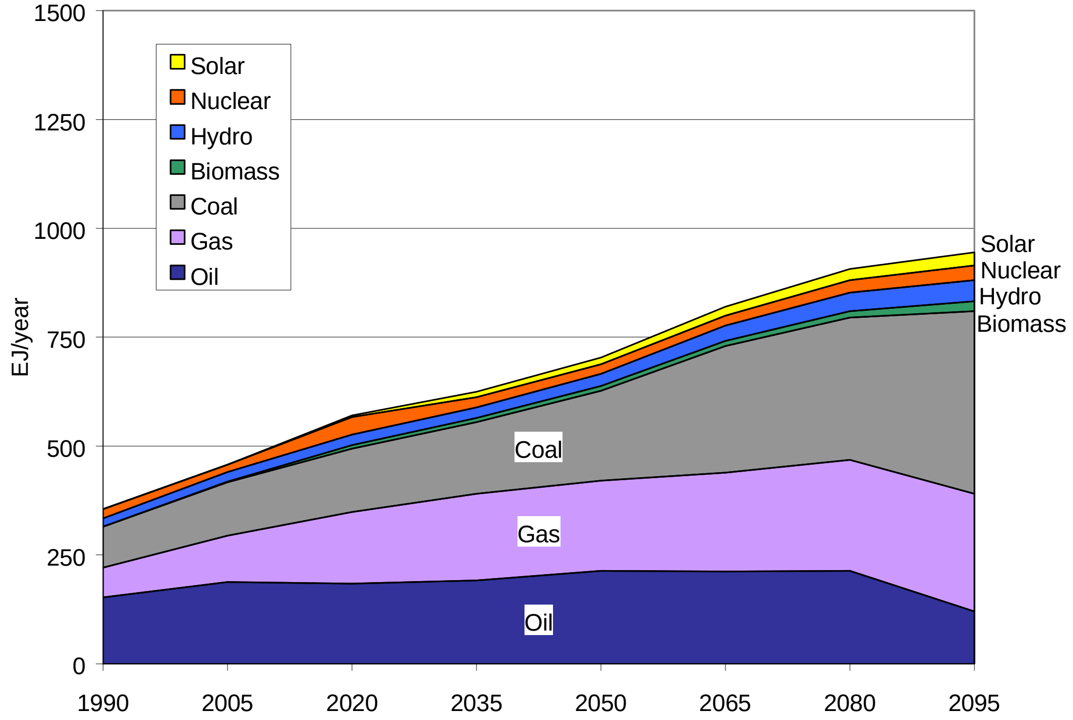


Figure 26. Comparison of Primary Energy Consumption - US 550 ppmv Case (Exajoules per year)

