Climate Change Mitigation Costs: The Roles of Research and Economic Reform

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Abstract: The authors have applied the MiniCAM energy-economic model to estimate the economic costs of strategies for mitigating greenhouse gas emissions. The primary focus of the paper is a supply-side strategy: the application of low-cost, low-carbon energy production technologies over the next century. Results are summarized for six advanced technology scenarios. The authors also consider the economic impact of one demand-side strategy: reducing emissions by improving energy end-use intensity in transition economies over the next 20-30 years. This strategy is represented by one scenario of economic rationalization and reform in the formerly-planned economies.

The findings indicated that even with relatively low rates of market penetration, new energy supply technologies could result in a dramatic reduction in mitigation costs. For example, when advanced biomass technologies reached even 25 percent of the global energy supply market, total discounted mitigation costs to 2100 fell from $2.2 trillion to $790 billion. When these technologies were deployed in conjunction with an emissions stabilization path that allowed for a later onset in reductions, costs fell to $207 billion.[1]

The results have important implications for both the models and the policies that they inform. First, findings suggest that technology can generate cost savings in both the United States and formerly planned economies in Eastern Europe and the New Independent States. These cost savings increase with the effectiveness and level of penetration of the advanced energy technologies, a relationship that holds across emissions paths and levels of stabilization. Second, the finding suggest that previous macroeconomic modeling efforts have overestimated the costs generated by the inefficient formerly planned economies.

Introduction

This study uses a mixed energy-economy model to address two types of issues: questions about how advanced energy technologies, such as low-cost biomass and solar technologies, might affect the costs of mitigating CO_2 emissions in different regions; and questions about the validity of macroeconomic modeling efforts when applied to formerly planned economies.

Leading macroeconomic models have traditionally treated planned and formerly planned economies as if they mimicked market economies.[2] As a result, the distorted sectoral structures

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and antiquated technologies inherent in planned economies are carried forward in the model but not in reality. The impact of post-Soviet economic restructuring, and its subsequent effects on technological improvement and energy efficiency, goes unacknowledged.

We constructed a series of cases reflecting changes in energy technology and energy efficiency for a model called MiniCAM, which we describe below, in order to address technological change and economic costs in formerly planned economies. Specifically, we asked:

- What does the application of a set of technology cases imply about the role of technological innovation and the cost of emissions reductions?

- What do the cases imply about regional costs and the impact of introducing advanced energy technologies in different economies?

Approach

The MiniCAM 2.0

We employed the MiniCAM 2.0 model (Mini Climate Assessment Model), to assess the potential implications for technologies to reduce fossil fuel CO_2 emissions mitigation costs. The MiniCAM 2.0 is an integrated assessment model with four major component parts: Human activities, Atmospheric Composition, Climate and Sea Level, and Ecological Systems. The model considers both energy and land-use change explicitly and interactively. The energy system model is the Edmonds-Reilly-Barns (ERB) model (Edmonds and Reilly, 1985), while the agriculture land-use model (ALM) was developed explicitly for MiniCAM 2.0. The approach to modeling atmospheric composition, climate change, sea level, and economic damages is the same as in MiniCAM 1.0 (Edmonds, Wise and MacCracken,1994).

The MiniCAM model is a "top-down" energy-economy model with "bottom-up" assumptions about end-use efficiency. The model provides output for 9 regions and for the world as a whole. Selected runs were also performed to provide insight into the relative effects on and importance of Annex 1 and Annex 2 countries, as defined by the Framework Convention on Climate Change.[3]

Construction of the Reference Case

This study uses the reference case from Wise, et al. (1996). The assumptions for this case are outlined in Appendix A. The reference case was constructed using a combination of sources. For the year 1990, we benchmarked energy and carbon emissions results to the United States Department of Energy's International Energy Outlook (DOE 1995) which based its estimates on data from the International Energy Association (IEA). For the period 1990 through 2010, we tuned MiniCAM to produce results similar in character to the World Energy Outlook (WEO) "Capacity Constraints Case" (IEA 1995). For the period from 2010 through 2050, we approximated reference projections of carbon emissions based on the growth rates in the Intergovernmental Panel on Climate Change (IPCC) IS92a case over those years. The IPCC

IS92a case represents a projection of a "business as usual" scenario for certain baseline indicators such as population and economic growth, and it is used as a standard baseline to provide comparability among different models.

The main difference between the WEO and IS92a scenarios lies with the estimates of emissions from the countries of the Former Soviet Union (FSU). The IS92a estimates were made at an earlier point in time when the full impact of the recent decline in emissions in the FSU was not known. Because of the manner in which the cases in this study are constructed, it was critical to use a more accurate estimate for 1990 emissions and a more recent projection of emissions growth. We emphasize that this reference case is chosen not because it is particularly likely. No specific emissions case is likely. Rather, it is based on well defined studies accessible in the open literature, and it provides a global emissions trajectory which is well within the range of trajectories found in the published literature (IPCC, 1995).

The Advanced Technology Cases

Based on the modified IS92a assumptions, we constructed 48 advanced technology scenarios based on combinations of four parameters: technology set, effectiveness level, concentration goal, and emissions path.

Technology Sets

Table 1 shows the assumptions used for the reference case and the six technology sets.

