EXPLORING A TECHNOLOGY STRATEGY FOR STABILIZING ATMOSPHERIC CO_2

by
Jae Edmonds and Marshall Wise

August 27, 1997

Pacific Northwest National Laboratory
Washington, DC

GTSP Pubs

ABSTRACT

The goal of the Framework Convention on Climate Change (FCCC) is to stabilize the concentration of greenhouse gases in the atmosphere at levels which avoid dangerous anthropogenic interference with the climate (United Nations, 1992). Work by the Intergovernmental Panel on Climate Change (IPCC, 1995; WG1) and others (Wigley et al., 1996; WRE) have explored the issue of stabilizing the concentration of atmospheric CO_2. This work developed emissions trajectories consistent with various atmospheric concentration ceilings. Since an emissions path is not uniquely prescribed by a concentration ceiling, various criteria have been added to shape trajectories, including implied climate impacts and costs.

The attraction of efficient instruments for achieving atmospheric stabilization is great, and most of the analysis to date has focused on either tradable permits or taxes as the instruments of implementation (Hourcade et al., 1996). Clearly, efficient instruments are a first-best alternative for achieving any emissions mitigation objective. But they are not without their own difficulties, not the least of which is the income distribution problem.

The purpose of this paper is to examine the performance and cost characteristics of an alternative, technology based, policy instrument. Such instruments are of interest because they potentially offer a strategy for stabilizing the atmosphere, while requiring relatively minor financial transfers and allowing economic development to proceed. They accomplish these goals at the expense of economic efficiency, although our study shows the effect of the economic inefficiency is limited to approximately 30%. On the other hand, a technology strategy approach can offer wide technological flexibility in meeting the performance standard.

The technology protocol we study here requires new powerplant and coal-based synthetic fuels capacity to scrub carbon from the waste gas stream in Annex I nations, and provides a mechanism by which non-Annex I nations can graduate into obligations. We examine this protocol under two alternative reference energy futures: one dominated by coal and the other dominated by unconventional oil and gas.

We show that under the coal dominated reference future (CBF) that the simple protocol effectively stabilizes the concentration of CO_2 in the atmosphere. If the protocol is initiated in the year 2020 the atmosphere stabilizes at approximately 510 ppmv, less than double the pre-industrial concentration. Under the unconventional oil and gas dominated reference future (OGF) the simple protocol holds concentrations to approximately double the pre-industrial level, but the atmosphere is not stabilized. Emissions are rising at the end of the century.

Atmospheric stabilization under the OGF requires a second stage to the protocol beginning 30 years after the initiation of the simple protocol; the second stage would require that new refining and processing capacity remove all carbon from the fuel stream in Annex I nations, with imports of refined and process fuels phased out over a 45-year period, and the same graduation mechanism for non-Annex I nations as in the simple protocol. The imposition of this second stage leads to the creation of an energy system utilizing hydrogen and electricity in end-use applications and enforces atmospheric stabilization in the OGF as well as the CBF.

The date at which the protocol goes into effect strongly influences the concentration in the year 2100. From this study, we found the year 2100 concentration of CO_2 approximately a linear function of the date at which the protocol is initiated in Annex I nations. Starting in 2005 gives a lower bound of CO_2 concentration levels reachable under the protocol, a level near 450 ppmv. Keeping the concentration of CO_2 below 550 ppmv requires that the first stage of the protocol be initiated between 2030 and 2040, depending on fossil energy technology developments.

The cost inefficiency penalty associated with the technology protocol varies with time. Initially, annual costs under the protocol are higher than an equivalent efficient policy. As the second stage of the protocol becomes effective in the later years, the inefficiency of the protocol diminishes. However, the present discounted costs of the technology protocols are about 30 % higher than efficient costs when summed over the next century.

The inclusion of joint implementation mechanisms could reduce the cost penalty of the hypothetical protocol and is promising avenue for further work.

INTRODUCTION

The goal of the Framework Convention on Climate Change (FCCC) is to stabilize the concentration of greenhouse gases in the atmosphere at levels which avoid dangerous anthropogenic interference with the climate (United Nations, 1992). Work by the Intergovernmental Panel on Climate Change (IPCC, 1995; WG1) and others (Wigley et al., 1996; WRE) have explored the issue of stabilizing the concentration of atmospheric CO_2. This work developed emissions trajectories consistent with various atmospheric concentration ceilings. Since an emissions path is not uniquely prescribed by a concentration ceiling, various criteria have been added to shape trajectories, including implied climate impacts and costs.

No consensus currently exists with regard to a concentration that can be regarded as "safe," and the issue remains subject to debate, fueled at least in part by the enormous difficulties in predicting and valuing the consequences of climate change.

Greater consensus exists regarding the cost of stabilizing the atmosphere. If undertaken universally and efficiently, with flexibility with regard to both where and when emissions mitigations occur, the present discounted costs of stabilizing the concentration of atmospheric CO_2 at twice pre-industrial levels could be less than 1% of present discounted GDP over the period to 2100 if technologies evolve and disseminate at rates at least as rapid at those prescribed by the IPCC IS92a scenario (Edmonds et al., 1997).

But the potential for inefficient and ineffective policy regimes also exists. Richels et al. (1996), for example, showed that the present discounted value of an OECD-only obligation to reduce OECD emissions 20%, is between two and eight trillion dollars. And these reductions would have only a marginal impact on the concentration of atmospheric CO_2.

The attraction of efficient instruments is great, and most of the analysis to date has focused on either tradable permits or taxes as the instruments of implementation (Hourcade et al., 1996). Clearly, efficient instruments are a first-best alternative for achieving any emissions mitigation objective. But they are not without their own difficulties, not the least of which is the income distribution problem.

An unavoidable problem associated with either taxes or tradable permits is that income must be re-distributed both within and among nations. Employing either taxes or permits generates income flows as well as sending signals to decision makers. These income flows can be large relative to GDP and relative to the cost of the climate mitigation problem. For example, stabilizing the concentration of carbon dioxide at 550 ppmv generates an annual global cost in the year 2020 ranging from $11 to $200 billion, depending on whether the WRE or WG1 emissions path is followed. On the other hand the value of the permits associated with a tradable emissions quota system ranges from $230 to $830 billion per year. Thus the distribution of permits raises a problem of income allocation many times larger than the cost of the environmental problem they are intended to help solve (Edmonds et al., 1997). By the year 2050 the value of the permits exceeds $1 trillion per year, more than 1% of gross world product, under both the WRE and WG1.

A second problem encountered in negotiations is that poor nations place a higher priority on economic development than on environmental protection. Climate change is a particularly challenging environmental problem for developing nations in that benefits will be received by future generations, who will be richer than present generations, making it difficult to justify present sacrifice for emissions mitigation.

These problems may make it difficult to reach a consensus in the creation and maintenance of a protocol where the principal instrument for controlling emissions is a system of tradable emissions permits distributed across most of the nations of the world.

The purpose of this paper is to examine the performance and cost characteristics of an alternative, technology based, policy instrument. Such instruments are of interest because they potentially offer a strategy for stabilizing the atmosphere, while requiring relatively minor financial transfers and allowing economic development to proceed. As we shall see, they accomplish these goals at the expense of economic efficiency, although the effect of the economic inefficiency is limited to approximately 30%. On the other hand, a technology strategy approach can offer wide technological flexibility in meeting the performance standard.

The instruments we examine key on the fact that primary energy production passes through a small number of critical transformation points. Coal is consumed predominantly in the generation of electric power, and in the future it may become the feedstock from which liquids and gases are derived. Liquids and gases in turn pass through refineries and processing plants, and final products also play a significant role in power generation. These transformation nodes are natural points for removing carbon from the fuel stream.

The potential protocols we examine are ones which require carbon removal and sequestration from the energy system at two points: power generation and refining/processing.

We will consider the effectiveness of such agreements in stabilizing the concentration of atmospheric CO_2, and examine their costs, particularly relative to efficient policy instruments. Cost and effectiveness can be influenced by a variety of factors including the available technologies, the rate of growth of the global energy system, and the abundance of various fossil fuel resources.

We will begin our discussion by reviewing carbon and energy resources. For this paper, we have chosen to explore the impact of varying assumptions about Fossil Fuel Resources against a backdrop of one representative or reference scenario of the other two principal factors. We then proceed to describe MiniCAM 97.6, the model employed to examine these issues—the scale of economic systems and energy technology. We then create a hypothetical technology based agreement around which to conduct analysis and explore how the cost and effectiveness of the agreement varies under alternative assumptions regarding the timing of initial implementation.

CARBON AND ENERGY RESOURCES

Any strategy for stabilizing the concentration of atmospheric CO_2 must recognize that the potential evolution of future emissions trajectories are highly uncertain, ranging from those in which energy use rises dramatically to those in which energy use barely rises at all. This does not contradict the fact that policies and agreements can and should be revisited periodically to take into account the continual advance in knowledge. Nonetheless, it is useful to examine how the cost and effectiveness of agreements vary under alternative circumstances.

We begin by considering the fossil fuel resource base. The most important observations to be made are that, while the fossil fuel resource base provides no meaningful constraint on carbon potentially vented to the atmosphere during the course of the next century, conventional oil and gas resources, the backbone of the modern global energy system, are limited. This does not mean that total oil and gas resources are limited. Rather, the **conventional** oil and gas resource base, that is the resource base with which we are familiar, is limited. There is an important implication of these limits—that there will be a transition during the first half of the next century from an energy system dominated by conventional oil and gas, to one of three alternative futures:

1. The energy system will move toward a coal based future in which coal becomes the backbone of the energy system, being transformed into electricity, synthetic liquids, and synthetic gases;
2. The energy system will move toward unconventional oil and gas; or
3. The energy system will move toward conservation, and non- and low-carbon emitting forms.

These paradigms are relative and not absolute. There will, for example, be solar energy production in the coal based future.

Clearly, physical resources are available to support any of these three alternative futures. Which of these courses of development dominates will depend on both technology and policy developments. We begin by reviewing the fossil fuel resource base, and then proceed to explore the potential for land-use emissions.

