Technology Policy and World Greenhouse Gas Emissions in the AMIGA Modeling System

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In this paper we examine the interaction between technology policy and its impact on the full basket of worldwide greenhouse emissions over the 21st century. The heart of the analysis is the Argonne National Laboratory's AMIGA Modeling System, a technology rich, general equilibrium model that (depending on data availability) characterizes as many as 200 sectors of the regional economies. We suggest in this paper that technologies and technology policies exist which could reduce carbon emissions enough to achieve stabilization targets at relatively modest costs given the size of the world economy. This can be accomplished largely through harnessing market forces and creating incentives with the use of efficient prices on greenhouse gas emissions, combined with complementary programs and policies to reduce market failures and to promote new technology improvements and investments.

1. INTRODUCTION

In this paper we examine the interaction between technology policy and its impact on the full basket of worldwide greenhouse emissions over the 21st century. Our assessment is part of the current Stanford University's Energy Modeling Forum study on a multigas climate policy assessment (EMF-21). For this analysis we are using two models: the Argonne National Laboratory's AMIGA modeling system (Hanson and Laitner, 2004; see also *http://amiga.dis.anl.gov*) and the National Center for Atmospheric Research's MAGICC model (Wigley, 2003; and also see *http://www.cgd.ucar.edu/cas/wigley/magicc/*). The

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emission projections from the AMIGA model feed into the MAGICC climate model to estimate greenhouse gas concentrations, radiative forcing (in watts per square meter), and global mean temperature change.

For the EMF-21 exercise we explored two types of climate goals: (1) long-run climate stabilization at roughly 2 degrees centigrade higher than 1990 levels by the year 2100, and (2) a rate of temperature change constrained to an increase of no more than 0.2 degrees centigrade per decade beginning in 2030 through the year 2100. As part of this exercise, the EMF-21 study also examines the many carbon and non-carbon options which might slow the rate of temperature increases. The options included: (i) both efficiency gains and abatement reductions in the emissions from the full basket of greenhouse gases, (ii) slowing the rate of deforestation, and (iii) the examination of carbon sinks in soils and geological formations. In this paper we focus on the first of these technology paths. More specifically, we explore the influence of technology and technology policy on both the energy-related carbon dioxide emissions and the non-carbon dioxide emissions including methane, nitrous oxides, and the so-called fluorinated-gases.[1]

2. THE GREENHOUSE GAS EMISSIONS AND TECHNOLOGY STORY IN BRIEF

We open the discussion by providing an overall context to help understand the analysis that follows. As mapped out in the description of the model runs that follow, we find that over the next 100 years oil and natural gas prices rise in the business-as-usual case. These price increases are partly due to more costly production and partly due to increased demand for energy services as incomes rise worldwide. This spurs the increased use of combined heat and power (CHP) and other waste-to-energy technologies, renewable energy resources, energy efficiency investments, advanced hybrid vehicles, and emission abatement systems. Increased experience with these different technologies (often referred to as “learning effects”) brings down their cost which, in turn, expands their market shares. This is a world similar to that characterized in the “Technology Triumphs” scenario of a previous EPA-Argonne study that occurs partly in response to the increasing relative scarcity of oil and natural gas resources (Hanson et al., 2004). Despite the improved rate of technological progress, however, total greenhouse gas emissions grow over the 100-year time horizon of the study.

Climate scientists continue to debate what would constitute prudent emission reduction trajectories. There are concerns about the effects of rapid

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[1] The fluorinated gases have very long atmospheric lifetimes, so controlling their emissions would have benefits for many centuries to come. However, this study examines only the climate effects over the next century. Methane, on the other hand, has a relatively short atmospheric lifetime of about 15 years. Atmospheric concentration reductions for methane by 2050 are important for slowing the rate of climate change, but would have little remaining influence by the year 2100. Long-term climate stabilization will likely require on-going control efforts for carbon, methane and other greenhouse gas emissions.

temperature change on bio-diversity and human societies. There is also concern about abrupt shifts in atmospheric-ocean interactions (Baranzini et al., 2003, Weart, 2003). As further climate data becomes available and as our interpretation and understanding of the information improves, there could be a need for aggressive reductions in all greenhouse gas (GHG) emissions to slow the rate of climate change. Medium-term reductions in methane and other non-CO_2 GHG would be important for slowing the rate of temperature change. For long-term stabilization with radiative forcing being gradually reduced, non-CO_2 greenhouse gas emission reductions can play an important role in lowering the cost of achieving the long-term target. Hence, it may be cost-effective to attain a long-term stabilization target using a larger set of greenhouse gases, rather than only reducing carbon emissions. A whole different set of technologies are applicable to non-CO_2 emission control. By simulating a multi-greenhouse gas long-term stabilization scenario, we examine a broader approach to environmental and technology policy.[2]