Table 1
Technology Scenarios

Scenario Name	Scenario Assumptions
REF	Baseline Case • IPCC IS92a case under the WG1 or WRE 550 ppm CO_2 concentration emissions paths
AFF	REF with Advanced Fossil Fuel technologies: • Fossil Fuel technologies reach 66% efficiency by 2050 (from 33% in REF)
BIO	REF with Low Cost Biomass: • by 2020, 20% of Biomass resource available at $1.40 / GJ; 80% available at $2.40 / GJ (from $2.50/$4.40 in REF)
BioAH2	BIO with Advanced Hydrogen Fuel Cell technologies available in 2020: • Hydrogen fuel cells used to power transportation • Hydrogen available from (1990 US$ per GJ; Williams)

	• Natural Gas Steam Reforming @ \$1.71 + P_{gas} / 0.901 • Biomass BCL Gasifier @ \$4.83 + $P_{biomass}$ / 0.784 • electrolysis @ \$2.36 + P_{elec} / 0.900
BioNH2	BioAH2 with additional costs for liquefaction and other (Rogner) • Liquefaction @ \$3.90 / GJ • Fuel Storage @ \$1.16/GJ • Fuel Cell Lifecycle Capital Cost @ \$138 / GJ
SOL	REF with Advanced Solar Technologies • Cost of solar power reaches busbar cost of \$0.04/kWh by 2020 and decreases by 0.5% per year thereafter
ALL	REF with AFF, BioAH2, and SOL technology assumptions

Effectiveness Levels

The assumptions in Table 1 describe the costs and efficiencies for the fully effective technology sets. To determine the relative impacts of achieving intermediate cost and efficiency goals, we added three additional levels of effectiveness to the fully effective, or 100-percent, technology sets: 25-, 50-, and 75-percent effectiveness. The assumptions for these scenarios were derived by interpolating linearly between the technology assumptions for reference and 100 percent effectiveness scenarios. For example, the AFF50 scenario uses a fossil fuel technology efficiency level of 49.5 percent, halfway between the 33 percent level used in the reference case and the 66 percent level used in the AFF100 scenario. In the remainder of the paper, technology cases will be referenced by their scenario name and their effectiveness level (i.e., AFF25 to represent the 25% effectiveness level of the Advanced Fossil Fuel technology case).

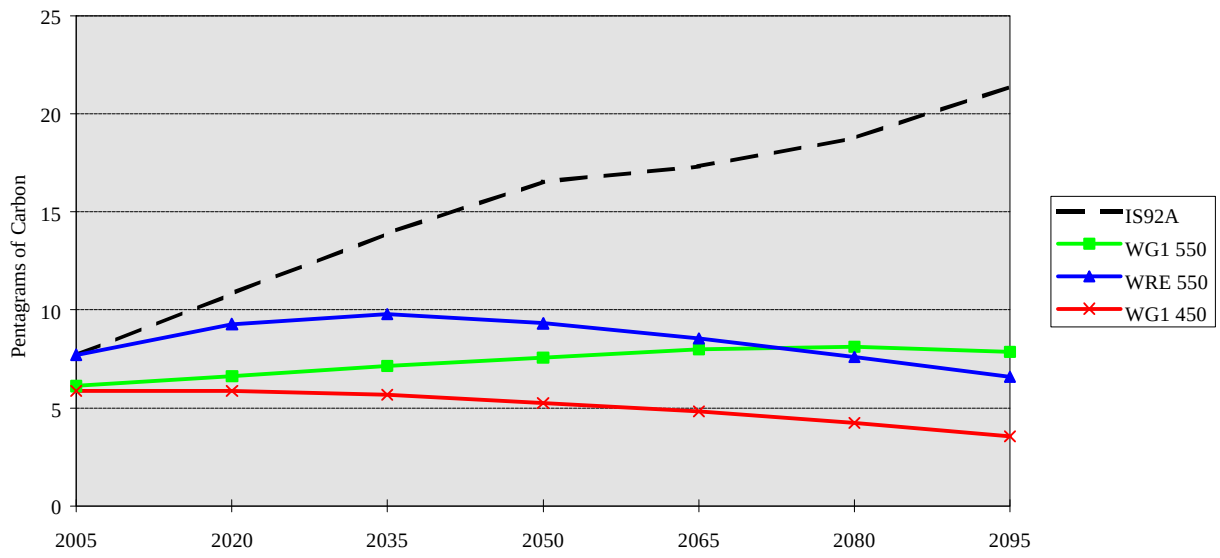
Differentiated effectiveness levels also allowed us to examine the possible effects of uneven distribution of advanced technologies across world regions. For example, if an advanced technology were to penetrate only 50 percent of a regional or world market, its benefits could be significantly less than if the entire world market had access to it. Current barriers to trade and investment in certain world regions indicate that the diffusion of technologies is not likely to be uniform. Therefore, four additional scenarios were added to assess the costs of a failure to introduce technologies into the energy-intensive EUSSR region: 1) an Annex 1 scenario, where only the EUSSR and OECD regions received the ALL100 technology set; 2) an Annex 2 scenario, where only the OECD regions received the ALL100 technology set; 3) a scenario where 100 percent of the OECD region and 25 percent of the EUSSR region received the technology set; and 4) a scenario where 100 percent of the OECD region and 50 percent of the EUSSR region received the technology set.

Emissions Paths and Stabilization Levels

We used two carbon emissions paths for this study, each of which was run with all of the above technology sets and effectiveness levels. Both global emissions paths result in CO_2 concentrations of 550 ppm in the year 2100. The MiniCAM must solve each period to meet the emissions level specified in the chosen path. Figure 1 shows the two emissions paths used for this assessment and the MiniCAM IS92a emissions trajectory. The Wigley-Richels-Edmonds (WRE) trajectory departs gradually from the IS92a path and has its most severe restrictions in the later half of the century. The IPCC Working Group I (WG1) series, on the other hand, begins in 2005 with severe limitations and allows limited growth in emissions until 2080. The difference in the timing of the emissions reductions has significant impacts on the costs of meeting those trajectories.

Figure 1 also shows the emissions trajectory for the WG1 450 ppm CO_2 concentration emissions path. Unlike the WG1 550 ppm path, the 450 ppm trajectory does not allow for any emissions growth over the next century. We ran several of the technology sets with this emissions path to compare the cost implications of this more ambitious concentration goal with the 550 ppm path.

Figure 1
Comparison of the Base Case and Three Emissions Trajectory Scenarios by Path and Stabilization Level



Energy Intensity

In order to reflect recent changes in energy use in the EUSSR region, we constructed a variation of the WG1 reference scenario to examine the impacts of energy intensity on mitigation costs. The adjusted path reduces the EUSSR's energy intensity level to United States levels by 2020, 40 years earlier than in the reference case.

