BUILDING BACKSTOP TECHNOLOGIES AND POLICIES TO IMPLEMENT THE FRAMEWORK CONVENTION ON CLIMATE CHANGE

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ABSTRACT

The goal of the Framework Convention on Climate Change is to stabilize the concentration of greenhouse gases in the atmosphere at levels which avoid dangerous anthropogenic interference with the climate (United Nations, 1992). No consensus currently exists with regard to a concentration that can be regarded as "safe," and the issue remains subject to debate, fuelled at least in part by the enormous difficulties in predicting and valuing the consequences of climate change.

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 efficient instruments have 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, which might serve as a "backstop" in the event that efficient policy instruments could not be employed. 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 backstop 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.

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

This has led researchers to examine a range of concentration ceilings. To date, researchers have examined the cost and character of efficient, cost-minimizing, policy instruments. They have focused primarily 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 efficient instruments have their own difficulties, not the least of which is the fact that a great deal of money can potentially change hands, when taxes are applied or when emission permits are distributed. And these monies can exceed the cost of emissions mitigation itself.

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 might provide a backstop on emissions, which could be employed to stabilize the concentration of greenhouse gases in the event that negotiations to establish a globally efficient system stalled. The instruments examined here 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 focus 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.

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.

Assumptions

Key assumptions behind the scenarios are discussed in further detail in Edmonds and Wise (1997) . In brief, these assumptions create scenarios with a steady-state population of approximately 11 billion people, and rising per capita incomes around the world. In addition, many, but not all, developing countries close the per capita income gap with the presently developed world. The principal difference between the **CBF** and **OGF** scenarios is that former has abundant coal resources but limited conventional oil and gas resources, while the latter has abundant conventional oil and gas resources in addition to abundant coal.

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 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 with operating efficiency penalties of 10% to 20% and capital and other non-energy cost penalties of 20% to 50%, depending on the carbon content of the fuel (Edmonds and Wise, 1997).

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 1.

Table 1: 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

A HYPOTHETICAL "BACKSTOP" PROTOCOL

We initially explore a three-part, hypothetical "backstop" 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 1 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.

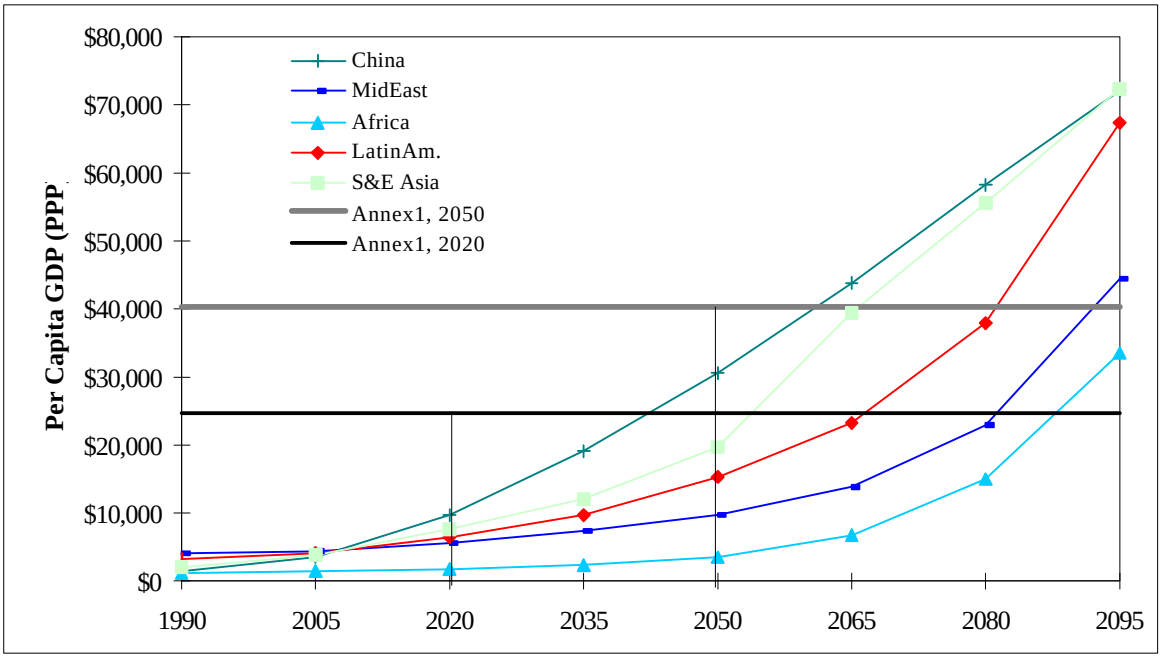

Figure 1. Non-Annex I Graduation into Protocol

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 2. 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. Coal supplies are assumed to be fairly elastic, and this expansion of production occurs with roughly a doubling of 1990 real coal prices.