Below, we summarize the four GHG emission reduction scenarios for which least-cost control strategies are examined in this study. We consider three pure long-term stabilization cases and a fourth case with an additional constraint on the rate of temperature increase:

1. Achieve the given long-term stabilization target with carbon dioxide (CO_2) emission reductions, but without controls on emissions growth of other emissions, and using only the price mechanism to achieve those reductions;
2. Achieve a given long-term stabilization target with CO_2 emission reductions only, but implementing additional policies and programs to complement the price signal and ease the economic costs of the transition;
3. Achieve the same long-term stabilization target with reductions on both CO_2 and non-CO_2 emissions using both the price signal and other programs and policies; and
4. Limit temperature rise to 0.2 degrees centigrade per decade, starting in year 2030, using reductions of both CO_2 and non-CO_2 emissions, plus achieve the long-term stabilization target.

The least-cost policy approaches for these scenarios include efficient pricing of carbon dioxide and other GHG emissions (if other GHGs are controlled in the scenario). In addition, and following the success of existing programs (Climate Protection Partnerships Division, 2003, Laitner and Sullivan, 2001), we assume that cost-effective information and other voluntary programs and policies are used because of the economic and social importance associated with implementing a climate policy. These non-price programs and policies provide

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[2] The inclusion of non-CO_2 greenhouse gases and the constrained temperature scenario distinguish this EMF-21 study from our previous EMF-19 analysis (Hanson and Laitner, 2004).

guidance to early adopters of low-carbon technologies, promote earlier and more rapid technological learning, and address existing market failures.[3]

A number of caveats are in order. First, consistent with past EMF exercises, we are modeling for insights not for numbers. More specifically, we want to understand the technology and market relationships under different policy scenarios rather than create specific forecasts of greenhouse gas emissions and economic activity. Second, a full accounting for both costs and benefits clearly matter; yet, these have not always been adequately captured in most modeling exercises. The tendency is to understate both, with benefits receiving less attention both in past and (unfortunately) in these current exercises. Third, uncertainties abound. This is true whether we explore the pace and magnitude of climate change or the development of new technologies and innovative markets. Finally, as climate issues continue to receive more attention, the world community will undoubtedly provide continual adjustments in what it perceives as improved technology policies or strategies. In short, a world which acts, then learns (as it appears to be already doing with respect to climate-related markets and technologies), and then acts again is a world that is likely to embark on a different path than might be reflected in a set of modeling exercises from today's perspective and that do not incorporate information feedback. Hence, as we first noted, we are modeling for insights rather than precise estimates; the analyses and forecasts will surely be refined with time.

3. ABOUT THE MODEL

The heart of the analysis is based on the scenarios mapped into AMIGA (**A**ll **M**odular **I**ndustry **G**rowth **A**ssessment) modeling system. The system, programmed in the structured "C" language, is developed and supported by the Argonne National Laboratory in cooperation with the US Environmental Protection Agency's Office of Atmospheric Programs. AMIGA is a general equilibrium model that examines the impact of changes in more than 200 individual sectors (measured in dollar value and where appropriate in physical units as well). It integrates a detailed energy end-use and energy supply market specification within a structural economic model. The model allows firms to maximize net wealth and consumers to maximize intertemporal utility. In the absence of perfect foresight, agents act on approximate intertemporal rules. AMIGA calculates prices and macroeconomic variables such as consumption, investment, government spending, gross domestic product (GDP), and employment. In this exercise, the model provides equilibrium paths from the present through the year 2100.

AMIGA integrates eleven modules that describe the various economic

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[3] An example of an existing market failure is the absence of marginal cost pricing of electricity. We assume that market failures, such as this one, are gradually corrected over time. Correcting these market failures is critical to achieving cost-effective climate policy. Under a climate target scenario, combustion of fossil fuels is costly, encouraging the substitution of demand-side measures and low-carbon energy sources. However, if prices of electricity do not reflect underlying social costs, there will be an under-investment in valuable demand-side measures and renewable energy.

interactions among twenty-one world regions. For purposes of this analysis, however, we explore a more aggregated, three-region view of the world: the United States, other OECD countries, and the other nations of the world. Each region's assets include existing capital stock, labor resources, and exhaustible resources. The model tracks a detailed accounting of major goods and services demanded by households and the various production sectors of the economy that lead to changes in energy use and production, greenhouse gas emissions, and temperature changes. In short, AMIGA combines a bottom-up representation of the demand for energy and the many other goods and services sectors available with regional markets together with a detailed interaction among those sectors and among the regions of the world. Various choices within these sectors are modeled through nested constant elasticity of substitution (CES) production functions which determine how economic output is supported through inputs of capital, labor, electric and non-electric energy.