Fossil Fuel Resources

The relatively low estimates of conventional oil and gas emissions growth (in comparison to coal) over the course of the next century reflect the present knowledge and expectations of occurrences of resources. Table 1 shows present estimates and ranges of fossil fuel resources in terms of their carbon content. The carbon content of coal is an order of magnitude greater than the estimated carbon content of conventional oil and gas combined. The range of potential oil and gas resources roughly doubles when additional occurrences are included. (Additional occurrences also expands the range of coal resource estimates by a factor of two.) Unconventional gas resources are approximately twice the total of conventional gas resources, leaving a potential oil and gas resource base of more than 1,500 PgC. The availability of tar sands and heavy oils would bring the total carbon in oil and gas resources to more than 2,000 PgC.

For comparison, Table 2 shows cumulative emissions from 1990 to 2100 associated with various ceilings for CO_2 concentrations. Conventional oil and gas resources alone, even with the inclusion of additional occurrences, are insufficient to sustain a concentration of 450 ppmv. Only with the inclusion of unconventional resources is there sufficient carbon in oil and gas resources to exceed emissions for stabilization of concentrations below 550 ppmv using the Wigley et al. (1996) emissions paths.

Table 1: Carbon Content of Fossil Fuel Energy Resources Potentially Available After 1990

Energy Form	Resource Base (PgC)	Range of Resource Base Estimates (PgC)	Additional Occurrences (PgC)	Resources plus Additional Occurrences (PgC)
Conventional Oil [a]	170	156-230	200	156-430
Conventional Gas [a]	140	115-240	150	115-390
Unconventional Gas [a]	410	--	340	750
Coal [a,b,c]	3,240	--	3,350	3,240-6,590
Tar Sands & Heavy Oils [c,d]	720	600-800	--	600-800
Oil Shale [c,e]	40,000	--	--	40,000
Gas Hydrates [a]	--	--	12,240	12,240

Source: [a] Source: IPCC (1996) p.87. [b] Assumes 50% unrecoverable coal in the resource base. [C] Range estimates are not available due to the abundance of the resource. [d] Source: Rogner (1996). [e] Source: Edmonds and Reilly (1985).

Table 2: Cumulative Carbon Emissions 1990 to 2100 Under WRE CO_2 Stabilization

Concentration Ceiling	Cumulative Emissions 1990 - 2100 (PgC)
350 ppmv	363
450 ppmv	714
550 ppmv	1,043
650 ppmv	1,239
750 ppmv	1,348

Source: Wigley, et al. (1996).

Land-Use Change Emissions

There are approximately 560 PgC in the form of above-ground biomass. There are an additional 1200 PgC in soils and detritus. These pools form the principal reservoirs from which terrestrial systems can exhaust or sequester carbon. They vary greatly, though long-term emissions are bounded and most trajectories show little or no net emission of carbon by the end of the twenty-first century. Land-use emissions scenarios do not exhibit emissions levels on a scale similar to fossil fuel carbon emissions (Alcamo et al., 1995).

Cumulative emissions from land-use change range from 30 to 320 PgC over the years 1990 to 2100, with afforestation scenarios estimating net uptake in the range 30 to 150 PgC. In contrast, the range of cumulative emissions from published fossil fuel emissions scenarios range from as little as 490 PgC to 3,450 PgC over that same 110-year period (Alcamo et al., 1995).

MODELING FUTURE CARBON EMISSIONS

In this exercise, we employ the energy, agriculture-land-use, and carbon cycle components of the MiniCAM model, version MiniCAM 97.6. This is an updated version of the MiniCAM model described in Edmonds et al. (1997), and Edmonds et al. (1996). The model has been augmented to incorporate carbon scrubbing and sequestration technology options, to incorporate a hydrogen fuel option, and to provide a global market for biomass energy.

We use the MiniCAM 97.6 to develop two qualitatively different future energy and greenhouse gas emissions scenarios. We refer to these scenarios as **Coal Bridge to the Future (CBF)** , and **Oil and Gas Forever (OGF)**. CBF is characterized by relatively inexpensive coal based synthetic oil and gas production, and OGF is characterized by relatively inexpensive unconventional oil and gas resources. A **Low Carbon Future (LCF)** is also possible, where the LCF is characterized by relatively inexpensive conservation and non- or low-carbon energy supply technologies. But we have not constructed a separate LCF scenario in that if it materializes without policy intervention, no greenhouse mitigation policy is necessary to stabilize the atmosphere, and all is well. On the other hand, it is also the end-state into which policy seeks to transform CBF and OGF. We construct the CBF and OGF starting with a common reference in terms of population and economics, with differences in the energy character of these scenarios traceable to different assumptions regarding energy supply technology.

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. Assumed regional population, per capita income, and regional GDP are given in Figure 1-3 respectively.

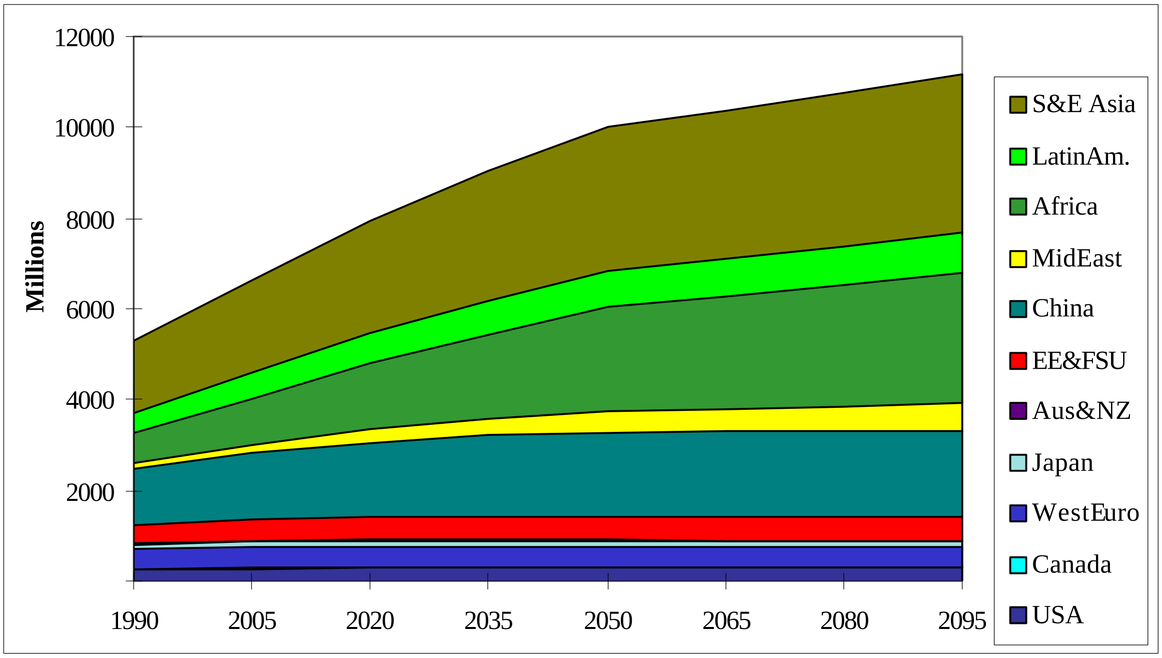

Figure 1. Population, by Region

Economic growth is assumed to proceed in a heterogeneous manner. We assume that regions that are rapidly developing 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.

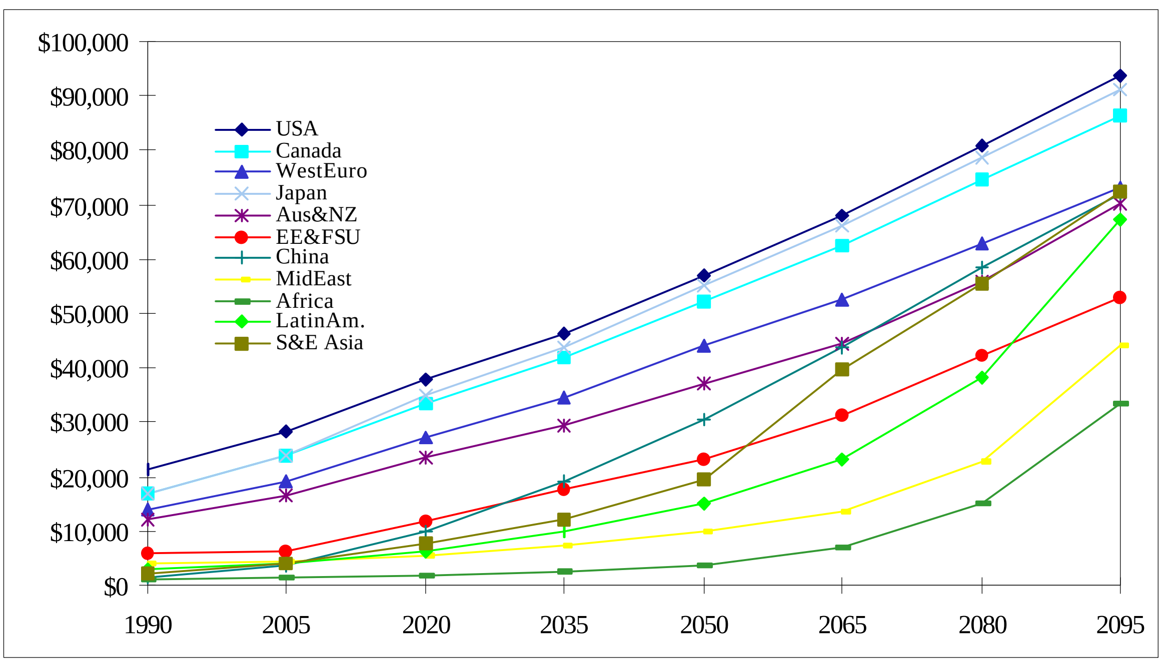

Figure 2. Per Capita Income (PPP Basis), by Region

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 not all developing nations make the transition simultaneously. Rather 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.