The MiniCAM includes an exogenous variable for end-use intensity improvement that is expressed as an annual percentage; it, in turn, affects primary energy consumption. The rate of end-use energy intensity improvement is assumed to be the same for all three end-use sectors in the formerly planned economies.

The MiniCAM reference case produces large differences in energy intensity between the United States and the formerly planned economies in the EUSSR region through 2020. Significant differences in intensity persist between those regions and China through 2080. In 2005, for example, the EUSSR's rate of energy intensity improvement is more than 150 percent that of the United States region, while ACENP countries have rates more than 540 percent higher.

The high levels of energy intensity assumed for ACENP and EUSSR countries in the very near future are consistent with what is known about the inefficient use of energy in formerly planned economies, largely due to market inefficiencies and a previous emphasis on the development of heavy industry.[4] However, these high levels of energy intensity continue to exist in the model even after 1990, when primary fuel prices for most fuels have converged in the model.[5] The assumed trends in energy intensity are also problematic because they do not reflect recent history; other studies have shown them to be unlikely.[6] Although energy intensity has been high in China's recent past, the rate of improvement in energy intensity has also been very high. Over the past decade, China's rate of energy intensity improvement has consistently been equal to half of its GDP growth rate. The demand-side energy intensity improvement scenario for the EUSSR is included to better understand the impacts of the regional energy intensity assumptions on the costs of meeting the WG1 emissions path.

Calculation of Costs

The technologies were evaluated on the basis of their costs in meeting the concentration goal. The total cost of meeting the desired CO_2 concentration emissions trajectory is defined as the sum of the product of each unit of emissions reductions and the marginal cost to the economy of making those reductions.

$$Total\,Cost = \sum (Q_{ER} * MC_{ER})$$

where,

QER is a unit of emissions reductions,

MCER is the marginal cost of mitigating that unit of emissions.

The marginal cost of reducing the emissions is equal to the carbon tax necessary for the same amount of mitigation. Emissions reductions are defined as the difference between CO_2 emissions without taxes and emissions with taxes. If pre-tax emissions are greater than the emissions level specified by the path, the emissions reductions will be positive. If pre-tax emissions are lower than the path level, the MiniCAM imposes a negative tax, or subsidy, on CO_2 emissions that increase them to the level defined by the path. The result will be negative emissions reductions. In the latter case of subsidies and negative emissions reductions, the result is a negative cost, or a

benefit to the economy.

It is important to remember that the cost computations reported here implicitly assume perfect flexibility in where emissions are mitigated. These calculations ignore the admittedly formidable problem of creating a global multinational setting in which mitigation can occur efficiently. These cost estimates can be interpreted as a minimum cost for achieving a given mitigation goal.

The costs used in this assessment do not include research and development expenses for the various technology sets. Our cost calculations assume that the technologies are available and in place in the periods specified in Table 1.

Technology Scenario Results

In this section, we break the results down by case parameter as listed in Table 2. The impacts of the six technology sets on global costs will be discussed first, with the WG1 550 ppm emissions path used as the basis for comparison across scenarios. We will then discuss the impacts of varying the effectiveness level, concentration goal, and timing of emissions reductions. The results in this section will focus primarily on global mitigation costs. We will discuss the regional results in the following section.

Table 2
Case Parameters

Parameters	
Advanced Technology Sets	AFF, BIO, BioAH2, BioNH2, SOL, ALL
Effectiveness Levels	25%, 50%, 75%, 100%
Emissions Paths	WRE & WG1
Concentration Goals	450 & 550 ppm CO_2

Discussion of the modeling runs will focus on several types of cost projections: total and annual costs through 2100, total and annual costs through 2020, and annual per capita costs through 2020 (both global and regional).[7] All costs were discounted to 1990 at a rate of 5 percent.

WG1 Concentration Path Reference Case

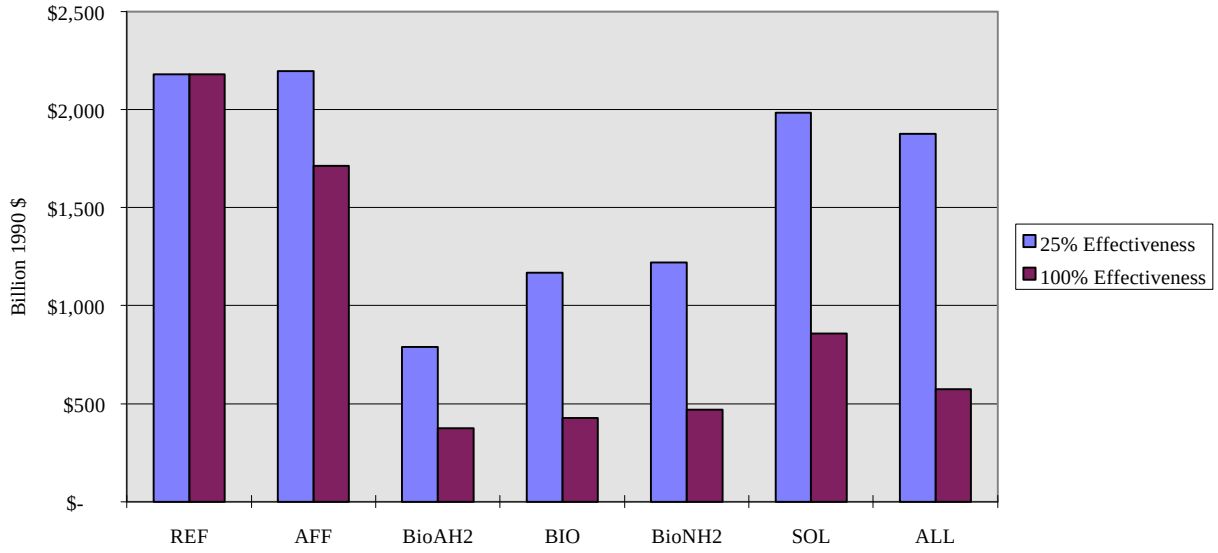
Imposing the WG1 emissions path on the MiniCAM IS92a baseline assumptions results in steadily increasing carbon taxes, ranging from $25 per tonne of carbon to in 2065 to $194 per tonne in 2035. The taxes reduce total energy consumption after 2005 and alter the composition of the total. Biomass, solar, and nuclear sources of energy become increasingly more important as the consumption of coal drops by over 70% relative to the baseline IS92a case in the later periods. Demand for energy decreases substantially in the industrial sector, largely due to a 50% increase in the price of oil by 2095.