The model allows for autonomous improvements in technologies as well as both price and other policy-induced improvements which can lead to reductions in greenhouse gas emissions.[4] AMIGA also incorporates macroeconomic feedbacks. Higher energy and other resource costs lead to substitution of capital and labor for energy. As previously suggested, a number of gases have been identified which contribute to climate changes and which have been mapped into the AMIGA model. In addition to the production of carbon dioxide (CO_2), emissions from methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorcarbons (PFCs), and sulfur hexafluoride (SF_6) are also included. The atmospheric impacts from these gases are estimated using the MAGICC model; or more formally, the Model for the Assessment of Greenhouse – gas Induced Climate Change. MAGICC is the climate model that has been used in the IPCC Second and Third Assessment Reports to produce projections of global-mean temperature. AMIGA estimates the annual worldwide emission reductions for each of the desired scenarios which are then passed to MAGICC as inputs. MAGICC then calculates the imputed GHG concentrations, radiative forcing and temperature that results from the emission paths. The projected climate impacts are compared with the climate goal for the scenario, and if they are not close, the AMIGA model is re-run with adjusted policy stringency. This iterative process continues until AMIGA/MAGICC converge on the same desired scenario target.

4. THE BASELINE ASSUMPTIONS

We next turn to the review of data that more specifically describe the macroeconomic and emissions trends in a non-policy baseline generated for this assessment. We have two overriding assumptions that underpin the reference case as well as the alternative policy scenarios. The first set of assumptions,

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[4] For a more complete description of how AMIGA incorporates other policy-induced improvements into emission scenarios, see Hanson et al. (2003).

drawing from an extensive literature reviewing economy-wide and sector performance, highlights an economy that is suboptimal in performance. By this we mean that while there is a level of robustness which underpins current growth patterns, it appears that price and non-price policies can encourage greater use of capital and other resources which are generally characterized as high-return energy efficiency applications that also reduce greenhouse gas emissions (see Table 4 for a summary of impacts and their resulting cost effects). The implication is, therefore, that under a different mix of prices and policies, an alternative pattern of technologies and market arrangements may emerge that can simultaneously maintain economic performance and reduce greenhouse gas emissions. The second major assumption is a continuing improvement in energy-related technology and markets that would be accelerated as a result of GHG price signals and complementary non-price policies.

As a result of these starting assumptions, we build a reference case economy (measured by world wide Gross Domestic Product) that follows a combination of population and productivity growth trends. Table 1 summarizes the regional GDP data for selected years. At the same time, the technology performance of the regional economies improves at a rate comparable to the change in regional greenhouse gas intensities summarized in Table 2 for those same years.

Table 1. Reference Case GDP (Trillion 2000 US Dollars)

Region	2000	2010	2020	2050	2100	AAGR
United States	9.7	12.7	16.3	31.1	60.6	1.8%
Other OECD	15.7	19.2	23.4	42.5	73.2	1.5%
Rest of World	7.5	10.4	14.3	37.5	162.1	3.1%
World Total	33.0	42.2	54.0	111.1	295.9	2.2%

Table 2. Reference Case GHG Intensity (grams per dollar of GDP)

Region	2000	2010	2020	2050	2100	AAGR
United States	190	158	137	93	66	-1.1%
Other OECD	129	114	100	69	53	-0.9%
Rest of World	659	528	439	243	80	-2.1%
World Total	268	229	201	135	71	-1.3%

Table 3. Reference Case Emissions (Million Metric Tons Of Carbon Equivalent)

Greenhouse Gas	2000	2010	2020	2050	2100	AAGR
Carbon	6,290	6,881	7,701	11,015	17,643	1.0%
Methane	1,610	1,782	2,040	2,630	2,074	0.3%
Nitrous oxide	838	880	914	981	854	0.0%
High GWP	82	115	196	335	352	1.5%
World Total	8,820	9,658	10,850	14,960	20,924	0.9%

Our baseline assumptions in Table 1 show different rates of economic growth for the US and other OECD countries compared to the other regions of the world. For all regions economic growth is expected to be somewhat faster in the next 20 years compared to the expected growth over the full century. Driven by larger population growth and productivity gains (in as much as they currently have less efficient technology on average but begin to catch up to OECD levels), the developing countries are expected to grow more rapidly than OECD countries. Overall world gross domestic product, measured in trillions of 2000 US dollars, increases at a 2.2 percent annual average growth rate (AAGR) over the period 2000 through 2100.