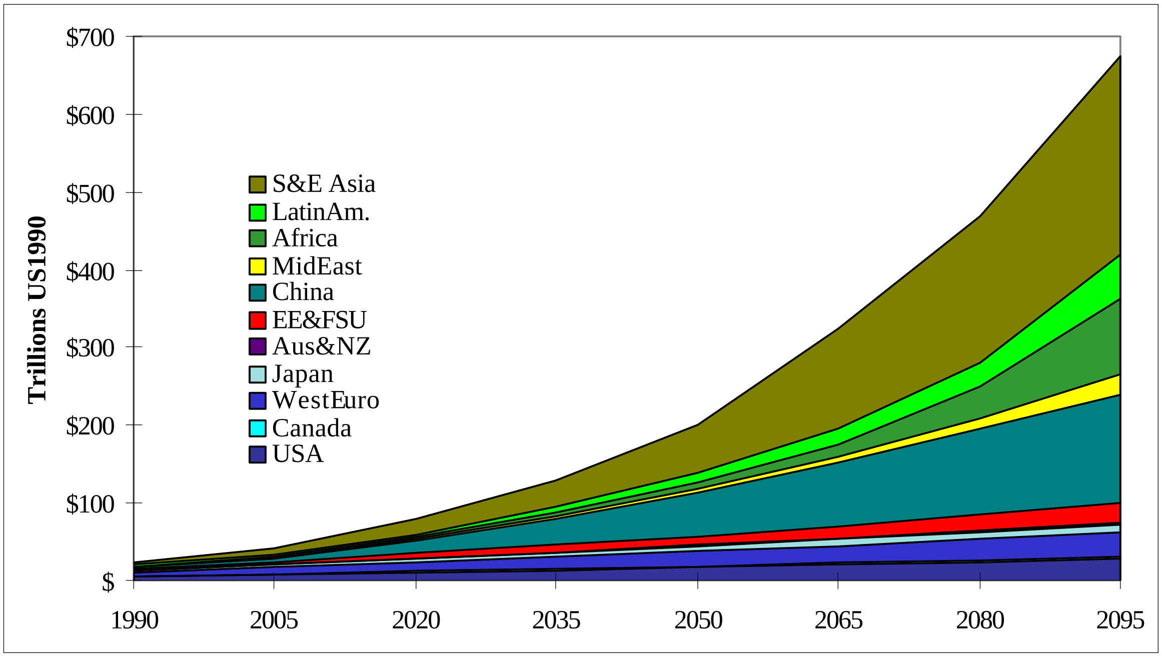

Figure 3. Gross Domestic Product (PPP Basis), by Region

Unconventional Oil and Gas Resources

The principal difference between the CBF and OGF scenarios is the technology assumed for extracting unconventional oil and gas resources. In the OGF scenario unconventional oil and gas resources, including clathrates are initially available at oil prices of $20/barrel, with technological change lowering costs at 1%/year. In CBF these technologies are available at $50/barrel with technological progress proceeding at only 0.5%/year. While the same resources are available in all scenarios, differences in technology assumptions determine relative economic performance.

Carbon Capture and Sequestration

Carbon can be removed from fuels either before or after combustion. We consider carbon capture and sequestration from electric power plants burning fossil fuels. Various of techniques for removal have been considered, (see Herzog, 1997). Post-combustion techniques involve scrubbing carbon dioxide from the waste gas stream.

Alternatively, the carbon could be removed prior to combustion. For example, natural gas could be used as a feedstock for hydrogen. That hydrogen could in turn be used in a variety of applications, including power generation through, for example, fuel cells, and for the generation of heat and/or power. Hydrogen is attractive from the perspective of carbon emissions mitigation in that the byproduct, water vapor, would be insufficient in magnitude to affect the Earth's radiative balance.

Hydrogen can also be derived from other fuels, even coal. The Hydrocarb process (Steinberg and Grohse, 1989) allows hydrogen to be harvested from solids such as coal or biomass, with the resulting carbon being claimed in the form of an unoxidized solid. The successful application of this technology would have the benefit of creating a hydrogen feedstock with a byproduct which could be stored without significant environmental uncertainties. Furthermore, applying this process to commercial biomass (assuming that the biomass was not derived via net deforestation) could provide hydrogen and net carbon removal from the atmosphere equal to the capture rate (Steinberg, 1991).

We assume that carbon can be captured from power plants as follows:

	Coal	**Oil**	**Gas**
Power reductions	20%	20%	10%
Non-energy cost increase	50%	30%	20%
Efficiency of capture	←	90%	→
Sequestration costs	←	$75/tonne C	→

In addition, carbon not incorporated in the fuels during the conversion of coal to synthetic liquids and gases can be captured and sequestered. We assume that capture technology is available as follows:

Degradation of transformation process	0%
Non-energy cost increase	0%
Efficiency of capture	90%
Sequestration costs	$75/tonne C

There are several types of carbon reservoirs. The most obvious are oil and gas wells -both active and depleted - but this reservoir is limited in capacity. Other reservoirs are also potentially available including acquifers, caverns, salt domes, and deep oceans. Estimates from Herzog et al. (1997) are displayed in Table 3.

Table 3: Estimates of Global Carbon Storage Reservoirs

	Range (PgC)	
Carbon Storage Reservoir	**Low**	**High**
Deep Ocean	1,391	27,000
Deep Aquifers	87	2,727
Depleted Gas Reservoirs	136	300
Depleted Oil Reservoirs	41	191

Of these reservoirs, oil and gas reservoirs are the most attractive. Active oil and gas wells can utilize the CO_2 as a method of tertiary recovery. Furthermore, the geological formation has already demonstrated its ability to hold oil and gas. There are no obvious environmental consequences to long-term storage in locations which have held oil and gas. The same cannot be said for deep oceans and deep aquifers. These sites, while promising, hold potential uncertainties in retention and environmental impacts.

Biomass

In MiniCAM 97.6 modern commercial biomass energy is produced in the context of overall agriculture and land-use management decision making. This modeling structure is described in Edmonds et al. 1996. The modeling structure includes an endogenous land-use emissions component. Land is partitioned between managed and unmanaged components. An expansion of the managed component typically has carbon emissions consequences. Thus the expansion of commercial biomass production implies that land-use patterns must change. Land must be acquired, with some of the land coming through competition with other activities within the managed land system and some coming at the expense of net intrusion into unmanaged ecosystems.

The cost of producing commercial biomass varies with the state of biomass technology, the level of production (land costs depend on overall demands for land), the technology for producing competing agricultural and sylvacultural products, and the demands for competing agricultural and sylvacultural products. Table 4 shows assumptions for the agriculture and land-use component of the model are used for all of the eleven regions.

Table 4: Agriculture-Land-Use Module Assumptions
All Cases

PARAMETER	Reference Case
Rate of Exogenous Productivity	
Improvement	1.5%/yr
Crops	1.5%/yr
Livestock	0.5%/yr
Managed Forests	0.5%/yr
Fuelwood	0.0%/yr
Initial Price Elasticities	
Crops	-0.2
Livestock	-0.2
Managed Forests	-0.4
Fuelwood	-0.4
Initial Income Elasticities	
Managed Forests	0.2
Fuelwood	-0.2
Asymptotic Demands	
Crops	0.95 Mg/cap/yr
Livestock	0.21 Mg/cap/yr
Biomass Productivity	
1990	6 Mg/ha/yr
2095	10 Mg/ha/yr

Other Technology Assumptions

Assumptions for other important technologies are as follows. Fossil fuel powerplants reach an efficiency level of 66% by 2050. The cost of solar electricity reaches 10 c/kWh in 2035, and decreases by 1% per year thereafter. Excluding any carbon capturing costs, coal liquefaction cost asymptotically declines to a level about three times higher than the current cost of oil. Biomass liquefaction, due to its higher cost as a feedstock fuel, is approximately 10% more costly than coal liquefaction.

End-use energy intensities are also expected to decline in all regions. During periods of high economic growth, e.g. China's current 8%/yr rate, we assume end-use energy intensities to decrease at rates up to 3%/yr. As a region's income reaches developed country levels, these rates drop to 0.5%/yr, consistent with our current assumptions for OECD regions.

A HYPOTHETICAL TECHNOLOGY PROTOCOL

We initially explore a three-part, hypothetical technology protocol. This hypothetical protocol requires that:

1. *Any new fossil fuel electric power capacity in Annex I nations installed after the year 2020 must scrub and dispose of the carbon from its exhaust stream;*
2. *Any new synthetic fuels capacity must capture and dispose of carbon released in the conversion process; and*
3. *Non-Annex I nations that participate must undertake the same obligations that Annex I nations undertake when their per capita income, measured by purchasing power parity, equals the average for Annex I nations in 2020.*

This hypothetical protocol is structured around technology rather than either financial penalties or physical emissions constraints.

The protocol does several things differently from policies and protocols which utilize taxes and permits to control emissions. First, it sets a clear technological target. By setting the implementation date in the future, it provides time for focused technology development to occur. It creates the clear signal that non-carbon technology development is needed. On the other hand, it does not prescribe which technologies should be developed as substitutes for fossil fuel carbon based power generation, or the technologies to be employed for carbon capture and sequestration.

Second, it eliminates the need for a complex set of financial transactions to control emissions. Costs are incurred at the source of the mitigation. The maximum marginal cost that can be encountered is the cost of removing and sequestering carbon from the power generation system. Utilities have an incentive to install any type of non-carbon capacity that costs less than carbon scrubbing. As the cost of scrubbing declines, the marginal cost of reducing carbon declines.

Third, there is a graduation clause. Developing nations are not asked to participate in the protocol until they reach the level of per capita income in Annex I nations when they undertook their obligations. It is important to note that the measure of per capita income used to measure development in non-Annex I nations is based on purchasing power parity calculations and not on current exchange rates. This measure is chosen to avoid the potential for exchange rate manipulation to avoid an obligation. The graduation clause allows developing nations to develop, as well as requires them to undertake the responsibilities of developed nations when they have achieved levels of material well-being comparable to the developed nations when they undertook the obligation. By connecting the non-Annex I obligation to per capital material well-being, the protocol recognizes that nations change over time. When poor nations graduate, they will have different priorities than when they were poor. Further improvements in material standards of living will be a lower marginal priority, while environmental amenities will become marginally more valuable.

Figure 4 illustrates the graduation clause by comparing the income growth paths of the non-Annex I regions versus the Annex I average per capita income levels of 2020 and 2050. From the figure, China's income is the first to reach Annex I 2020 values, and it therefore joins the protocol within 20 years after Annex I initiates it. The South and East Asia Region lags China, but its later rapid growth puts it into both stages of the protocol with Annex I and China by 2065. The rest of the world eventually becomes subject to the protocol by the end of the next century.