The present discounted cost of meeting the concentration goal in the WG1 reference case is $2,180 billion (1990 dollars). The majority of the costs come before 2050 when the emissions restrictions are most severe -- annual discounted total costs for the reference case increase through the year 2025 to a level of $41 billion per year and then decrease to $2 to $3 billion per year in 2065.

Impacts of Technology Sets on WG1 Concentration Path Case

Figure 2 illustrates total discounted costs by technology through the year 2100 for the 25% and 100% effectiveness levels. As shown in the figure, advanced technologies can significantly reduce the costs of meeting the desired CO_2 emissions path even at the 25% effectiveness level. The results for each technology set are discussed in more detail below.

Figure 2
Present Discounted Total Costs to 2100 by Technology Effectiveness Level:
WG1 Emissions Path



Advanced Fossil Fuel Technologies

Of the six technology sets, the AFF set results in total costs closest to the reference case. As seen in Figure 2, total costs decline from reference levels only slightly as the effectiveness level increases from 25% to 100%. AFF25 is the only case of all the technology sets with costs exceeding those of the reference case. The higher costs result from the shift in energy consumption away from clean fuel sources, such as solar and nuclear energy, toward natural gas and coal. The efficiency gains in the AFF25 case, however, do not fully offset the increase in emissions caused by the increase in coal use.

Table 3 shows total primary energy consumption levels in 2095 for the six technology scenarios

and the reference case. It also shows the percent change in total consumption from the reference case for the technology scenarios. In the AFF scenarios, the required emissions reductions are met because of a significant reduction (53% relative to the reference case in the AFF100 case in 2095) in total primary energy consumption. The decline in consumption is made up almost completely of reductions in the consumption of solar and nuclear energy sources, as the share of fossil fuel sources increase relative to the reference case.

Table 3
Total Global Primary Energy Consumption and Percent of Reference Levels in 2095
by Technology Set: WG1 Emissions Path at 100% Effectiveness Level

Scenario	Total Energy Consumption in 2095 (EJ)	Percent Change from Reference Value
REF	3109	-
AFF	1451	-53%
BioAH2	4077	31%
BIO	3510	13%
BioNH2	3902	26%
SOL	3320	7%
ALL	1987	-36%

Low Cost Biomass

The three technology sets centered around low-cost biomass assumptions all produce significant cost savings for the economy at the higher effectiveness levels. The savings result from rapid penetration of the 'clean' low cost biomass fuels. Total energy consumption actually increases relative to the reference case, reaching up to 31% higher in the BioAH2100 case. The increase is supplied almost exclusively by biomass fuels, although coal consumption does rise above reference levels as a result of subsidies given in the early periods. Consumption of solar and nuclear sources drops off significantly until the latest periods when their prices approach the prices of the other fuels.

The composition of energy demand differs across the three low cost biomass cases. The BIO and BioNH2 scenario sets face very similar demands. Industrial and residential/commercial demands increase substantially relative to the reference scenario. The BioAH2 scenario sets share this characteristic but differ markedly in demand by the transportation sector. The availability of efficient hydrogen fuel cells causes transportation sector demand to decrease by almost 50% relative to the reference case in the middle of the next century in the BioAH2100 case. Although the same result might be expected from the fuel cell technologies available in the BioNH2 cases, the added costs of liquefaction prevent the technology from penetrating as rapidly as the BioAH2 technologies. The result in the BioNH2 cases is a significant increase in energy demand by the transportation sector.

Advanced Solar Technologies

The advanced solar technology scenarios also result in cost savings over the reference case. Although not as large as the savings generated by the low cost biomass cases, cost savings in the advanced solar technology cases are greater than those in the advanced fossil fuel cases. As with the low cost biomass cases, the emissions reductions are achieved primarily through fuel switching, even in the face of increasing energy demand by every sector. Solar energy sources displace nuclear sources and slow the penetration of biomass fuels. Total energy consumption increases by up to 15% above reference levels in the middle periods. Solar energy supplies over 60% of the total energy consumption in the SOL100 case by 2095.

All Advanced Technologies

At the 100% effectiveness level case, the ALL scenario produces cost savings to the global economy similar to the low cost biomass scenarios. The concentration goal is met by decreasing emissions with a combination of substantially reduced energy consumption and fuel switching. Consumption levels in the ALL cases are very similar to those in the AFF cases, with significant reductions in energy consumption relative to the reference case. Primary energy consumption declines because it requires less fuel to meet the same energy demand. The composition of energy demand is much more similar to the BioAH2 cases, however. As in the BioAH2 case, energy demand in the transportation sector is markedly lower than in the reference case. Industrial and residential/commercial sector demands are higher than in the reference case. This increase in demand is driven by the similar increases seen in the SOL and AFF cases.

Although the total energy consumption is much lower in the ALL cases than in the reference case, the composition of the total energy consumption is very similar. Coal consumption makes up a slightly higher percentage of total consumption in the ALL cases, as do oil and natural gas. Solar energy sources penetrate much more quickly in the ALL case and, as in the reference case, make up about one half of total consumption by 2095. Biomass penetrates the energy supply market somewhat more quickly than in the reference case, although it does not have the same impact in the ALL cases as it does in the low cost biomass cases. The greatest difference between the ALL scenarios and the WG1 reference scenario is consumption of nuclear energy. In the ALL scenarios, nuclear energy, aside from hydroelectric power (the price of which is set exogenously), is the only source of energy supply not enhanced by advanced technology assumptions. Nuclear power's share of total energy consumption in the ALL100 scenario in 2095 is only half that of the reference scenario, making up a significant portion of the difference in total energy consumption between the two cases.