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 real 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.

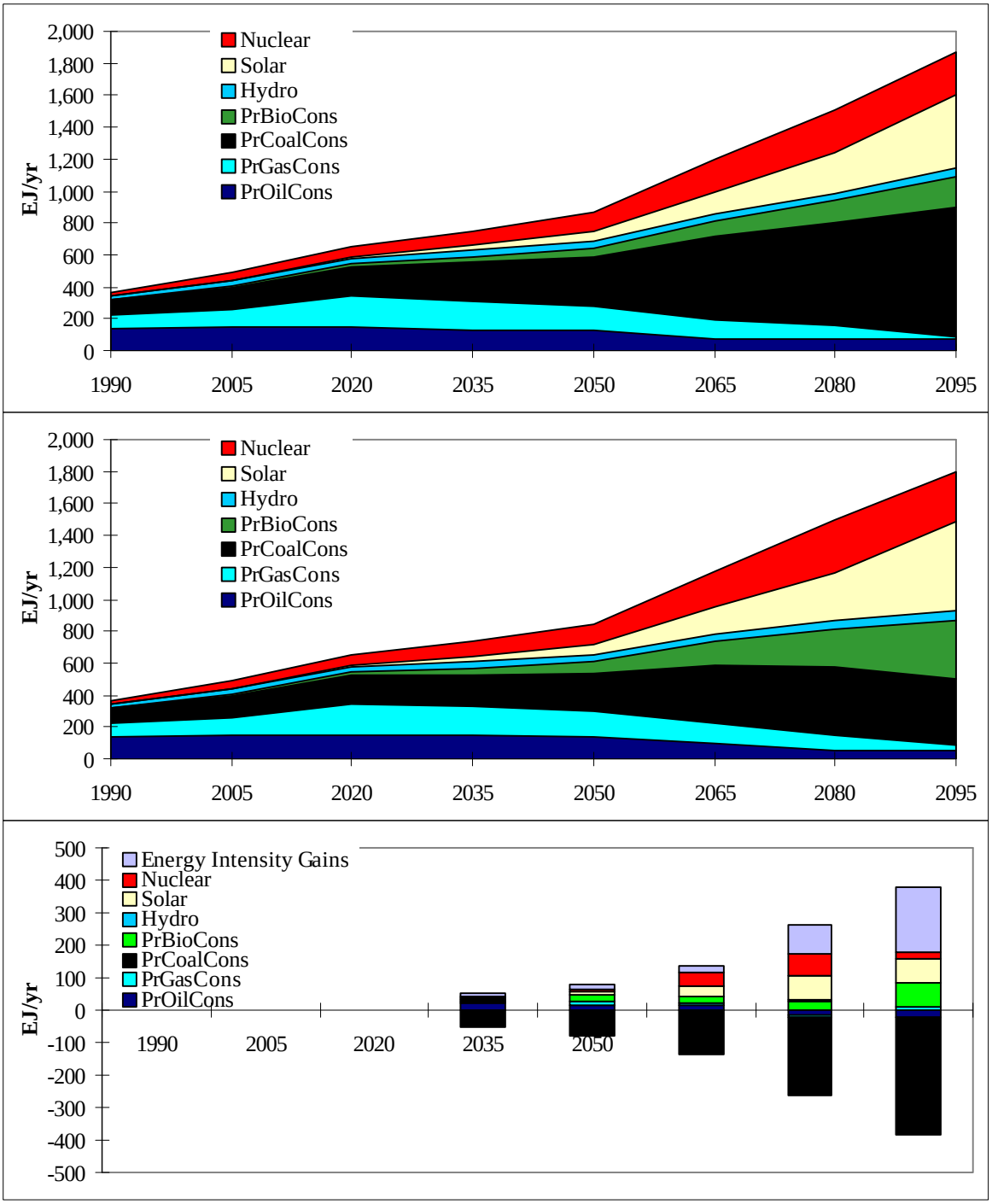

Figure 2. The CBF Global Energy System: Reference Case, Protocol, and Changes

CBF reference carbon emissions and concentrations are shown in Figure 3. 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.