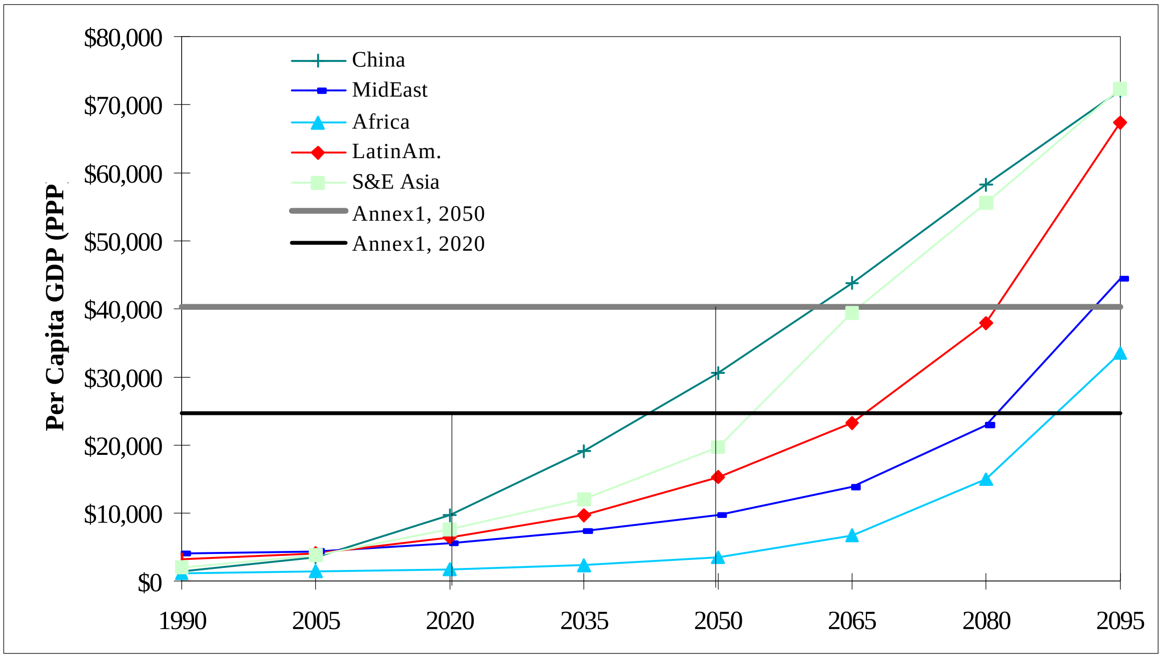

Figure 4. Non-Annex I Graduation into Protocol

The protocol is simple, but it is also economically inefficient. Marginal costs will vary both across nations and within nations. By focusing on the energy transformation sectors, it fails to capture opportunities in other sectors of the economy that are unrelated to electricity. Thus energy conservation related to power generation will be captured, but not the component related to direct fossil fuel consumption, for example, residential heating.

Furthermore, the protocol does not directly guarantee the stabilization of atmospheric CO_2 concentrations. Stabilization may or may not result from such an agreement. We next consider the implications for atmospheric concentration of such an agreement in our two cases: CBF and OGF.

THE HYPOTHETICAL PROTOCOL AGAINST ALTERNATIVE REFERENCE BACKGROUNDS

We impose the protocol on two qualitatively different energy futures: CBF and OGF. These two futures provide distinctly different backgrounds against which the protocol operates. In the CBF case, coal is the most important energy form. It provides the world with its liquid and gaseous fuels. Importantly, the coal resource is presently thought to be unevenly distributed among nations, with a dozen nations holding more than 95% of the enormous resource base (Edmonds et al., 1995). All nations except these few hold insufficient carbon to effect a doubling of the pre-industrial concentration of CO_2. In the CBF case coal production is an important pressure point for controlling carbon emissions in the energy system.

The OGF case contrasts sharply with CBF. Here oil and gas are in abundant supply, and distributed broadly around the world. Many nations control sufficient carbon to effect a doubling of the pre-industrial concentration of CO_2. Large quantities of carbon are in the form of liquids and gases and need only conventional refining and processing to be usable in end-use applications. There is little natural pressure from the transition process to change the way in which energy is used. In the OGF case the problem of controlling carbon is fundamentally more difficult.

The CBF Case

The reference energy system trajectory, the energy system under the hypothetical protocol, and the changes to the global energy system are displayed in the three frames of Figure 5. By construction, the transition from conventional oil and gas in the reference CBF case is dominated by coal. Coal is used to generate electric power and to provide liquids and gases in the second half of the next century. By the end of the next century more than 750 EJ/yr of coal are produced, accounting for more than 40% of the global energy system. Coal production increases by a factor of eight, expanding at an average annual rate of 2% per year.

The production of conventional oil and gas peaks in the year 2020 and begins a long-term decline. By the end of the next century conventional oil and gas production has virtually ceased, having been replaced by synthetic oil and gas produced from coal. The price of oil drifts upward from 1990 to 2050, at which time it stabilizes at approximately double the 1990 level. The price stabilizes because, at that price, unlimited quantities of liquids from coal and biomass become available. The expansion in the production of coal after the year 2050 corresponds to the point at which coal becomes the primary and cheapest source of liquids and gases.

Even in the reference CBF case, substantial non-carbon emitting energy forms penetrate the market. Of the world’s 1,750 EJ used in the year 2095, 175 EJ, 10%, is in the form of commercial biomass, and 750 EJ is in the form of solar, nuclear, and hydro electric power. Thus, even in the CBF scenario more than half of the world’s energy is provided by non-carbon emitting technology.

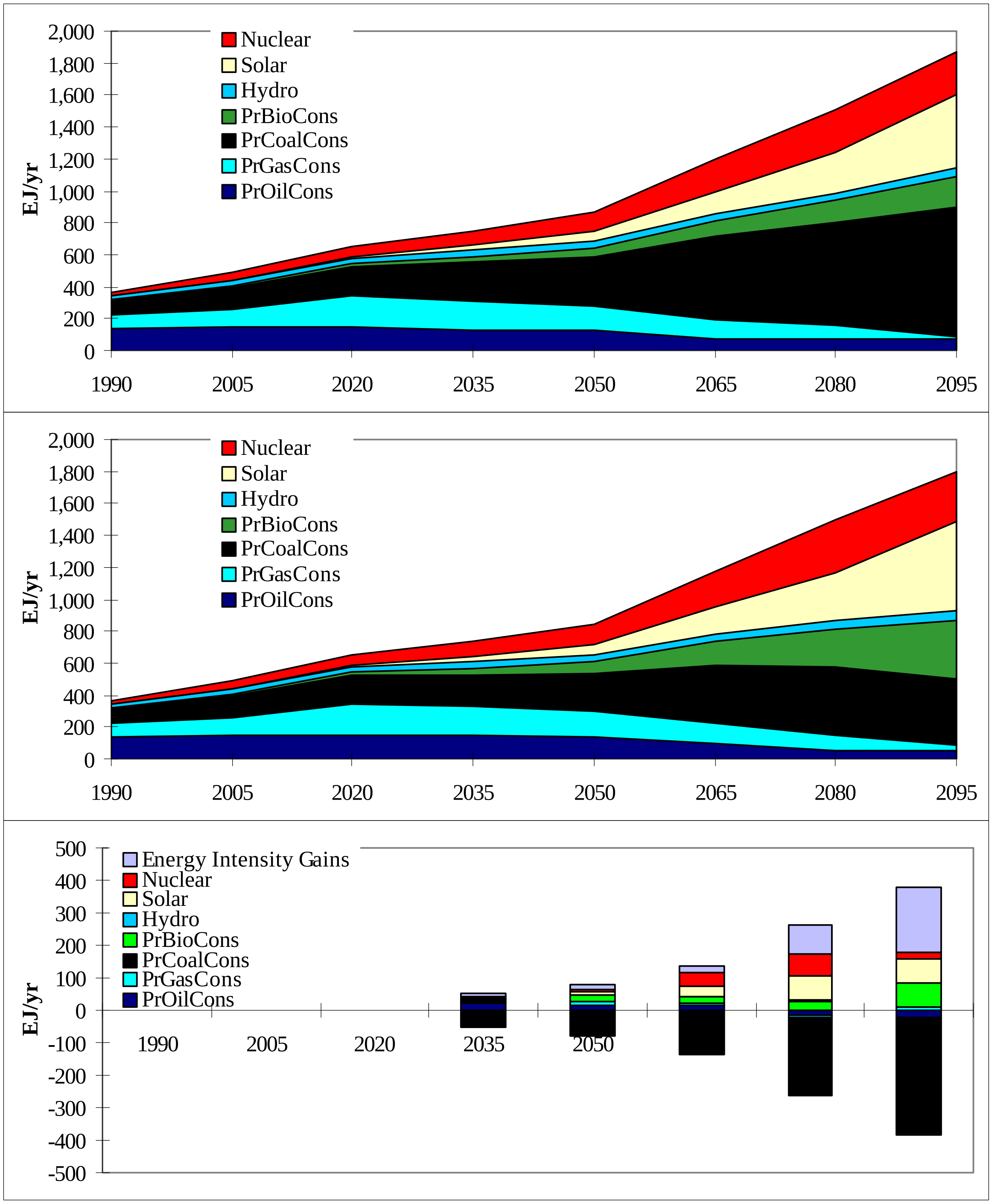

Figure 5. The CBF Global Energy System: Reference Case, Protocol, and Changes

CBF reference carbon emissions and concentrations are shown in Figure 6. Emissions increase throughout the next century, rising to more than 20 PgC/yr and continuing to rise in the year 2095. As a consequence CO_2 concentrations rise above 700 ppmv, with concentrations continuing to increase in the year 2095.