Impact of Effectiveness Level

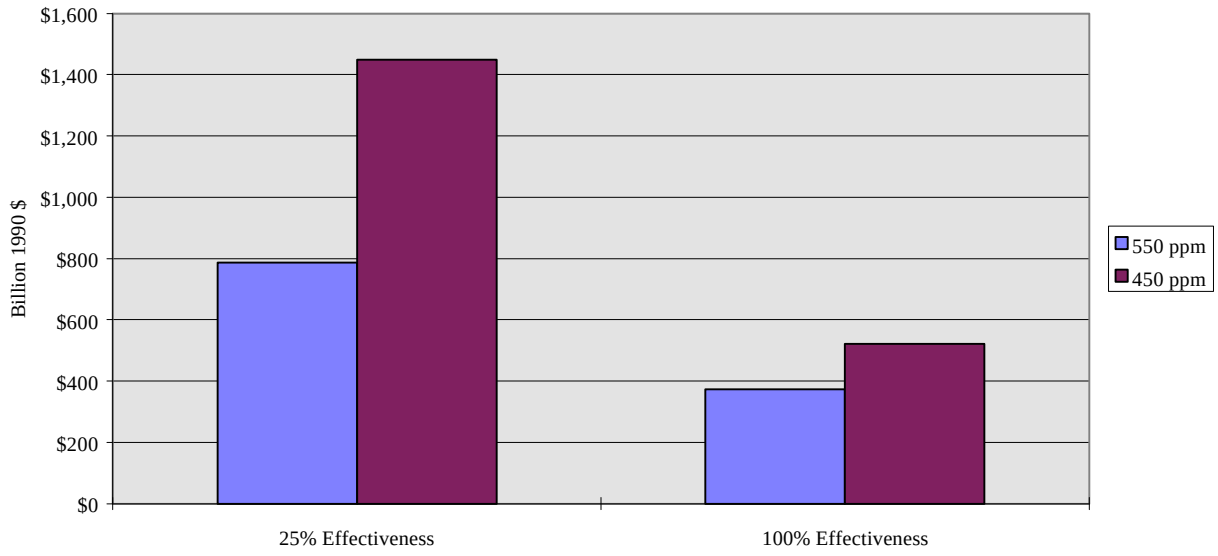
As shown in Figure 2, costs can change significantly across effectiveness levels, with total costs decreasing as the effectiveness level increases. Total global discounted costs of the ALL technology set at the 25 percent effectiveness level, for example, are over three times greater than costs at the 100 percent effectiveness level. The degree of change from one level to the next depends on the technology set, including assumptions on the timing of the implementation of the

technology. Increasing from the 50 percent to the 75 percent effectiveness level in the BioAH2 scenarios results in a 12 percent decrease in costs, whereas the same level change in the BIO cases results in a 35 percent decrease. However, trends in energy supply and demand within a single technology set are very similar across effectiveness levels.

Impact of Concentration Goal

Figure 3 compares the total present discounted costs of the WG1 550 ppm and WG1 450 ppm emissions paths for the BioAH2 technology set. When there is no flexibility in the timing of reductions, tighter emissions restrictions under the 450 ppm path more than double the global carbon taxes required to meet the concentration goal, thereby increasing the marginal cost of reducing emissions for each region. However, the cost differential decreases as the advanced technologies penetrate the market further. It is nearly $300 billion less expensive to achieve a more stringent stabilization level of 450 ppm (see Figure 4) with the BIOAH2 technology set at 100 percent effectiveness than it is to achieve a higher level—550 ppm—with the same technology set at a lower effectiveness level.

Figure 3
Total Discounted Costs to 2100 of the WG1 550 and 450 ppm Emissions Paths for the BioAH2 Technology Set at Selected Levels of Effectiveness

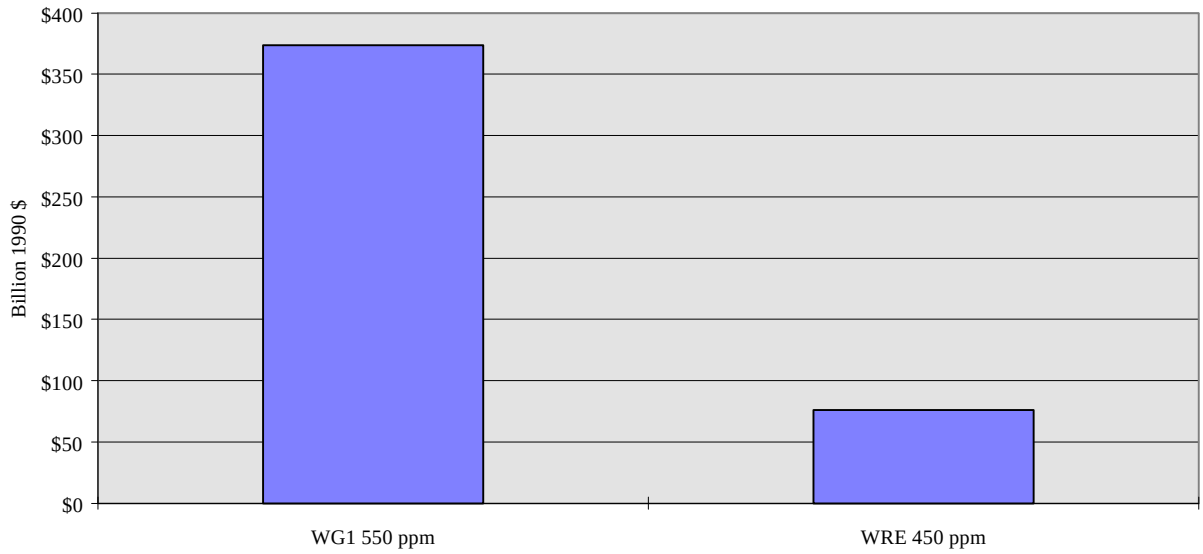


Impact of Timing of Emissions Restrictions

The findings indicated that an emissions trajectory that permits more emissions early in the 21st century and fewer emissions later would result in costs savings. This type of trajectory, labeled the WRE path for Wigley et al., provided a "natural windfall" in the model due to the carbon cycle. When the WRE path was combined with cases assuming penetration of advanced technologies, the savings were substantial. In fact, WRE cases with advanced technologies were

able to meet a more stringent stabilization level of 450 ppm CO_2 at a lower cost than achieving a higher level of 550 ppm CO_2 under the WG1 emissions path (see Figure 4).