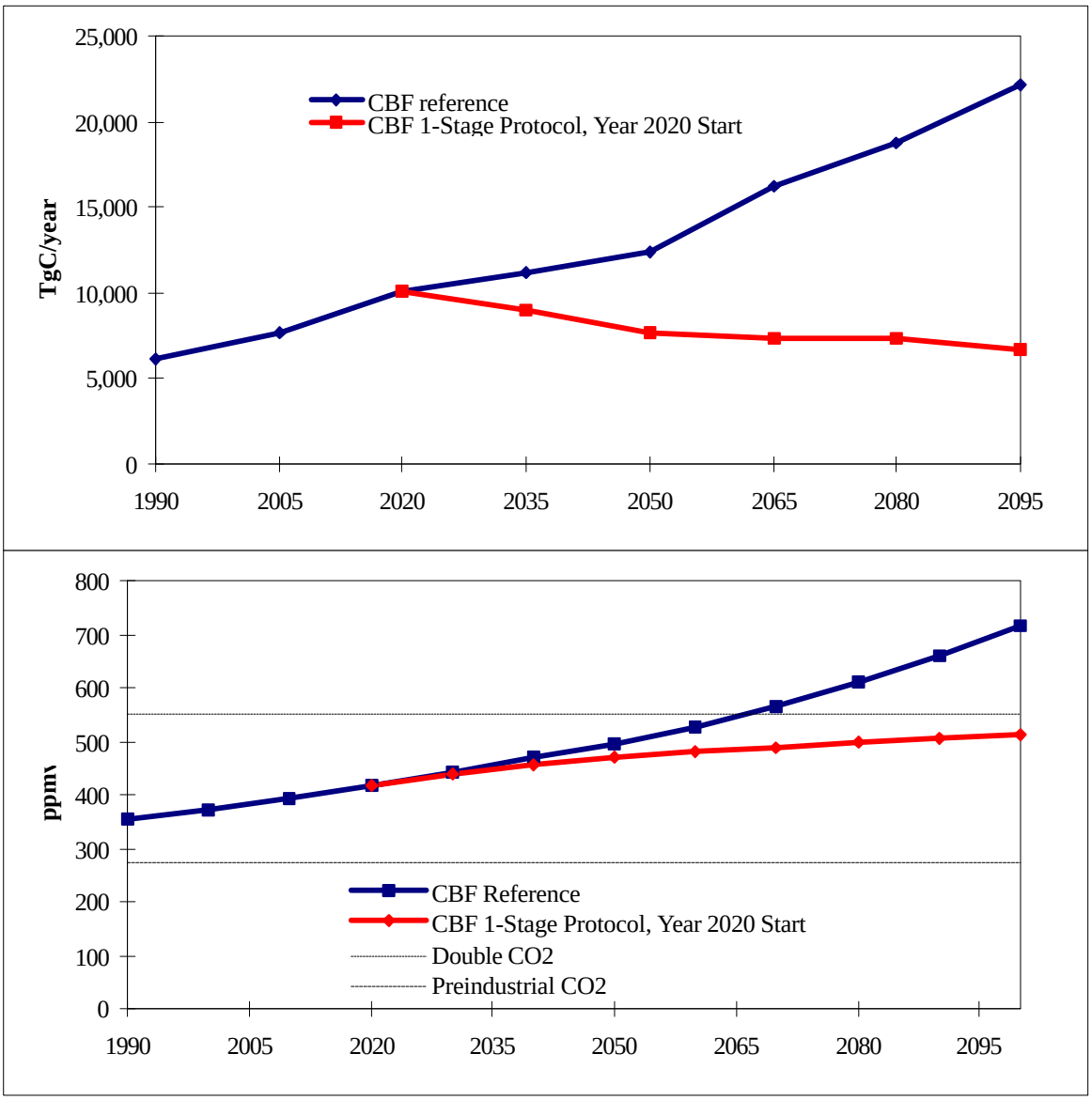

Figure 3. CBF: Global Carbon Emissions and CO_2 Concentrations

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. 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, a 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 4. 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 5, 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.