Table 2 summarizes the expected trends in technology performance as measured by declining greenhouse gas intensities (grams of carbon equivalent for all gases per dollar of GDP). Over the 100-year time horizon, technology worldwide is expected to improve at a moderate pace of 1.3 percent per year; or stated differently, technology is expected to improve so that annual GHG emissions intensities will decrease on average by 1.3 percent. The non-OECD regions are expected to improve more quickly since their level of GHG intensity is currently at a much higher level than either the US or the rest of the OECD nations.

Table 3 illustrates the interaction of economic growth together with a reasonable improvement in technology by charting the actual greenhouse gas emissions (in million metric tons of carbon equivalent). With the world economy expected to grow on average at about 2.2 percent annually over the next 100 years (see Table 1), and with technology improvements expected to reduce the economy's expected greenhouse gas intensities by about 1.3 percent each year, total greenhouse gas emissions are anticipated to grow at just under 1 percent annually. By the year 2100, total emissions are almost two and a half times larger than in the year 2000. Again these rates will vary by region.

5. EMISSION REDUCTION SCENARIOS

Current research suggests that in the year 2000 the worldwide average global temperatures were about 1 degree centigrade above the pre-1900 temperatures. Our reference case projections suggest that without further technology development and without implementation of additional policy options, the global average temperatures might be expected to climb to 4 degrees above pre-1900 levels, or 3 degrees above year 2000 temperatures. The goal of the EMF-21 exercise is to determine the impact of a variety of greenhouse gas emissions reduction options rather than to identify an optimal level of reductions. Thus, in our emission reduction scenarios, we explore the impact of technology and policy paths that might limit temperature changes to no more than about 2 degrees centigrade by the year 2100, or no more than 3 degrees centigrade higher than pre-1900 levels. In our four scenarios, this is achieved with and without policies and programs to complement a price signal, with and without non-CO_2 emission reductions, and with and without a constraint on the rate of temperature rise.

The first scenario that we describe is one which limits carbon dioxide emissions only through a price signal. That is to say, we assume the only mechanism to stimulate the development of and investment in low carbon technologies is through some form of cap on energy-related carbon dioxide emissions with energy users and/or producers required to hold a permit for each ton that is emitted. The permits would be issued either by an auction, or allocated through some market-based arrangement. As a result, the only stimulus to encourage the adoption of more energy efficient or low-carbon technologies is a set of higher energy prices stimulated by the emissions cap. The second scenario assumes both a price mechanism and the implementation of other energy policies such as greater emphasis on research and development initiatives, accelerated technology standards, and investment incentives — all of which might complement and interact with the price signal. These complementary policies reduce the level of carbon prices necessary to meet the desired temperature target.

A third technology path is to incorporate price and non-price policy options within a multigas, rather than a carbon dioxide only, framework. The evidence suggests that non-CO_2 emission reductions may be cheaper than many carbon dioxide reduction options. The assumption, therefore, is that a multigas scenario would be less costly than one that emphasizes only CO_2 emission reductions. Finally, we add a constraint on the rate of temperature change so that the change increases by no more than 0.2 degrees centigrade per decade starting in year 2030. This last technology path also includes the full spectrum of policies as well as the availability of non-CO_2 options to meet the long-term temperature target. The availability of multiple greenhouse gas emission reductions is important in being able to meet the rate of temperature change constraint.

Table 4 is designed to help explain the low cost of climate stabilization policies utilizing available technology options. In particular, both prices and program effort are important in driving changes in the low-carbon technologies that are employed in the future. As these technologies mature, they have roughly the same cost as today's energy-related technologies (especially when taking into account the long period of capital stock turnover and the offset from lower fossil fuel costs due to reduced demand for energy).

To further explain the impacts suggested in Table 4, we now briefly describe the variety of low-carbon technologies and abatement technologies to reduce other non-CO_2 emissions.[5] Energy-efficiency technologies used in residential and commercial buildings and in industrial applications is a huge topic and has been treated in numerous other reports and papers. These technologies include efficient lighting and building shells, improved heating and cooling systems, combined heat and power and waste to energy systems, efficient appliances and electrical and electronic equipment (meeting or surpassing EPA

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[5] For greater description of carbon reduction technologies, see Interlaboratory Working Group (2000) and Hanson et al. (2004). For examples of other GHG abatement technologies, see Delhotal et al. (2004).