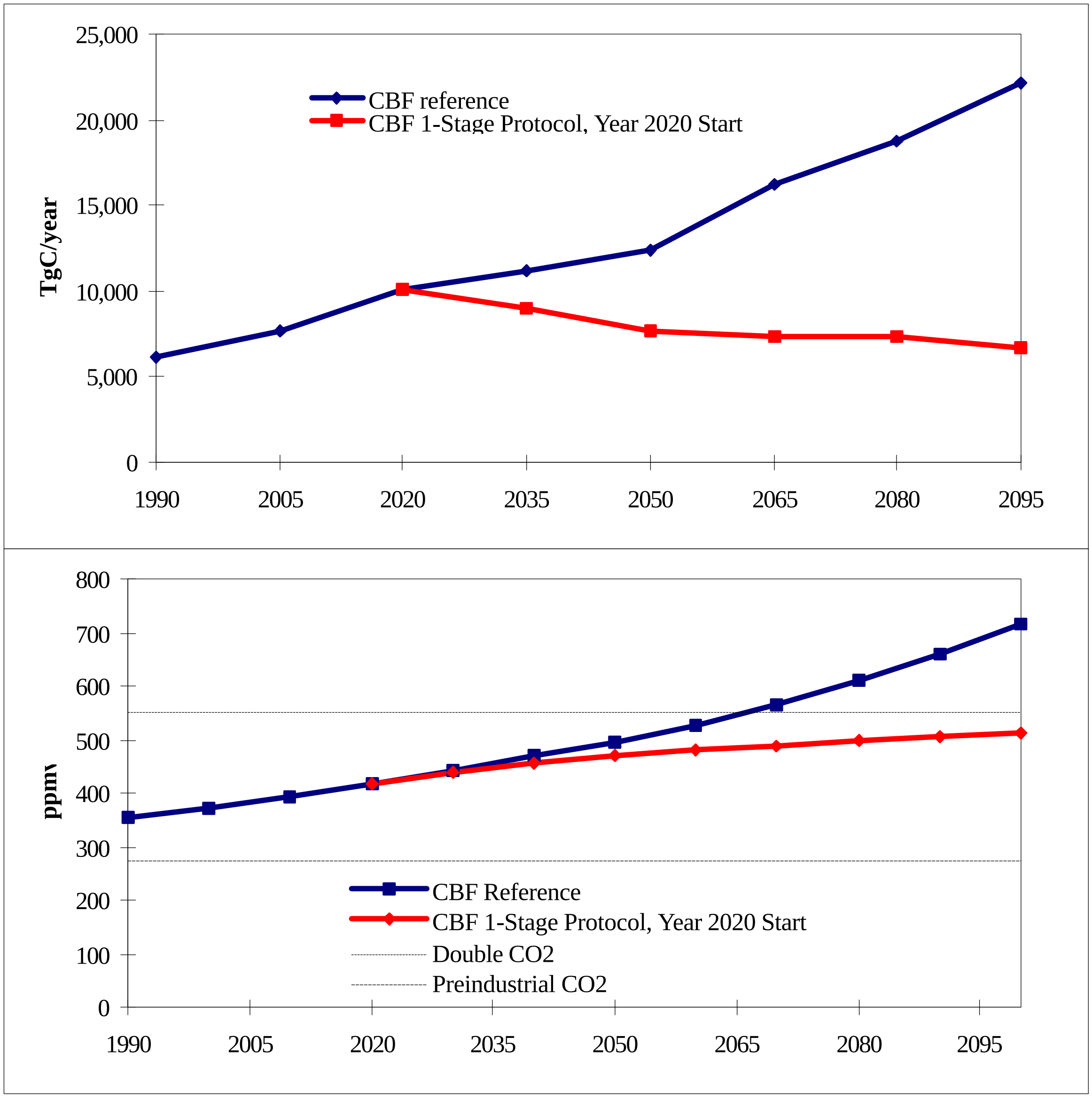

Figure 6. CBF: Global Carbon Emissions and CO_2 Concentrations

The effect of the protocol causes global carbon emissions to peak in the year 2020 at less than 11 PgC/yr and to decline thereafter. Non-carbon energy forms increase their market share, while reductions in energy intensity reduce the scale of the energy system. By the end of the century more than 70% of the global energy system is provided by non-carbon fuels. On the other hand, coal remains a major energy form. More than 400 EJ of energy is provided by coal. Coal production in the year 2100 exceeds the scale of the world's entire energy system in the year 1990.

The reduction in carbon emissions is accomplished by diminishing the role of unscrubbed coal in the second half of the next century. Unscrubbed coal is replaced by a mix of energy carriers including scrubbed coal, nuclear, solar, biomass, and improvements in energy intensity. The largest single change in the energy system in response to the protocol is the increased use of commercial biomass energy.

In the CBF case cumulative carbon capture amounts to approximately 335 PgC over the years 2020 through 2095. This is comparable with upper estimates for the available repositories in depleted oil and gas wells given in Table 3. The magnitude of carbon captured and sequestered is growing rapidly at the end of the next century, however. By the year 2095 it has reached more than 9 PgC/yr. This is half again as large as total global fossil fuel carbon emissions in the year 1990, and half of the year 2095 CBF reference case emission.

The peak of emissions in 2020 and subsequent decline causes the concentration of CO_2 to remain below 550 ppmv, the concentration double that of the pre-industrial era, throughout the next century with the year 2095 concentration at 511 ppmv.

The OGF Case

The OGF case is more complicated. By hypothesis oil and gas are available throughout the next century at prices that are near current levels. The extended oil and gas reservoirs are hypothesized to be distributed throughout the world - unlike coal, which is highly concentrated in the OECD, EEFSU and China. Oil and gas dominate the global energy future in the long term. By the end of the next century, oil and gas account for approximately 40% of the global energy system, as displayed in Figure 7. Conventional oil and gas production peak in the year 2020 as in the CBF case; however, they are supplemented by the introduction of unconventional oil and gas resources, including heavy oils and liquids from tar sand formations, and gas from deep reservoirs, coal beds, and clathrate formations.

The role of coal is correspondingly reduced. There is less coal use in the OGF base case than in the CBF protocol case. On the other hand, coal production remains large. More than 400 EJ/yr are produced in the scenario. This amount exceeds total global energy production in 1990.

The availability of inexpensive unconventional oil and gas resources leads to an increase in the overall scale of the energy system, even though the underlying economic and demographic assumptions remain the same as in the CBF case. Whereas the CBF global energy system grew to approximately 1750 EJ/yr in the year 2095, the OGF global energy system is almost 100 exajoules per year larger.

As in the CBF, renewables play a major role in the reference case, accounting for almost 40% of global energy consumption by the year 2095.

Carbon emissions in the OGF case, Figure 8, are also larger by approximately one PgC/yr by the end of the next century. The less than proportional increase in carbon emissions relative to the increase in energy system scale increase between the CBF and OGF cases results from the lower carbon intensity of oil and gas relative to coal.

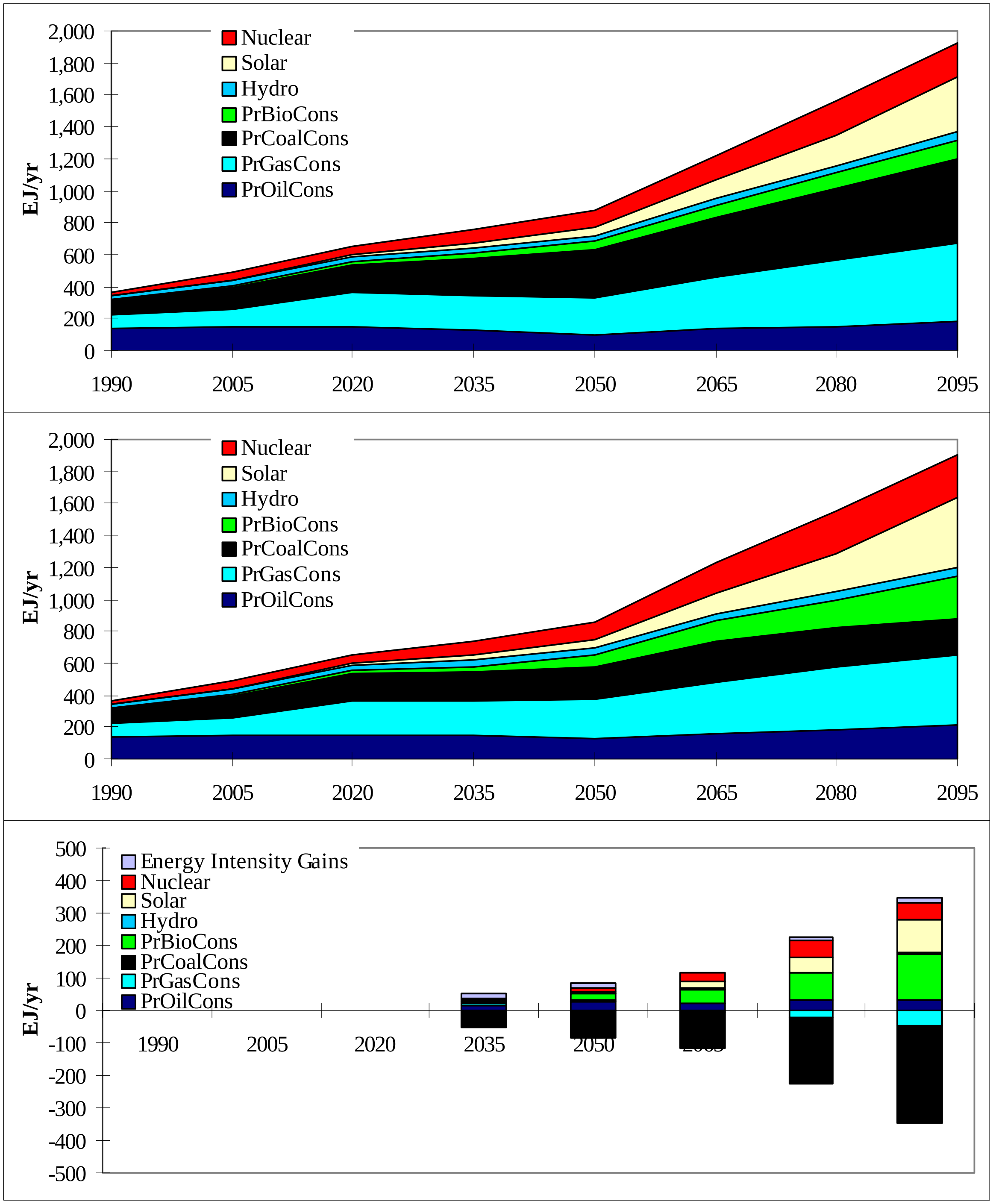

Figure 7. The OGF Global Energy System: Reference, Protocol, and Changes

The imposition of the protocol changes the shape of the energy transition. Demand for fossil fuels is depressed during the years 2020 through 2050, but increases thereafter. During the period 2020 through 2050 oil is replaced by natural gas, renewables and conservation technologies. Interestingly, there is little change in the role of coal, except that scrubbers are applied to some capacity, despite the relatively minor change in overall coal use.