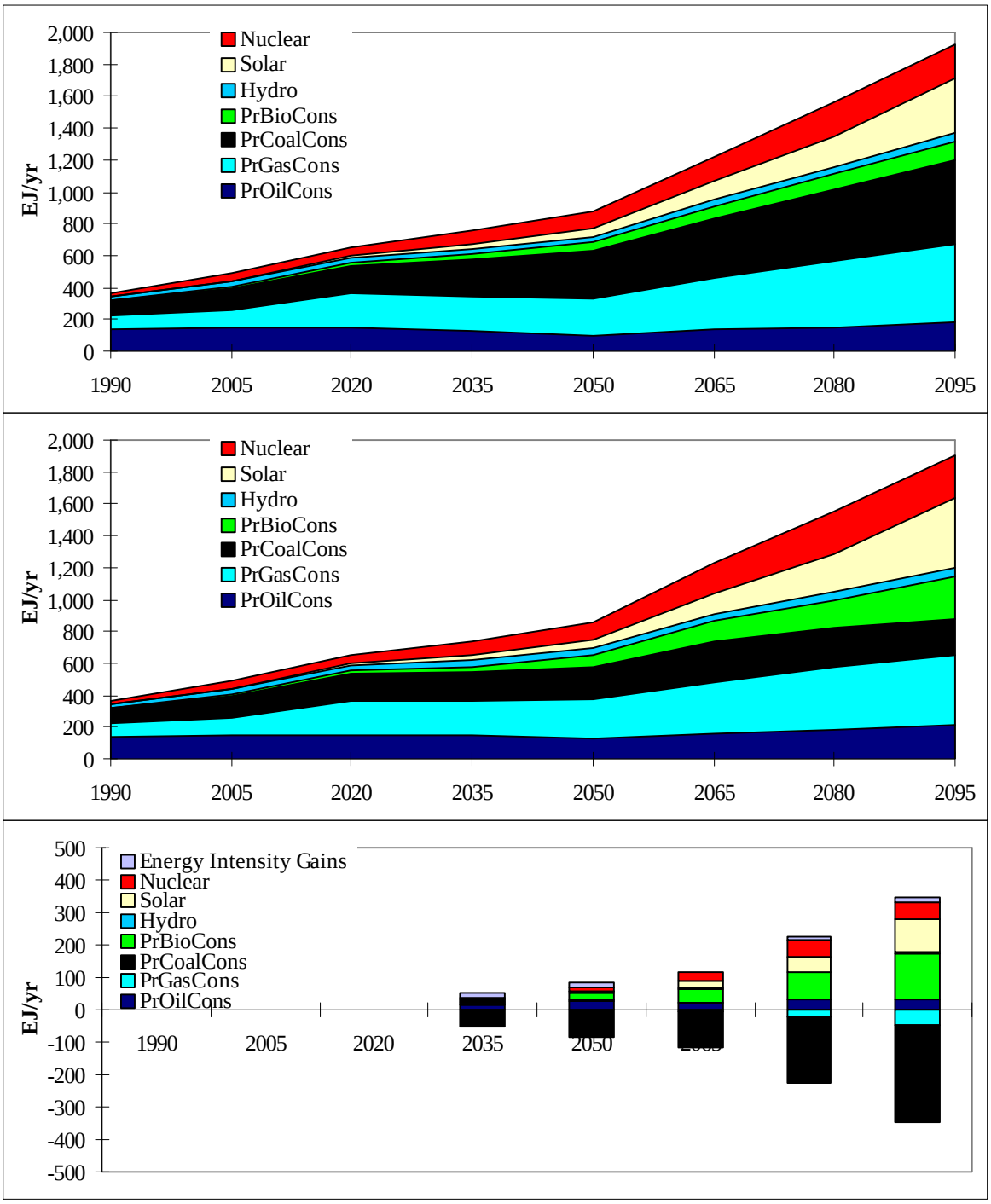

Figure 4. The OGF Global Energy System: Reference, Protocol, and Changes

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.