Table 4. Price Induced Substitutions and Cost Impacts: Broad Categories

Category of Impact	Price Effects	Cost Impacts
Learning and Technical Progress (Wene, 2000, McDonald and Schrattenholzer, 2001, Laitner and Sanstad, 2004)	Switch to technology paths that will allow economies of scale and experience with adoption of low-carbon technologies	Significant cost reductions can be achieved in the long run
Reduce barriers to distributed generation (Laitner et al. 1999, Lemar, 2001)	Encourage combined heat and power and waste to energy technologies	Both energy and economically efficient
Institutional Improvements (Argote, 1999, and Nadel et al., 2003, DeCanio, 1994, DeCanio et al., 2000)	Investment in electrical system network configuration and operations to be able to accommodate greater shares of intermittent and remote power sources	Cost lowering innovation
Efficient Pricing (Linton, 2004, Pizer, 2003, Newell et al., 1999)	Allow customers to see real time cost of supplying power (cycles significantly higher and lower than average costs),	Reduce a market failure that impedes the adoption of low-carbon technologies
End Use Opportunities (Metz et al., 2001, Interlaboratory Working Group, 2000, Nadel and Geller, 2001, and Energy Innovations, 1997)	Adopt cost-effective, efficient, energy-using technologies	Address information, principal-agent and other market failures to lower economy-wide costs
Gains from Systems Integration (Lipman et al. 2002, Interlaboratory Working Group, 2000)	Promote grid-connected hybrid vehicles to absorb and store surplus low-priced electricity when available	Reduce oil costs and increase national security through less imported oil.
Electronic controls and hybridization (Interlaboratory Working Group, 2000)	Take advantage of innovations in high tech fields to use energy smarter	Technology advance

Energy Star standards), applications of sensors and automatic controls, and use of heat pumps, passive and active solar thermal energy, and photovoltaic panels in some markets. For personal transportation, the application of power electronics and other smart technologies to modular, optimized hybrid electric vehicles is just at the beginning of an evolutionary path with tremendous potential for efficiency and performance gains. These vehicles can be connected to the power grid through electromagnetic coupling or by direct connection. Hybrid electric vehicles are a natural storage device to absorb surplus, off-peak power from a diversified network that can provide large quantities of intermittent renewable electricity. The surplus, low-carbon electricity absorbed in storage technology will displace the need for oil, gas or coal-based power. For electric generation, many renewable energy resources (wind, solar power towers, geothermal) and waste to energy technologies (combined heat and power, pressure recovery turbines, and gasification) are economic in the presence of even a modest carbon charge. Early adoption of many of these technologies, combined with large-scale manufacturing, will reduce costs and improve performance and customer satisfaction over time. Although these technologies are different than today's fossil fuel intensive technologies, they provide basically the same energy-related services. In some cases they have the potential to provide these services cheaper and more productively (see, for example, Martin et al., 2000).

No doubt there will be dramatic technological breakthroughs in many fields over the next century (largely explaining a much larger GDP to be expected in the future), but in this study we do not rely on unpredictable technological breakthroughs for GHG abatement.[6] Hence, the technologies described here are either existing ones, or are ones that are based on foreseeable incremental and evolutionary developments from the existing technologies. If a model does not represent these kinds of either near-term or evolutionary technologies, then (presumably) the resulting scenarios would overestimate the costs of complying with low-carbon future scenarios. The AMIGA model has been designed to include low-carbon technologies and to represent endogenous technical progress as the economies of the world proceed down low-carbon paths under climate change constraints. In the AMIGA model, energy efficiency and low carbon energy sources are employed more or less rapidly and to greater or lesser extents depending on the price of carbon and the impact of other non-price policies. In the multigas scenario, somewhat less carbon reduction is needed. In the constrained temperature rate of change scenario, all measures available have to be pursued in the near term, substantially raising R&D and investments in energy efficient and renewable energy technologies.