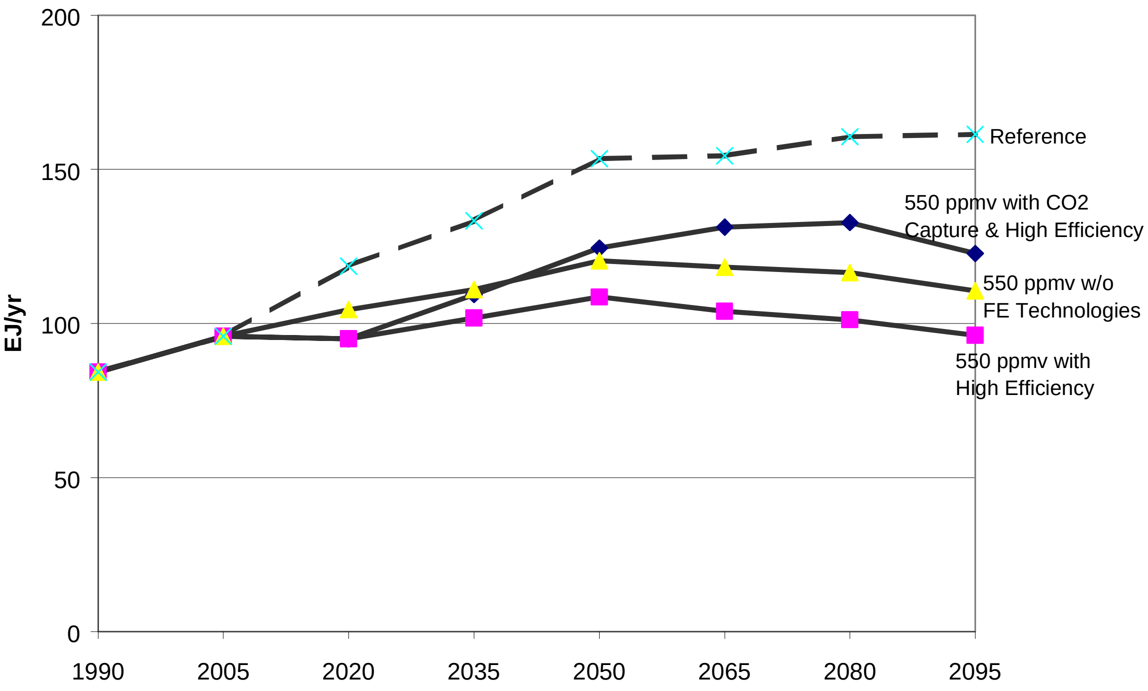


Figure 27. Comparison of Primary Energy Consumption - China 550 ppmv Case (Exajoules per year)

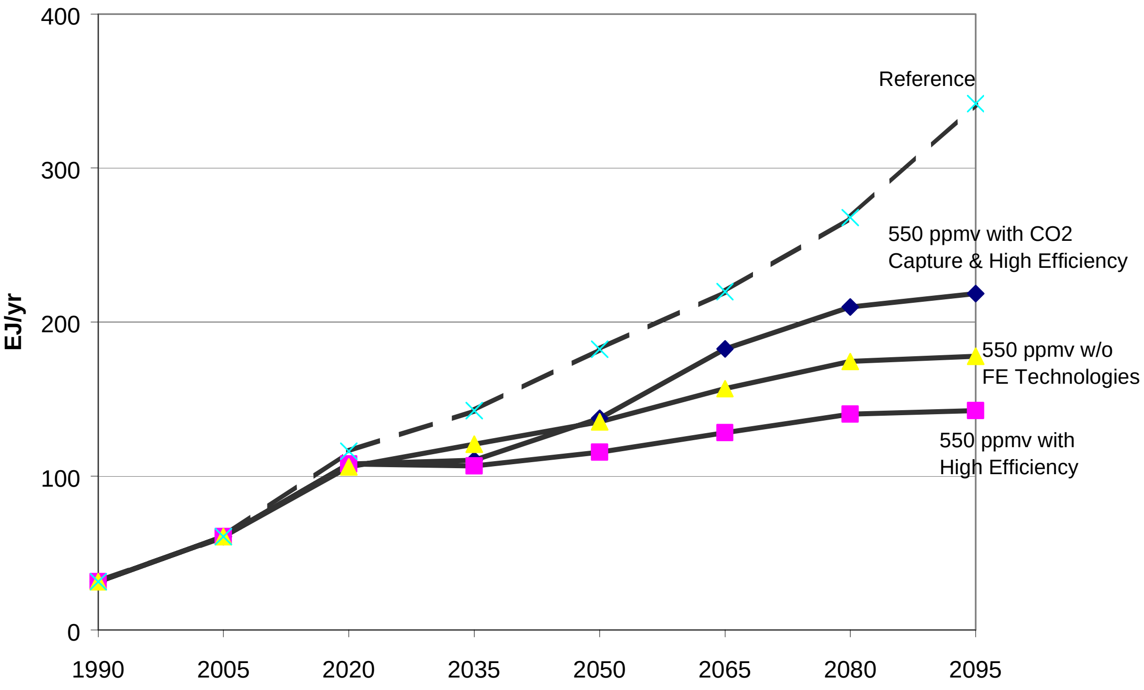


Figure 28. Primary Energy Consumption by Fuel - US 550 ppmv Case *With* Carbon Capture and Sequestration Technologies (Exajoules per year)