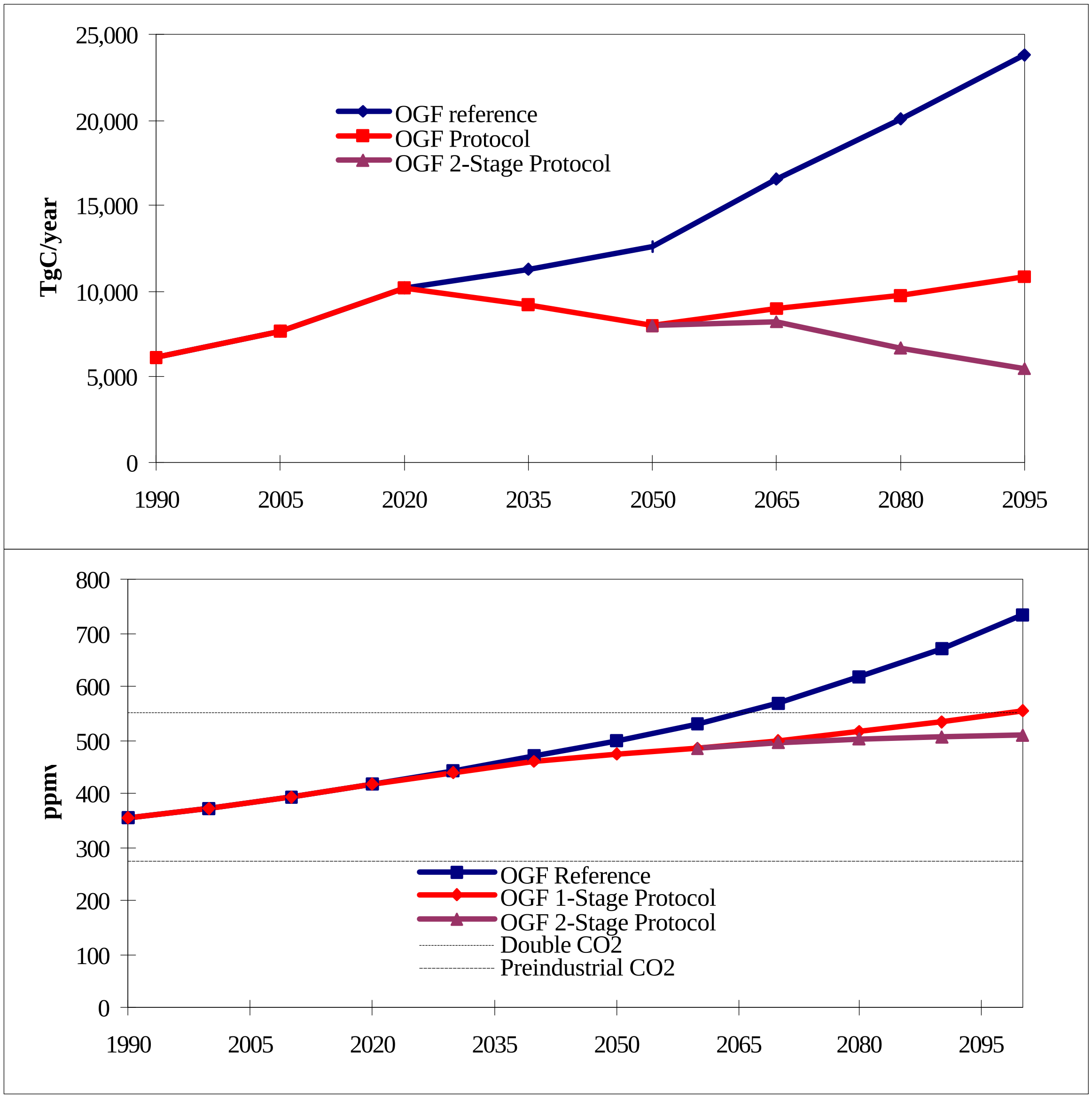

Figure 8. OGF: Global Carbon Emissions and CO_2 Concentrations

Cumulative carbon captured from scrubbing activities is similar to the CBF case, approximately 340 PgC, and is of a magnitude comparable to upper estimates of capacities in depleted oil and gas wells. Figure 9 shows the time profile of carbon captured, along with remaining emissions from fossil fuels, for both the CBF and OGF cases. As occurs in the CBF case, the magnitude of carbon captured in the OGF case grows rapidly, and annual capture is approximately 10 PgC/yr in the year 2095. Approximately two-thirds of cumulative capture occurs in the last third of the century. Clearly, by the end of the century reservoirs beyond depleted oil and gas wells will be required.

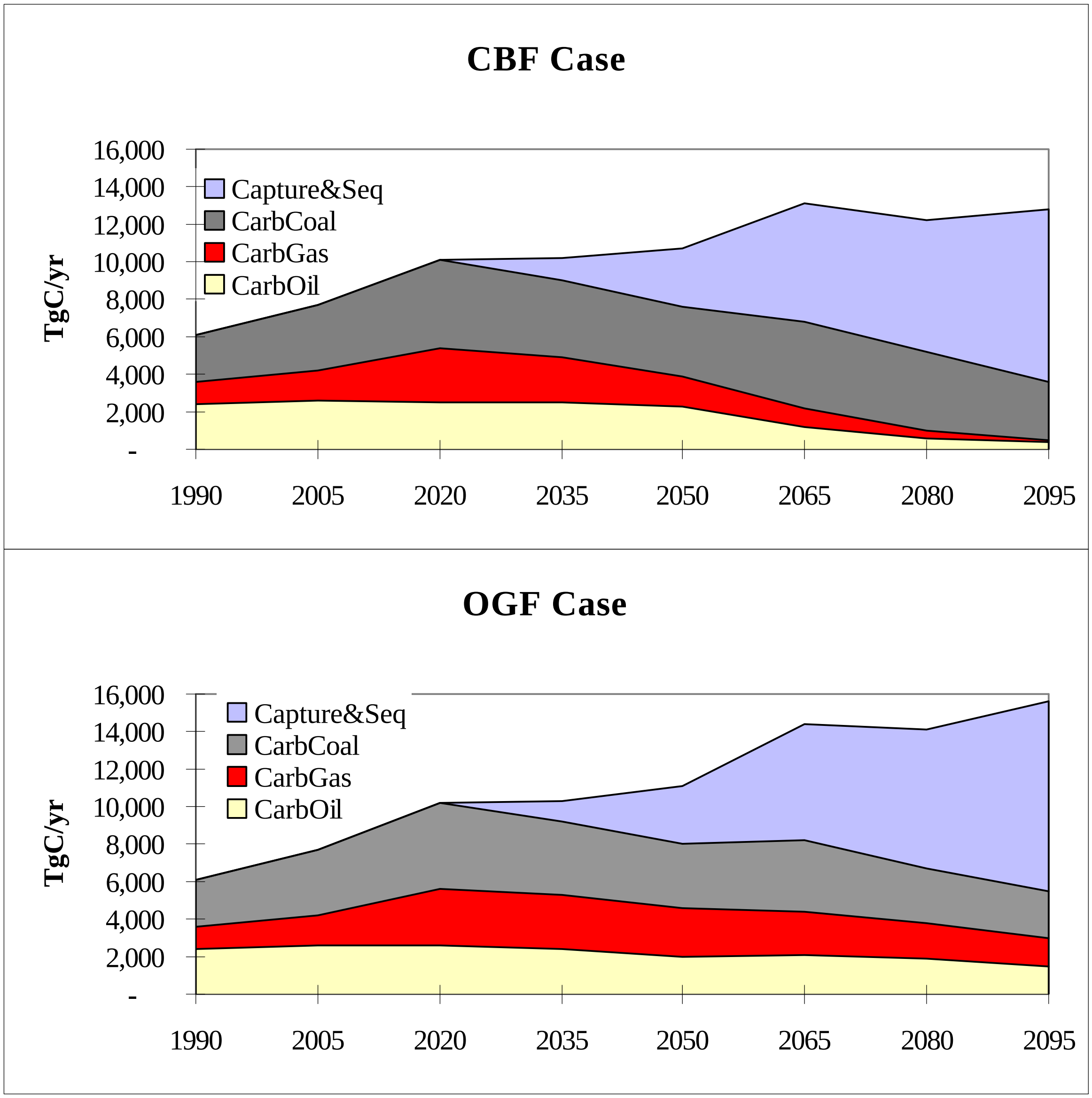

Figure 9. Global Carbon Emissions by Fuel, Capture and Sequestration

Carbon emissions in the OGF protocol case are substantially reduced during the years 2020 through 2050 relative to the OGF reference case, but rebound after 2050, as is shown in Figure 8. Still, overall emissions are sufficiently reduced that the concentration of CO_2 in 2095 is 555 ppmv, though rising. Emissions rebound because end-use fuels remain cheap. This is not what happens in the CBF case. Because coal provides the basis for liquids and gases in the CBF case, not only is the cost of transformation passed on to final consumers, but also the cost of capturing and sequestering the carbon that would have been previously vented in the transformation process. In the OGF case end-use fuels are available at the cost of extraction and refining. Thus in the OGF case not only do carbon emissions reflect growth in non-Annex I nations' economies, but also the growth in the non-electric sectors of Annex I nations.

TIGHTENING THE SIMPLE PROTOCOL

When oil and gas resources are available everywhere at relatively low cost, the concentration of CO_2 is not stabilized by the simple protocol, though the concentration is constrained to not exceed 555 ppmv in the year 2100. To stabilize the concentration requires an additional element in the hypothetical agreement. In addition to the three elements of the simple protocol, we require the following:

1. *Beginning in the year 2050, all new fossil fuel refining capacity in Annex I nations must remove and sequester carbon from fuels;*
2. *Imports of refined fossil fuel products are linearly phased out over the following 45 years; and*
3. *Non-Annex I nations which participate must undertake the same obligations that Annex I nations undertake when their per capita income, measured by purchasing power parity, equals the average for Annex I nations in 2050.*

Non-carbon fuels trade freely.

The above conditions commit Annex I initially, and non-Annex I nations upon graduation, to an energy system which is ultimately based on electricity and hydrogen as the final energy forms, with carbonaceous energy carriers provided by biomass. This does not mean that fossil fuels no longer play an important role in providing energy. It simply means that their role will be one of providing derived energy in the form of hydrogen and electricity, with the carbon removed and sequestered. The transition to a hydrogen based economy is managed incrementally over the entire second half of the twenty-first century.

The foundations for this transition may well be laid in the first stage of the commitment. To the extent that electric utilities develop fuel cell technologies, they have a strong incentive to develop hydrogen based fuel cells, as fuel cells based on carbon based fuels will be unavailable after the year 2020. To the extent that dispersed fuel cell power generation occurs, those fuel cells will require infrastructure. If the technology develops along a line which encourages residential and commercial fuel cell sites, the infrastructure will be in place for the further penetration of hydrogen technology into other markets such as transport.