Figure 1 shows the percentage reductions in World Total Primary Energy (TPE) in the four climate policy scenarios, compared with the Reference case described in Tables 1-3. As we might quickly note, the multigas stabilization path requires less reduction in energy consumption to achieve the same level of temperature stabilization. On the other hand, if the rate of temperature change needs to be constrained, energy demand would have to come down more rapidly over the next 50 years. In calculating TPE we value non-fossil generators (nuclear and renewable energy) at the average fossil generation heat rate (Btu/kWh) in the given year. These demand reductions (described generally in Table 4) are induced by the carbon charges along with significant voluntary program effort. The magnitudes of the price signal over time by scenario are shown in Table 5. The highest carbon charges are needed with a near-term effort to reduce temperature rise, and the lowest carbon charges are required under a broad-based, multigas, full policy, long-term stabilization target.

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[6] As one measure of technical progress, the largest rate of decline in worldwide energy intensity in any of the scenarios explored in this study is 1.5 percent annually, only slightly higher than the reference case rate of 1.2 percent suggested in the reference case assumptions. By contrast, a number of studies suggest that a 2.0 percent is technically possible and may be economically feasible with the advent of new materials, advances in microelectronics, and changes in consumer preferences (Laitner, 2004).

Figure 1. Change in World Energy Consumption

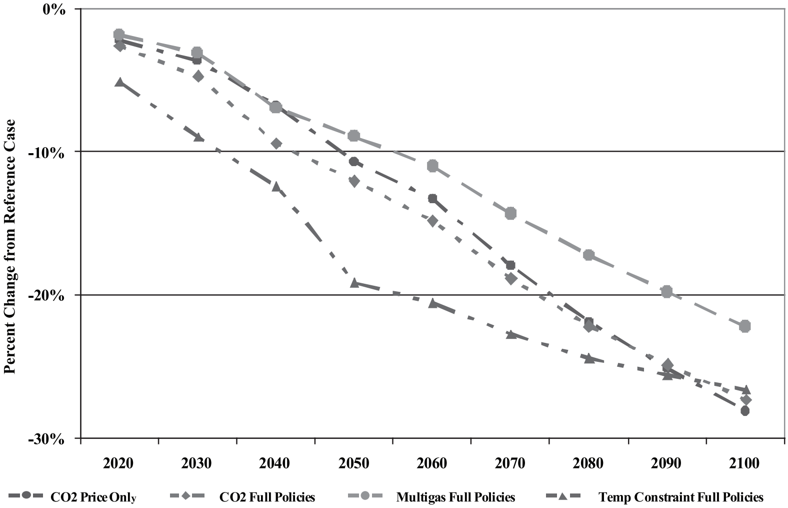


Table 5. Carbon Charge by Scenario (2000 US dollars Per Ton Carbon Equivalent)

Scenario	2020	2040	2060	2080	2100
CO_2 Reductions with Price-only Policy	92	148	183	203	216
CO_2 Reductions with Full Policies	63	102	124	138	147
Multigas Reductions with Full Policies	43	68	84	93	99
Temperature Constraint with Full Policies	171	245	253	231	193

Figure 2 shows the energy expenditure path for the four climate policy scenarios relative to the reference case. Energy expenditures are the sum over all end-use purchases of energy price times the quantity demanded. The price will include the net pass through of a carbon charge, partially offset by the lower fuel prices that emerge in the energy markets due to lower demand for oil, natural gas and coal. At first energy expenditures increase due to higher energy prices which reflect the carbon charge. This is most pronounced with the high carbon charges under a temperature change rate constraint case. Later as the price elasticity works through the capital turnover process, energy demand is sufficiently reduced so as to reduce expenditures on energy. These effects are less pronounced under the multigas stabilization scenario, due to lower carbon charges needed in this case. Indeed, the significant reduction in energy demand in the second half of the century drives a total set of energy expenditures that are lower than in the reference case.

Under all climate policy scenarios, total investment in the various mix of technologies are higher in order to meet the necessary GHG reductions, as shown in Figure 3. This is most pronounced in the rate of temperature change