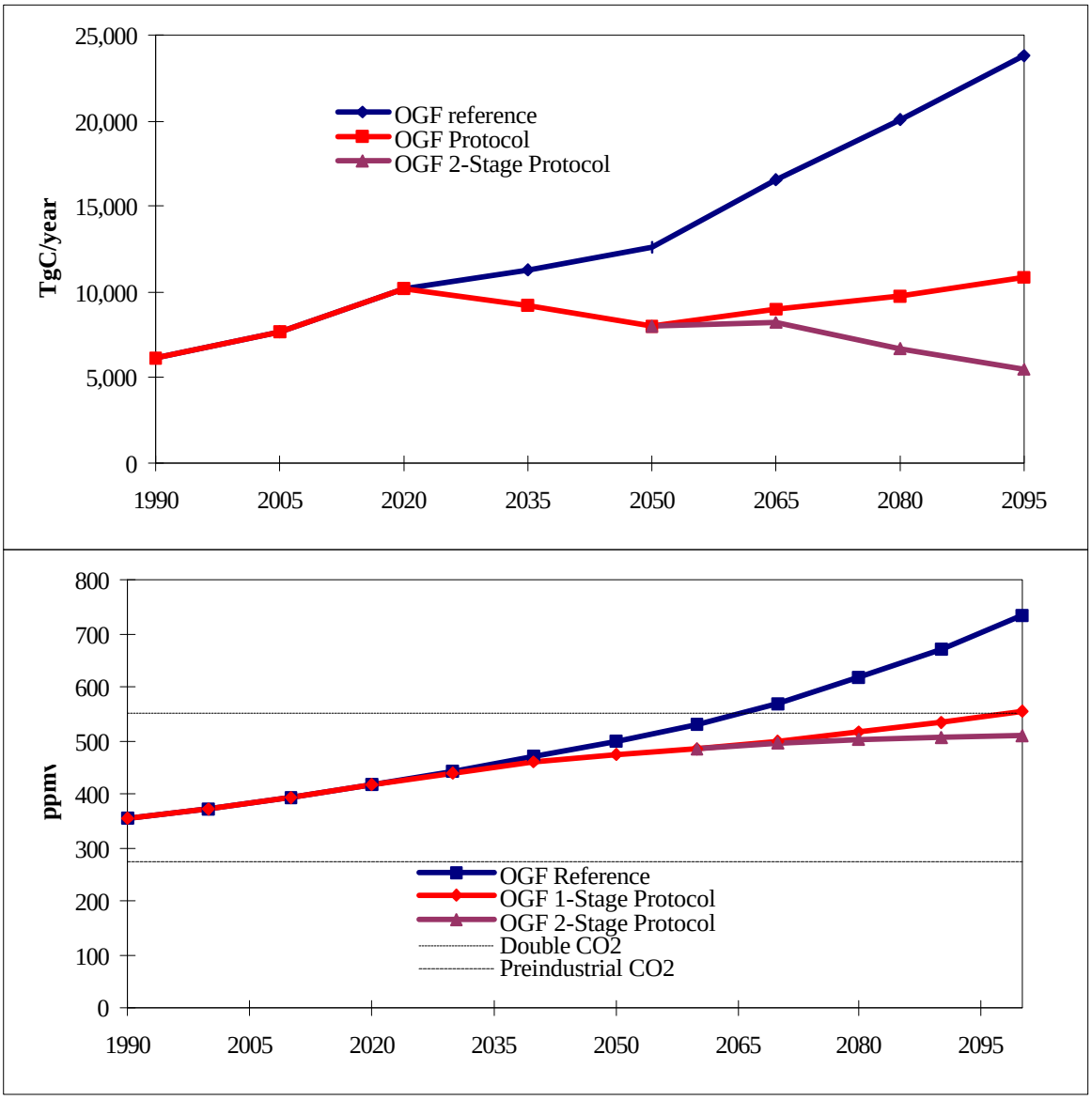

Figure 5. OGF: Global Carbon Emissions and CO_2 Concentrations

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. 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.

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 5. 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 are assumed to trade freely.

The above conditions commit Annex I nations 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 fossil 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 5.

THE COST OF A TECHNOLOGY BASED PROTOCOL

The economic cost of stabilizing the atmosphere with the hypothetical protocol is compared to the cost of an equivalent (in terms of annual emissions) efficient policy in Figure 6 and Figure 7. Figure 6 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.