When both the simple protocol and the above second stage are put into effect we will refer to the hypothetical arrangements as the “Two-Stage Protocol.” The effect of the Two-Stage Protocol in the context of the OGF case is to continue reductions in global carbon emissions, which in turn stabilizes the atmosphere at levels comparable to the One-Stage Protocol in the CBF case. The effect of the second stage on emissions and concentrations is shown in Figure 8.

TIMING

The date at which the protocol goes into effect strongly influences the concentration in the year 2100. The relationship between the concentration in the year 2100 and the year in which the protocol goes into effect in Annex I nations is shown in Figure 10. There is a clear upward trend in the relationship, later initiation dates leading to higher year 2100 concentrations. Initiation of the protocol in the year 2005 leads to a year 2100 CO_2 concentration of 447 ppmv for CBF and 468 ppmv for the OGF case. Obviously waiting to the year 2095 leads to the same concentration as in the unconstrained case. The relationship between initiation date and concentration appears to be approximately linear. Keeping the concentration of CO_2 below 550 ppmv requires that the first stage of the protocol be initiated between 2030 and 2040, depending on fossil energy technology developments.

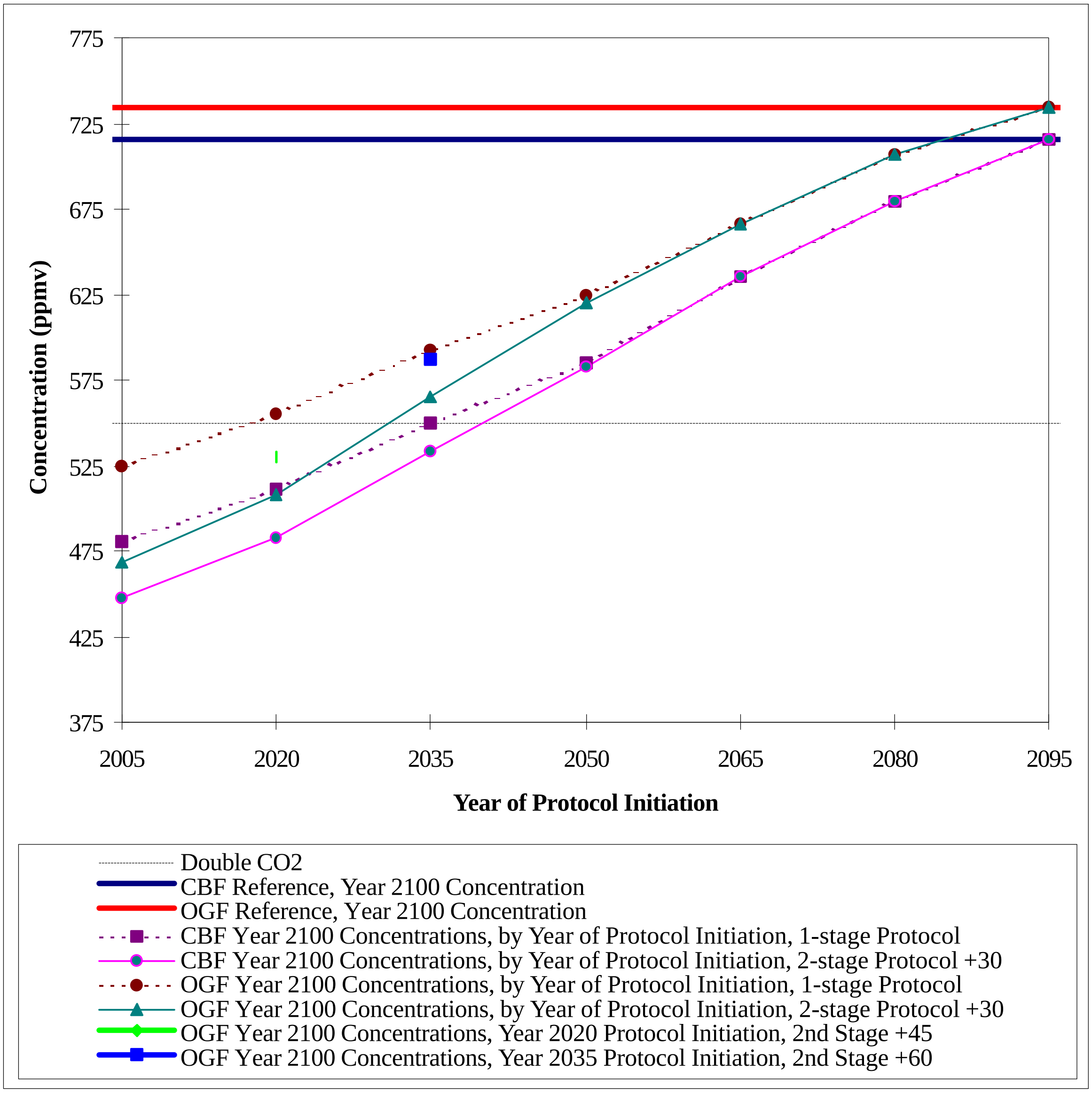

Figure 10. Year-2100 CO_2 Concentration vs. Initial Date of Protocol

The OGF reference case requires that both stages of the protocol be implemented to stabilize the atmosphere, while the CBF reference case does not. Even with the Two-Stage Protocol the OGF case has somewhat higher concentrations, attributable, as we have previously noted, to the lower cost of fossil fuels. Delaying the date of initiation of the second stage of the protocol in the OGF case increases the year 2100 concentration.

THE COST OF A TECHNOLOGY BASED PROTOCOL

Because the marginal cost of carbon control differs among sectors and among nations under the hypothetical protocol examined above, the cost of effecting atmospheric stabilization will be higher than under a regime in which carbon rights can be uniquely defined and a tradable asset can be created and exchanged. The latter system will minimize costs because there are no differences in costs over either time or space between marginal mitigation options. The hypothetical protocol is clearly a second-best option from the perspective of cost. Two questions naturally arise. First, how much more expensive is the technology protocol than an efficient system? And second, are there tools that would reduce the cost penalty?

Economic Cost

The economic cost of stabilizing the atmosphere with the hypothetical protocol is compared to the cost of an equivalent (in terms of annual emissions) spatially efficient policy in Figure 11 and Figure 12. Figure 11 provides annual costs for the protocol and the efficient cases under the CBF and OGF futures. Over the first half of the next century, the corresponding efficient cases are less expensive than the technology protocol by approximately 50 to 25%. During the second half of the next century, as nations come under the second stage of the protocol, the cost profiles for the protocols and the efficient cases tend to converge. This convergence is not surprising since the second stage of the protocol affects all fossil fuel carbon emissions, much like an ideally efficient mechanism would.

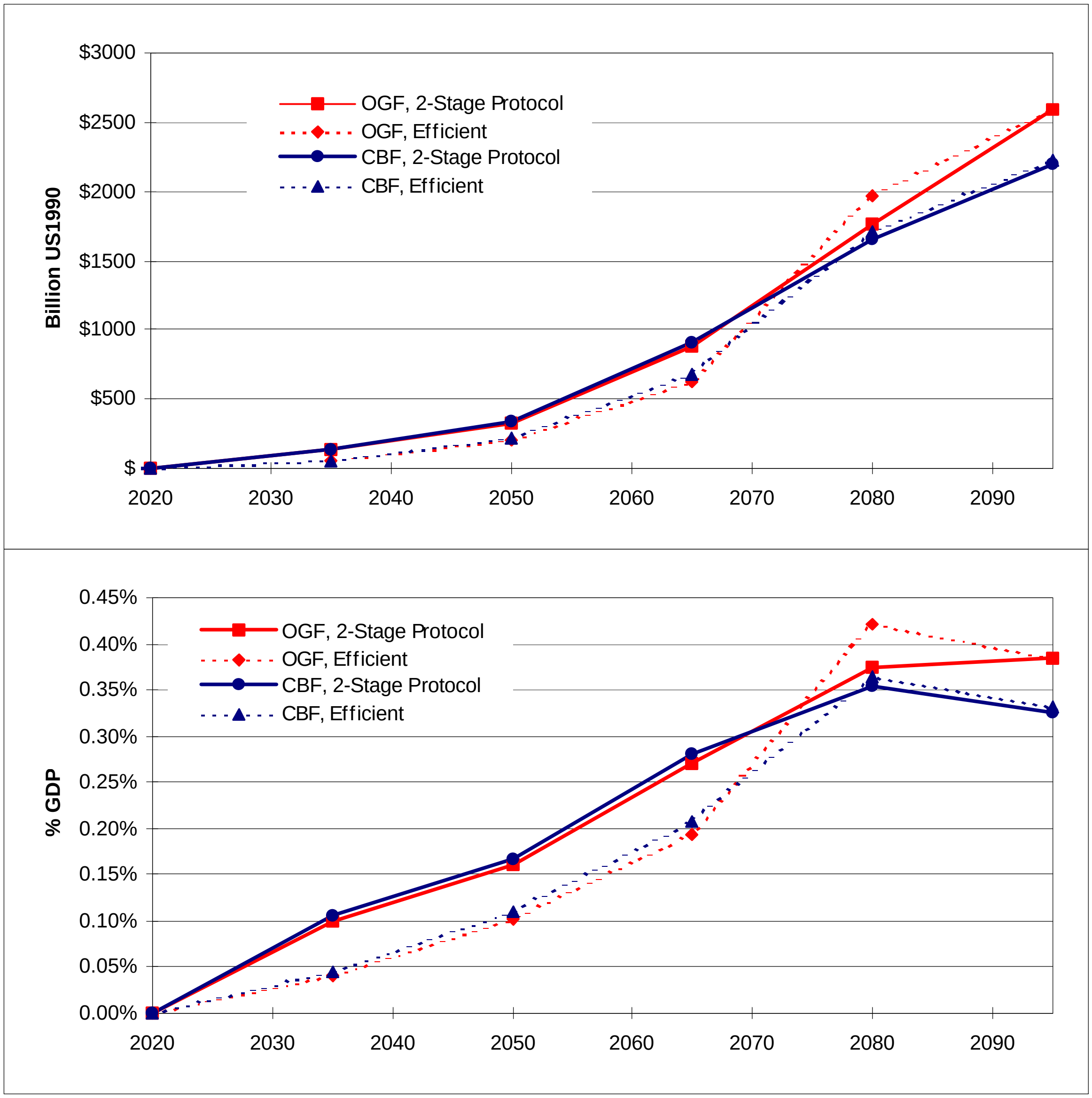

Figure 11. Comparison of Technology Protocol to Efficient Mitigation: Global Annual Costs

Note also from the figure that in year 2080 the efficient cases show slightly higher costs. Although this result is counterintuitive from a static analysis, it arises from the dynamics of higher costs in the earlier years of the protocol cases shifting investment away from fossil fuel production.