Figure 2. Change in World Energy Expenditures

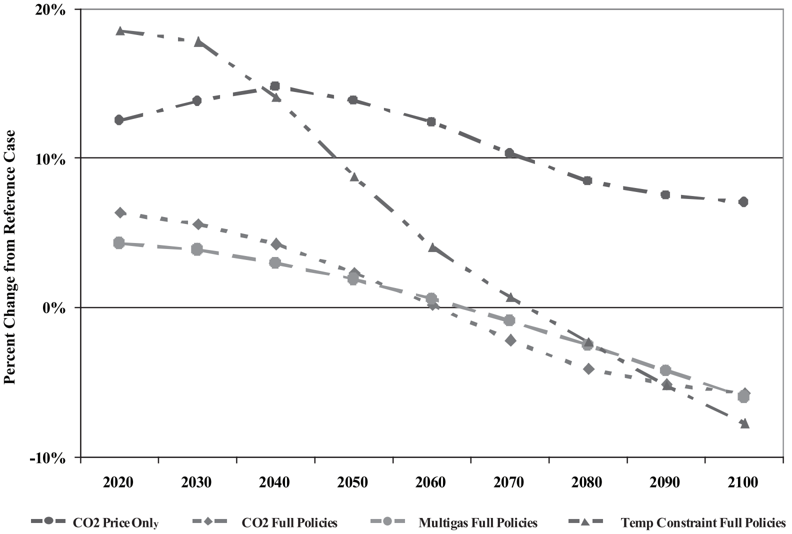
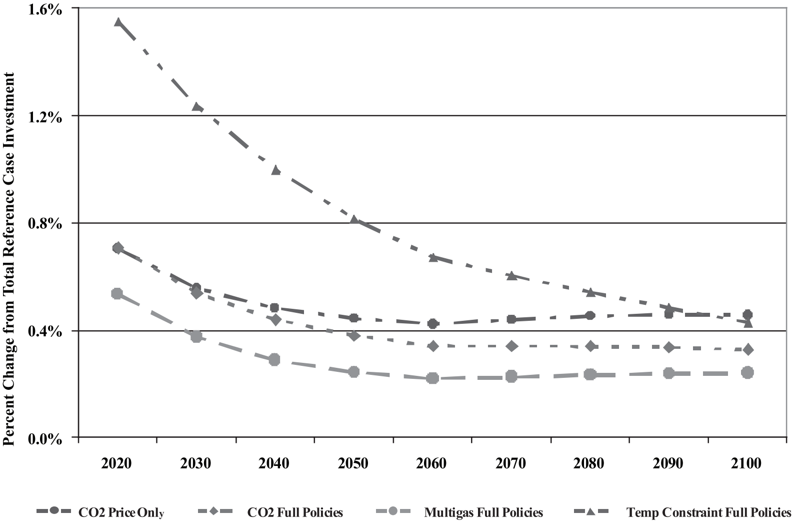


Figure 3. World Energy and Non-CO_2 Related Investments



constrained case in which substantial additional investments would be needed over the next 50 years. Figure 3 plots investments in each of the four scenarios by ten year intervals. Again, the temperature constrained scenario forces a more rapid turnover in capital stock in the early part of the century so that there is a big jump in capital outlays. Since replacement investments can swing substantially from year to year as existing capital retires, investment charts for any given sector typically are not smooth over time. Nevertheless, the general patterns are clear. Again, the multigas stabilization scenario requires less investment to meet the long term climate change target compared with only CO_2 reductions.

To provide a clearer insight into the required investment patterns, the outlays for both energy-related and non-CO_2 abatement technologies are shown in Tables 6a through 6d for the US, other OECD nations, rest of world countries, and the world total. The categories of different investments shown as annual averages for the first and second half of the century are as follows:

- Incremental residential and commercial building-related efficiency investments,
- Incremental industry energy efficiency investments,
- Incremental cost of more energy-efficient cars, vans, and light trucks,
- Measures applicable to other transportation modes including aircraft and heavy duty trucks,
- Electricity supply investment which decreases with lower electricity demand but increases with the substitution of renewable energy for fossil fuels,
- Reduced investment requirements in other energy supply, such as oil and gas drilling, oil refining, coal mining, and fuel transportation and distribution,
- Investments in systems integration, such as standard interconnection for distributed generation, net metering, real-time electricity pricing, price sensitive sensors and demand controls, energy storage technologies, transmission grid enhancements, diversification of renewable sources to increase reliable power from renewable technologies, and facilities to distribute surplus intermittent renewable electricity to grid-connected vehicles and other storage capacity.

Tables 6a-6d apply to the multigas stabilization case. It is seen that the investments needed for non-CO_2 GHG abatement are substantially less than energy-related investments which would otherwise be required to achieve the climate stabilization target. Energy-related investments are higher for CO_2 only stabilization scenarios than shown in Table 6. However, investments under the constrained rate of temperature change scenario are substantially higher than shown in Table 6.