Figure 4
Total Discounted Mitigation Costs through 2100 for Biomass with Advanced Fuel Cells at 100%



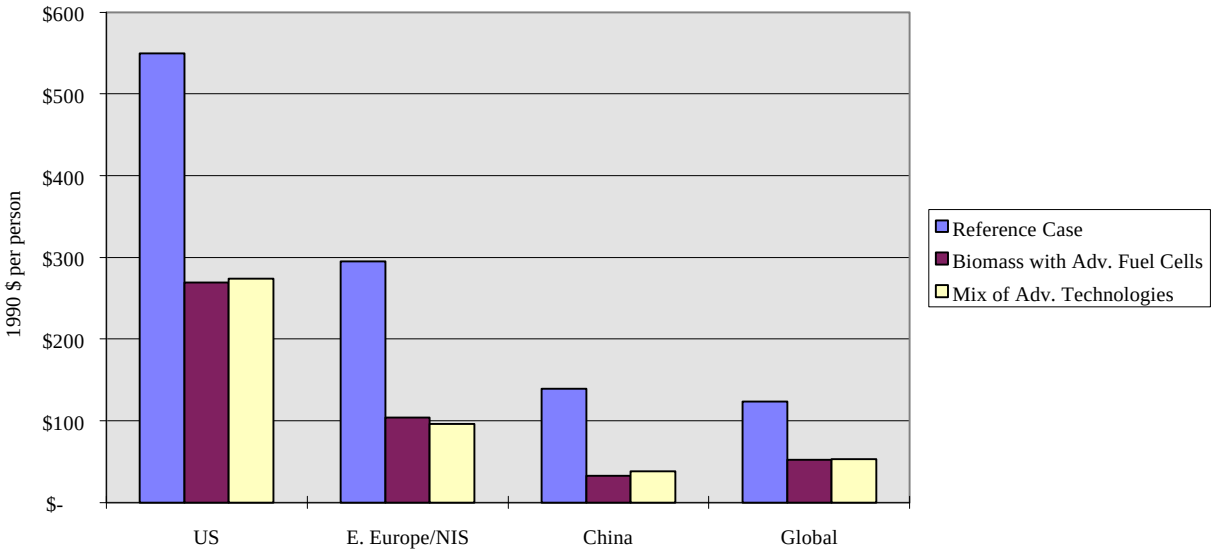
Regional Results

This section will discuss the regional results of the advanced technology scenarios and those of the regional technology penetration scenarios described above. The regions of greatest interest to us were the United States and other Annex 1 countries (OECD Europe and the EUSSR region, which is comprised of countries in Eastern Europe and the New Independent States).

Regional Cost Profiles of Advanced Technology Scenarios

Across regions, the technology sets have similar impacts with respect to costs. In every region, the SOL100 and AFF100 technology scenarios result in the second-highest and highest total discounted costs, respectively. The remaining four technology sets, all of which contain the low cost biomass assumptions, provide significantly lower cost solutions. Figure 5 shows the per capita discounted costs to 2020 for three sample regions and the world as a whole. The remaining regions follow the same pattern as the EUSSR; the ALL case generates the lowest mitigation costs, while costs for the BioAH2 case are only slightly higher.

Figure 5
Total Discounted Per Capita Cost to 2020 by Region
(Assumes 100% Effectiveness Level, WG1 550 Trajectory)



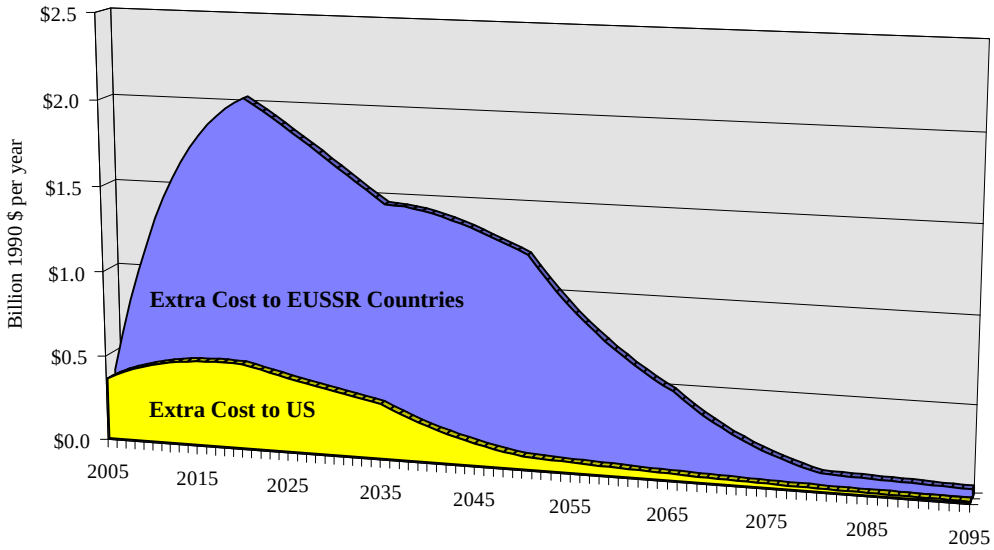
Within regions, the advanced technology sets have clear impacts on regional total and per capita costs. In the United States, for example, the total discounted per capita cost to 2100 of the BioAH2 100 percent effectiveness scenario, the least cost scenario for the United States, is $271. The per capita cost of the highest cost technology set, the AFF100 scenario, however, is $733. This $462 per person difference translates into a total discounted savings of $1.34 trillion. Appendix B provides a discussion of regional cost share by technology set.