Perhaps a more complete assessment of the relative costs is given in Figure 12, where the present discounted costs from 1990 to 2100 at 5% are shown. For both the CBF and OGF futures, the technology protocol cases are about 30% more expensive over the next century than the corresponding efficient policies.

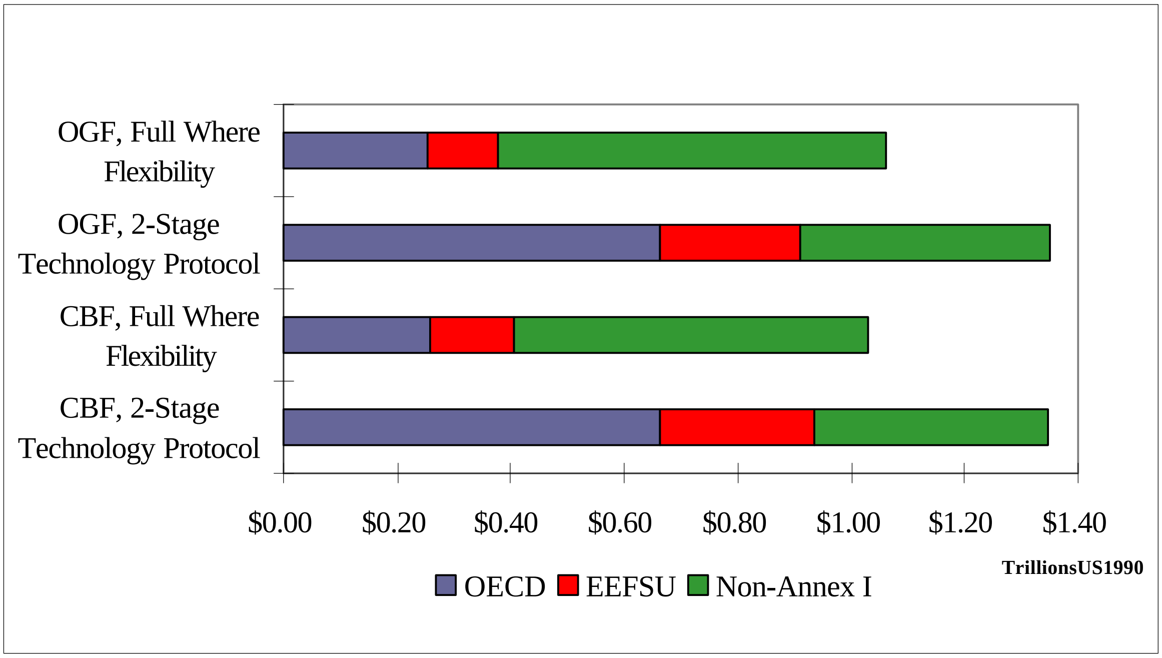

Figure 12. Comparison of Technology Protocol to Efficient Mitigation: Global Present Discounted Costs from 1990 to 2100

Reducing the Cost

Mechanisms to reduce the cost of implementing the hypothetical protocol might be added. Joint implementation (JI) measures hold some promise. For example, a fossil fired power plant might be allowed to continue to operate in an Annex I nation if it could be shown that emissions reductions of equivalent or greater magnitude had been achieved either in an uncontrolled sector or a non-obligated region. While it is not the purpose of this paper to consider JI, this avenue is being explored. The incentives for JI activities will be greatly enhanced under a program with real obligations.

CONCLUSIONS

There has been little work examining approaches other than taxes and tradable permits in the economic literature. This paper examines a hypothetical protocol focused on technology. The protocol requires new powerplant and coal based synthetic fuels capacity to scrub carbon from the waste gas stream in Annex I nations, and provides a mechanism by which non-Annex I nations can graduate into obligations. We examine this protocol under two alternative reference energy futures: one dominated by coal and the other dominated by unconventional oil and gas.

We show that under the coal dominated reference future (CBF) that the simple protocol effectively stabilizes the concentration of CO_2 in the atmosphere. If the protocol is initiated in the year 2020, the atmosphere stabilizes at approximately 510 ppmv, less than double the pre-industrial concentration. Under the unconventional oil and gas dominated reference future (OGF) the simple protocol holds concentrations to approximately double the pre-industrial level, but the atmosphere is not stabilized. Emissions are rising at the end of the century.

Atmospheric stabilization requires a second stage to the protocol beginning 30 years after the initiation of the simple protocol; the second stage would require that new refining and processing capacity remove all carbon from the fuel stream in Annex I nations, with imports of refined and process fuels phased out over a 45-year period and the same graduation mechanism for non-Annex I nations as in the simple protocol. The imposition of this second stage leads to the creation of an energy system utilizing hydrogen and electricity in end-use applications and enforces atmospheric stabilization in the OGF as well as the CBF.

The date at which the protocol goes into effect strongly influences the concentration in the year 2100. From this study, we found the year 2100 concentration of CO_2 approximately a linear function of the date at which the protocol is initiated in Annex I nations. Starting in 2005 gives a lower bound of CO_2 concentration levels reachable under the protocol, a level near 450 ppmv. Keeping the concentration of CO_2 below 550 ppmv requires that the first stage of the protocol be initiated between 2030 and 2040, depending on fossil energy technology developments.

The cost penalty associated with the hypothetical protocol varies with time. Initially, annual costs under the protocol are higher than an equivalent efficient policy. However, as the second stage of the protocol becomes effective in the later years, the inefficiency of the protocol diminishes. However, the present discounted costs of the technology protocols are still about 30% higher than efficient costs over the next century.

The inclusion of joint implementation mechanisms could reduce the cost penalty of the hypothetical protocol and is promising avenue for further work.

REFERENCES

Alcamo, J., A. Bouwman, J. Edmonds, A. Grübler, T. Morita, and A. Sugandhy. 1995. "An Evaluation of the IPCC IS92 Emission Scenarios," in ***Climate Change 1994: Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emission Scenarios***:247-304. Cambridge University Press, London.

Edmonds, J. and J. Reilly. 1985. ***Global Energy: Assessing the Future***, Oxford University Press, New York, pp.317.

Edmonds, J., M. Wise, D. Barns. 1995. "Carbon Coalitions: The Cost and Effectiveness of Energy Agreements to Alter Trajectories of Atmospheric Carbon Dioxide Emissions," ***Energy Policy***,**23**(4/5):309-336.

Edmonds, J., M. Wise, H. Pitcher, R. Richels, T. Wigley, and C. MacCracken. 1997a. "An Integrated Assessment of Climate Change and the Accelerated Introduction of Advanced Energy Technologies: An Application of MiniCAM 1.0," ***Environmental Modelling & Assessment***, (forthcoming).

Edmonds, J., Wise, M. and Dooley, J. 1997. "Atmospheric Stabilization and the Role of Energy Technology," forthcoming in ***Climate Change Policy, Risk Prioritization and U.S. Economic Growth***, American Council for Capital Formation, Washington DC. (pp15).

Edmonds, J., M. Wise, R. Sands, R. Brown, and H. Kheshgi. 1996. ***Agriculture, Land-Use, and Commercial Biomass Energy: A Preliminary Integrated Analysis of the Potential Role of Biomass Energy for Reducing Future Greenhouse Related Emissions***. PNNL-11155. Pacific Northwest National Laboratories, Washington, DC.

Herzog, H., E. Drake, and E. Adams. 1997. ***CO_2 Capture, Reuse, and Storage Technologies for Mitigation Global Climate Change.*** Energy Laboratory, Massachusetts Institute of Technology, Cambridge, MA.

Hourcade, J.-C., K. Halsnaes, M. Jaccard, Montgomery, W.D., R. Richels, J. Robinson, P.R. Shukla, and P. Sturm. 1996. "Estimating the Costs of Mitigating Greenhouse Gases," in ***Climate Change 1995: Economic and Social Dimensions of Climate Change. The Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change***. J.P. Bruce, H. Lee, and E.F. Haites (eds.). Cambridge University Press, Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change), 1995. ***Climate Change 1994: Radiative Forcing of Climate Change and An Evaluation of the IPCC IS92 Emissions Scenarios*** J.T. Houghton, L.G.M. Filho, J. Bruce, H. Lee, B.A. Callander, E. Haites, N. Harris, and K. Maskell. (eds.), Cambridge University Press, Cambridge, United Kingdom.

IPCC (Intergovernmental Panel on Climate Change), 1996. ***Climate Change 1995: Impacts, Adaptation, and Mitigation of Climate Change: Scientific-Technical Analysis. The Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change***. R.T. Watson, M.C. Zinyowera, R.H. Moss (eds.). Cambridge University Press, Cambridge, UK.

Richels, R., J. Edmonds, H. Gruenspecht, and T. Wigley. 1996. "The Berlin Mandate: The Design of Cost-Effective Mitigation Strategies." Forthcoming in ***Proceedings of the Workshop on Integrating Science, Economics and Policy,*** March 19-20, 1996, Laxenburg, Austria.

Rogner, H.-H. 1996. ***An Assessment of World Hydrocarbon Resources***. WP-96-56. International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria.

Steinberg, M. 1991. ***Biomass and Hydrocarb Technology for Removal of Atmospheric CO_2***, BNL-4441OR (Rev. 2/91), Brookhaven National Laboratory, Upton, NY 11973.

Steinberg M. and E.W. Grohse. 1989. ***The Hydrocarb Process for Environmentally Acceptable and Economically Competitive Coal-Derived Fuel for the Utility and Heat Engine Market***, BNL-43554, Brookhaven National Laboratory, Upton, New York.

United Nations. 1992. ***Framework Convention on Climate Change***. United Nations, New York.

Wigley, T.M.L., R. Richels & J. Edmonds. 1996. "Economic and Environmental Choices in the Stabilization of Atmospheric CO_2 Concentrations," ***Nature***. **379**(6562):240-243.