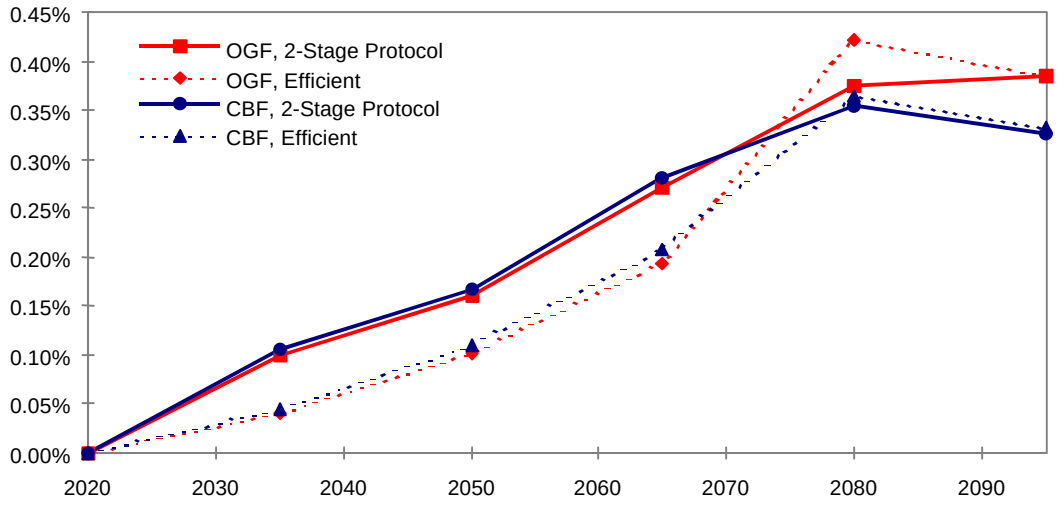

Figure 6. Comparison of Technology Protocol to Efficient Mitigation: Global Annual Costs

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.

The comprehensive assessment of the relative costs is given in Figure 7, where the present discounted costs from 1990 to 2100 at a discount rate of 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.

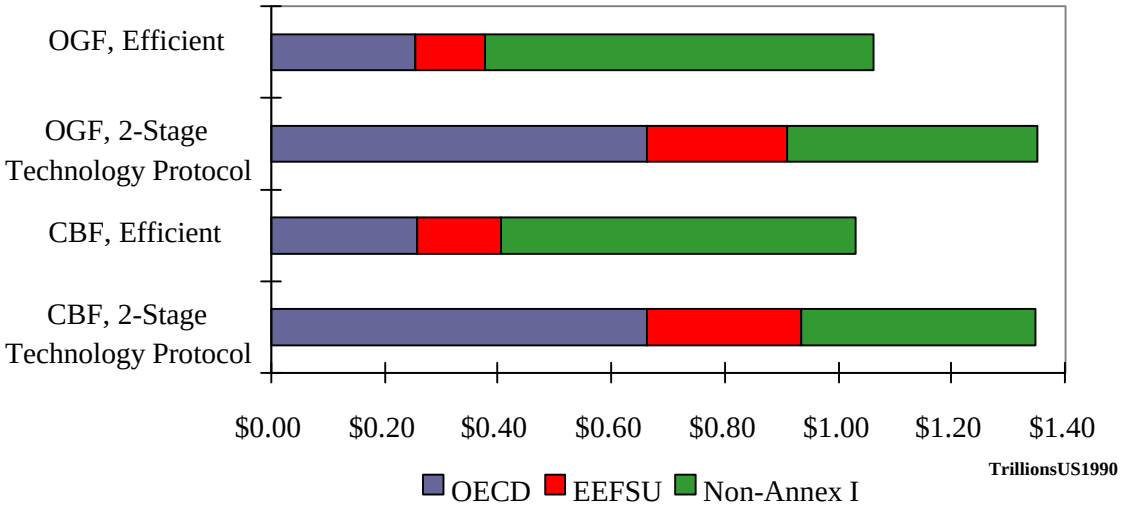

Figure 7. Comparison of Technology Protocol to Efficient Mitigation: Global Present Discounted Costs from 1990 to 2100

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) 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 21st 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 cases.

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 backstop 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 a promising avenue for further work.

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