Impact of Regional Market Penetration

Figure 6 illustrates the additional costs that would be incurred by the United States and the EUSSR region if the ALL100 technology set failed to penetrate EUSSR countries, reaching only the United States and OECD Europe instead. The additional cost to the United States is driven by the increase in global carbon taxes required to offset the higher emissions resulting from the EUSSR's less efficient technologies. The cost to the EUSSR includes the effects of the higher tax rate and the additional costs of using less efficient technologies.

The United States benefits as soon as the technologies have penetrated 25 percent of the EUSSR's economy, saving up to $0.4 billion per year. The EUSSR continues to benefit as the technology further penetrates its economy, as is consistent with the impacts of effectiveness levels discussed above.

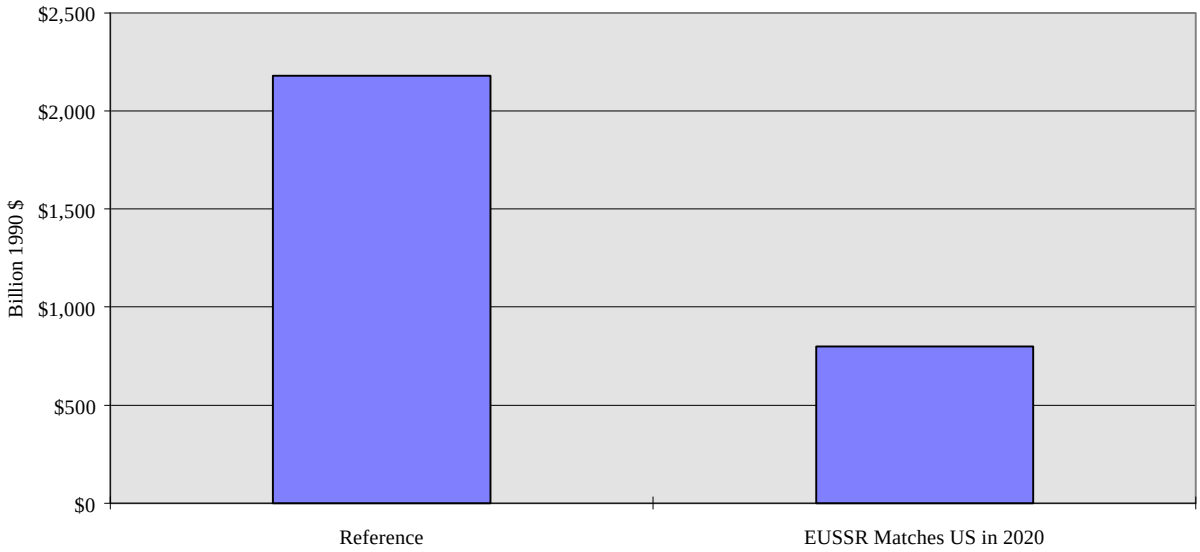
Figure 6
When Advanced Energy Technologies Fail to Penetrate EUSSR Countries: Additional Mitigation costs to the US and EUSSR Regions (Assuming ALL at 100%, WG1 550)



Impact of Energy Intensity Improvement Assumptions

The findings from the energy intensity case that allowed energy intensity levels in EUSSR countries to converge with those of the United States by 2020 indicated that this lower intensity level would save up to $1.5 billion per year between 2005 and 2020 (see Figure 7).

Figure 7
Comparison of Mitigation Costs for Reference Levels and an Efficiency Case for the EUSSR Region: Annual Discounted Total Costs through 2020



This translates into a total of nearly $37 billion worth of potential savings that would result if energy intensity end-use improvement improved by an additional percentage point annually until 2020.

Conclusion

This paper has reviewed the effect of introducing a selected set of advanced energy technologies on the economic costs of climate change mitigation. While the amount saved varies from case to case, the savings occur consistently across a variety of technology mixes, emissions paths and stabilization levels. Thus, the findings confirm that technologies will be important; they hold the potential to substantially reduce costs associated with mitigation, and in some scenarios they may even generate net benefits, which appear in the modeling runs in the form of negative carbon taxes. Under the WRE emissions path, for example, the 100 percent effectiveness levels of the four technology sets containing low cost biomass assumptions each provide net benefits to the economy. The BIO scenario, which provides the highest net benefit, results in a present discounted net benefit of $213 billion.

Technologies differ, however, in their effect on total primary energy consumption and the type of fuel mix that appears in the model runs over the longer term. For example, primary energy use increases by 31 percent over the reference case in a scenario where advanced hydrogen fuel cell technologies and low cost biomass are available but decreases by 36 percent from the reference case when a mix of technologies are made available in the ALL case. Although it was beyond the scope of this paper, the relative role of the other fuels, such as nuclear and solar energy in cases other than the SOL case, could provide important additional information when evaluating the merits of individual technology cases.

In the runs conducted with six technology sets, the low-cost biomass cases, which assumed an increase in energy consumption supported by 'clean' biomass fuels, resulted in the least cost solutions to meeting the concentration goal. The most cost-effective WG1 scenario, the biomass case with advanced hydrogen fuel cells, BioAH2, at a 100 percent of effectiveness level, resulted in a cost savings of $1,800 billion over the WGI reference case with the modified IS92a assumptions.

Another factor in cost savings was the level of effectiveness of a given technology. With the exception of the advanced fossil fuel technologies case at 25 percent effectiveness, costs decreased from the reference costs as the level of effectiveness of a given technology increased. This relationship was also interpreted in another way: costs decreased as the advanced energy technologies penetrated new markets. Although the cost differences between the scenarios involving Annex 1 and Annex 2 countries do not seem substantial when compared with overall technology cost savings, the amount saved by the United States when energy technologies penetrate the USSR region is very large when compared to U.S. spending on energy efficiency in the region. The U.S. Agency for International Development (USAID), for example, had spent $265 million on energy efficiency and energy markets programs for the NIS through the end of FY95. Cost savings from in the ALL technologies scenario will exceed that figure on an annual discounted basis beginning in 2000, even with only 25 percent penetration of the technologies in the EUSSR region.