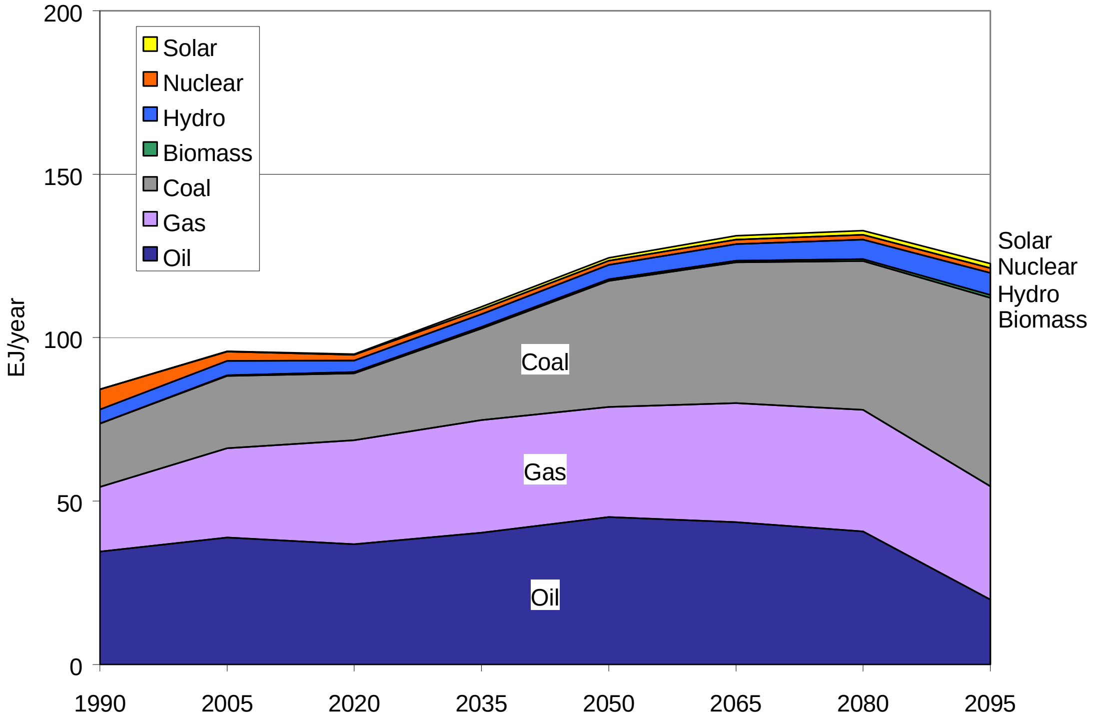


Figure 29. Primary Energy Consumption by Fuel - China 550 ppmv Case *With* Carbon Capture and Sequestration Technologies (Exajoules per year)