Table 6a. Average Annual Incremental Investment for USA: Multigas Long-term Stabilization Case (billion 2000 US dollars)

	2020-2060	**2060-2100**
Buildings-related	5.2	11.8
Industry	3.4	6.3
Light-duty Vehicles	4.8	11.3
Other Transportation	2.3	4.8
Electricity Supply	0.8	-8.9
Other Energy Supply	-2.9	-15.0
Systems Integration	2.0	13.5
Total Energy-Related	15.6	23.8
Non-CO_2 gas reductions	0.3	1.0
Total Investment	15.9	24.8

Table 6b. Average Annual Incremental Investment for Other OECD: Multigas Long-term Stabilization Case (billion 2000 US dollars)

	2020-2060	2060-2100
Buildings-related	5.5	11.9
Industry	3.6	6.1
Light-duty Vehicles	6.5	13.2
Other Transportation	2.5	5.1
Electricity Supply	0.4	-10.5
Other Energy Supply	-2.7	-13.1
Systems Integration	2.5	13.5
Total Energy-Related	18.4	26.2
Non-CO_2 gas reductions	0.3	1.1
Total Investment	18.7	27.3

Table 6c. Average Annual Incremental Investment for Rest of World: Multigas Long-term Stabilization Case (billion 2000 US dollars)

	2020-2060	2060-2100
Buildings-related	7.9	19.4
Industry	5.9	10.7
Light-duty Vehicles	11.1	32.8
Other Transportation	2.9	6.7
Electricity Supply	-7.4	-31.2
Other Energy Supply	-8.3	-50.3
Systems Integration	7.5	61.9
Total Energy-Related	19.6	50.1
Non-CO_2 gas reductions	1.9	7.9
Total Investment	21.5	58.0

Table 6d. Average Annual Incremental Investment for World Total: Multigas Long-term Stabilization Case (billion 2000 US dollars)

	2020-2060	2060-2100
Buildings-related	18.6	43.2
Industry	12.9	23.0
Light-duty Vehicles	22.4	57.3
Other Transportation	7.8	16.5
Electricity Supply	-6.2	-50.5
Other Energy Supply	-13.9	-78.4
Systems Integration	12.0	88.9
Total Energy-Related	53.6	100.1
Non-CO_2 gas reductions	2.5	10.0
Total Investment	56.1	110.1

6. FURTHER DISCUSSIONS

From an investor’s viewpoint the amount of capital necessary to switch from a development path dominated by fossil fuel technologies seems large as

Table 7. World GDP (Billion 2000 US Dollars Change from Reference Case)

Scenario	2020	2040	2060	2080	2100
CO_2 Reductions with Price-only Policy	-14	-17	-23	-3	21
CO_2 Reductions with Full Policies	-7	-9	-16	1	18
Multigas Reductions with Full Policies	-4	-2	-2	8	23
Temperature Constraint with Full Policies	-29	-43	-53	-35	-11

the emphasis shifts to one that relies primarily on energy-efficient, low-carbon technologies. But from the perspective of a world economy the total increase in new capital requirements does not seem quite so dramatic. As shown in Figure 3, incremental energy-related investments range from 0.2% to 1.6% of total investment in any given year, in order to achieve long-term climate stabilization. Compared to worldwide GDP, the scale of investment outlays is even smaller, ranging 0.1% to 0.6%.

The consequences for GDP, as shown in Table 7, are essentially in the noise. Above average rates of return on energy efficiency investments can have small positive effects in GDP. Displacements by climate stabilization investments of other investment will lead to a negative effect on GDP; but, again, this effect would be relatively small if the climate-related investments are relatively small. The case with the highest climate-related investments is the one where the rate of temperature change is constrained, as shown in Table 7. Note that the Table 7 changes in GDP are reported in billions of 2000 US dollars while the world economies are measured in trillions of 2000 US dollars.

Similarly, the change in the consumption path is relatively small. Reductions in consumption due to lower GDP and due to crowding out from increased investment expenditures are largely offset by increased real income in the non-OPEC world arising from lower oil import expenditures. Oil import expenditures are lower due to both reduced petroleum use in transportation and lower oil prices responding to reduced oil demand.

7. CONCLUSIONS

We have seen that methane and other non-CO_2 greenhouse gas reductions could significantly contribute to the low-cost achievement of climate goals, both for slowing the rate of temperature change and for long-term stabilization. However, carbon emission reductions will remain the primary objective. We have suggested in this paper that technologies and technology policies exist which could reduce greenhouse gas emissions sufficient to achieve the specified stabilization targets at relatively modest costs given the size of the world economy. This can be accomplished largely through harnessing market forces and creating incentives through the use of efficient prices on greenhouse gas emissions, combined with complementary programs and policies to reduce market failures and to promote new technology improvement.

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