The use of assumptions corrected for changes in energy intensity in the FSU resulted in substantial reductions in costs over traditional cases, indicating that traditional macroeconomics models may have underestimated the potential for cost savings in formerly planned economies. Even with the corrections, however, there is still a discrepancy between formerly planned economies in Eastern Europe and the NIS. Energy intensity improvement in the EUSSR region would still have had to grow by an additional 1% per year or so in order to match US levels in 2020.

These discrepancies indicate that there are still substantial opportunities to reduce energy intensity and, subsequently, future mitigation costs, by taking advantage of existing efficient technologies in all sectors of the economy in the time period proceeding the introduction of advanced energy technologies.[8] Thus, energy efficiency investments and incentives in formerly planned economies carry a double benefit; they support the transformation of economies in transition, and they reduce future mitigation costs by decreasing emissions.

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Appendix A: MiniCAM Reference Case Assumptions and GNP

Table A1
MiniCAM Reference Case Assumptions

Parameter	Value
Fossil Fuel Resources Oil Natural Gas Coal Uranium	 18,011 EJ 17,451 EJ 271,000 EJ 14,423 EJ (extended with breeder option)
Conventional Fossil Fuel Plant Efficiency	33%
Global Population (year 2100)	$11,312 * 10^6$
Biomass Energy Resource	400 EJ/yr.
Biomass Price 20% of the resource base available at 80% of the resource base available at	 $2.50/GJ $4.40/GJ
Global GNP Growth	2.3%/yr

Table A2
MiniCAM Population Assumptions
(Thousands)

	US	EUSSR	ACENP	World
1975	214,000	395,000	911,000	3,976,000
1990	248,900	428,210	1,223,440	5,293,130
2005	275,400	461,600	1,466,600	6,646,800
2020	294,600	487,400	1,657,400	7,972,200
2035	299,400	504,800	1,775,800	9,060,800
2050	297,000	518,000	1,858,000	10,031,000
2065	296,098	516,496	1,877,627	10,395,902
2080	295,197	514,995	1,897,370	10,773,738
2095	294,299	513,499	1,917,342	11,177,433

Table A3
MiniCAM Reference Case GDP
(Billion Dollars)

	US	EUSSR	ACENP	World
1975	$ 3,470	$ 2,411	$ 364	$ 11,969
1990	$ 5,663	$ 3,782	$ 570	$ 20,104
2005	$ 9,575	$ 4,094	$ 1,162	$ 30,775
2020	$13,053	$ 6,465	$ 2,477	$ 46,401
2035	$15,934	$ 8,598	$ 4,311	$ 63,359
2050	$19,480	$11,463	$ 7,559	$ 88,473
2065	$22,958	$13,504	$11,739	$116,206
2080	$27,100	$15,965	$18,481	$155,592
2095	$31,184	$18,391	$28,477	$205,105

Appendix B: Regional Cost Shares and Choice of Technologies

Determination of the least cost technology solution for various regions depends on the time horizon over which costs are calculated. The low cost biomass assumptions are not fully realized until 2020, so much of the impact from that advanced technology will be realized later in the century. In the EUSSR, for example, the BIO100 case advances from the fourth lowest cost per capita technology set to 2020 to the least cost technology to 2100. Also in the EUSSR, the ALL100 scenario drops from the least cost per capita technology to 2020 to the fourth lowest cost to 2100. Similar changes take place in the ACENP with the BioNH2 scenarios and in the United States with the SOL scenario.

The share of global costs for which each region is responsible also changes with the different technology sets. Africa, Latin America, and the Middle East are never individually responsible for over 4 percent of total discounted global costs. Africa, in fact, actually receives a net benefit from the rest of the world in the BIO100 scenario. The EUSSR region is responsible for 12 to 13 percent of global costs across all technology sets. The largest trade-off is made between the ACENP, Southeast Asia, and the collective OECD (US, OECD West, and OECD Asia) regions. In the three low cost biomass cases (excluding the ALL scenario), for example, the OECD's share of total costs increases from a Reference case level of 29 percent to an average of 45 percent. The ACENP benefits from the OECD's misfortune in the two fuel cell scenarios, dropping from a reference level share of global costs of 30 percent to half that level. Southeast Asia's share of costs is cut in half, from 20 percent to 10 percent, in the low cost biomass case. Similar trade-offs take place under the SOL technology scenario, but to a lesser extent than in the biomass cases.

Endnotes

[1] This assumed a stabilization level of 550 parts per million (ppm) CO_2.

[2] Manne AS and Richels RG (1992) *Buying Greenhouse Insurance: the Economic Costs of CO2 Emission Limits*, MIT Press, Cambridge; WRE *Nature*.

[3] Annex 1 and Annex 2 refer those countries which are signatories of the respective sections of the International Framework Convention on Climate Change (IFCCC). Annex 1 countries consist of both formerly planned economies and OECD countries, while Annex 2 is limited to OECD countries. For a complete list of countries in both sections, please see Appendix _.

[4] See William Chandler et al. (1990) "Energy for the Soviet Union, Eastern Europe, and China" in *Scientific American*, Vol. 9.

[5] Solar energy prices do not converge in the model until after 2020.

[6] See William Chandler (1988) "Assessing Carbon Emission Control Strategies: The Case of China" in *Climatic Change* 13.

[7] Total discounted per capita costs were calculated by determining per capita costs per period (1990, 2005, 2020) and then linearly interpolating between periods to determine annual costs, which were then discounted and summed.

[8] See William Chandler et al. (1996) "Climate Change Mitigation: A Review of Cost Estimates and Methodologies for the Post-Planned Economies" in *Energy Policy*, Vol. 24, No. 10 and Radwanski et al. (1993), *Case Study of Greenhouse Gas Emission in Poland: Final Report*, prepared for the Pacific Northwest Laboratory under Contract 1448890-A-Q2 by the Polish Foundation for Energy Efficiency.