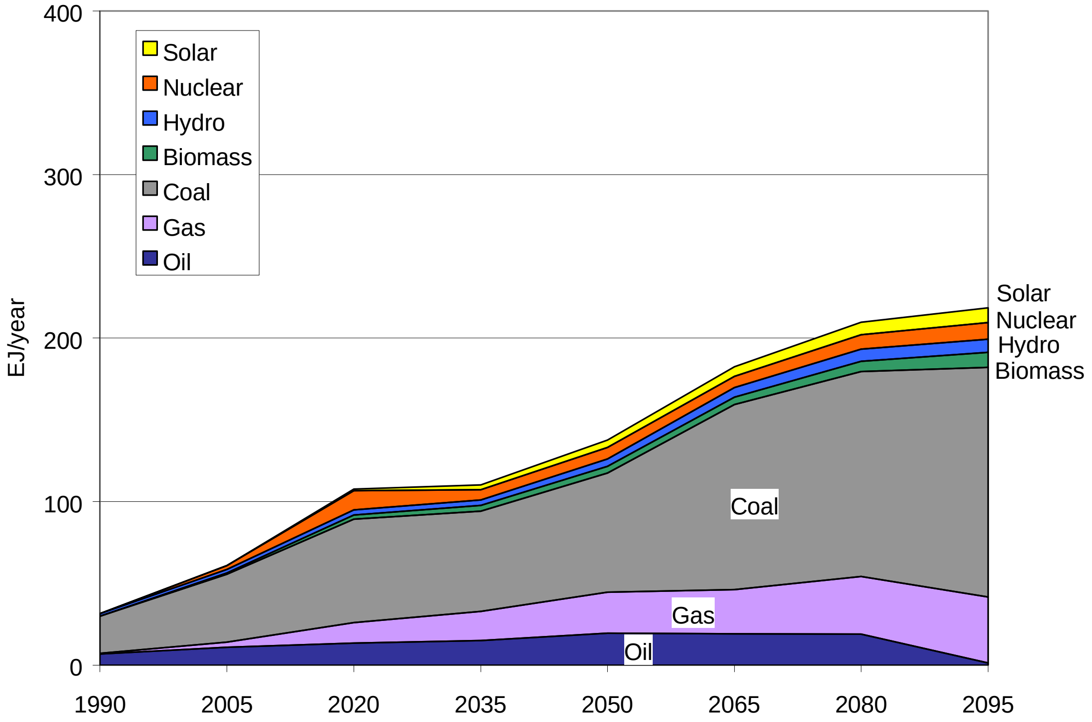
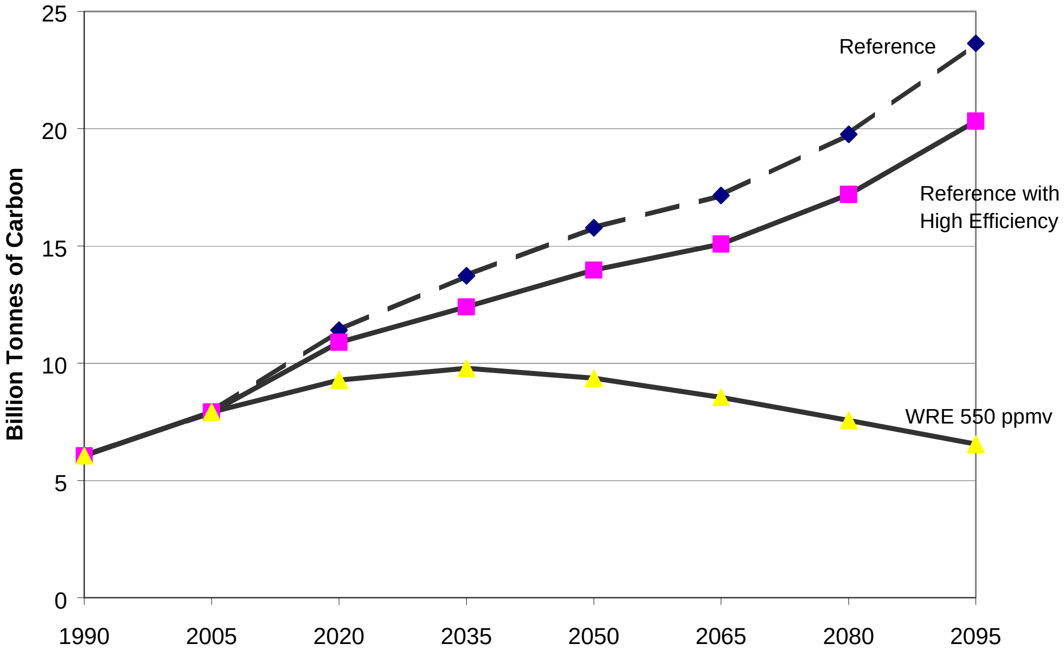


Figure 30. Comparison of CO_2 Emissions - Global Reference and Reference with High Efficiency (Billion Tonnes of Carbon)



Appendix

Energy Conversion

1 EJ = 10^{18} Joule
1 EJ = 9.48 x 10^{14} BTU
1 EJ = 2.778 x 10^{11} kWh
1 Quad = 1.055 EJ
1 Quad = 10^{15} BTU
1 Quad = 2.93 x 10^{11} kWh
1 kWh = 3.6 x 10^{6} Joule
1 kWh = 3413 BTU
1 BTU = 1055 Joule

Unit Conversion

1 metric ton (tonne) = 1000 kg
1 metric ton = 2205 lb
1 metric ton = 1.102 short ton
1 metric ton = 0.984 long ton
1 short ton = 2000 lb
1 long ton = 2240 lb

Typical Energy Contents

Bituminous Coal	25 million BTU/short ton 40 million short ton/Quad 29.1 GJ/tonne 34.4 million tonnes/EJ
Natural Gas	1000 BTU/ft^3 1000 billion ft^3/Quad billion mcf/Quad 37.3 MJ/m^3 26.8 billion m^3/EJ
Crude Oil	5.8 million BTU/barrel 172 million barrels/Quad 38.5 GJ/kl 26 million kl/EJ

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