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Current Carbon Emissions in Context: Final Report to the National Commission on Energy Policy

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Executive Summary

The challenge of developing policy for the mitigation of greenhouse gas (GHG) emissions arises from several different factors. In particular, GHG mitigation is a long-term task and sustaining policy over a long time can be difficult. Next, the cost benefit of GHG mitigation is not consistent with the preferred policy approach of delivering immediate benefit, with costs deferred to a later time. GHG mitigation is in many ways like buying insurance for future generations. Further, the total cost of mitigation appears to be very large, primarily because the scale of the systems that need to be changed is massive. Finally, the United States is currently the largest national emitter of carbon dioxide. There is a real question of how the U.S. should view itself within the context of this global challenge, particularly in light of the growing emissions from the developing world.

The idea of a "carbon shadow" is a new concept that might help policy makers as they wrestle with the important issues outlined above. The key idea that underlies the concept is that the current capital stock of fossil fuel generating and consuming technology will continue to produce carbon emissions until they are retired. The properties of existing capital stock limit the policy options available, because the premature retirement of capital stock is one of the most important costs in an aggressive GHG mitigation strategy. The rate at which capital stock produces GHG emissions is a property of the technology itself, reflected in the efficiency of a fossil-fired fuel plant or of a motor vehicle. Therefore if one understands how long the technology will be in use it is possible to calculate how much carbon dioxide will be emitted by an individual plant or vehicle.

In order to demonstrate the power of this approach we have conducted an analysis of the carbon shadows for existing U.S. electricity and transportation capital stock. For reference:

- Electricity generation accounted for 39% of 2001 U.S. carbon emissions
- Highway transportation (cars and trucks) accounted for 23% of 2001 U.S. carbon emissions

Together, these two capital stocks represent 62% of U.S. emissions, about 15% of global carbon emissions in 2001.

The analysis does several things:

1. It examines the ways in which one might determine the lifetime of a particular piece of technology, drawing a distinction between approaches based on the capital cycle and actual retirement data.

2. It focuses on the use of a retirement model based on historical data and describes retirement rates for U.S. electricity generation and transportation capital based on these data. These retirement rates are then used to derive the carbon shadows for

the technologies based on their inferred retirement rate.

3. It then describes how the desire for stabilizing carbon dioxide concentrations at a particular level leads, because of the nature of the carbon cycle, to a global budget for carbon dioxide emissions.

4. The carbon budget is then used to calculate "carbon shadow indices" for existing U.S. capital stock in the electricity generating and ground transportation sectors, which reflect the fraction of the global carbon budget (550 ppmv stabilization) that will be consumed by this capital stock over the next 50 and 100 years. These indices give insight into if and when premature retirement of capital stock might be required to meet emission targets.

5. The analysis of the electricity generation and ground transportation sectors were then used to generalize the carbon shadows for the entire U.S. economy.

6. Finally, the analysis is extended to show how various factors such as carbon cycle uncertainties, choice of stabilization level, and specific technology characteristics affect the basic results.

The results of these analyses provide an interesting perspective on current emissions. Figure ES1 shows the carbon shadow of currently existing U.S. electricity generating capital stock. The total projected emissions, based on the retirement model, exceeds 25 gigatons of carbon over the next 100 years and is dominated by coal-fired steam turbines. Note that almost 20% of these emissions come after 2050, showing the potential impact of continuing historical retirement practices into the future.

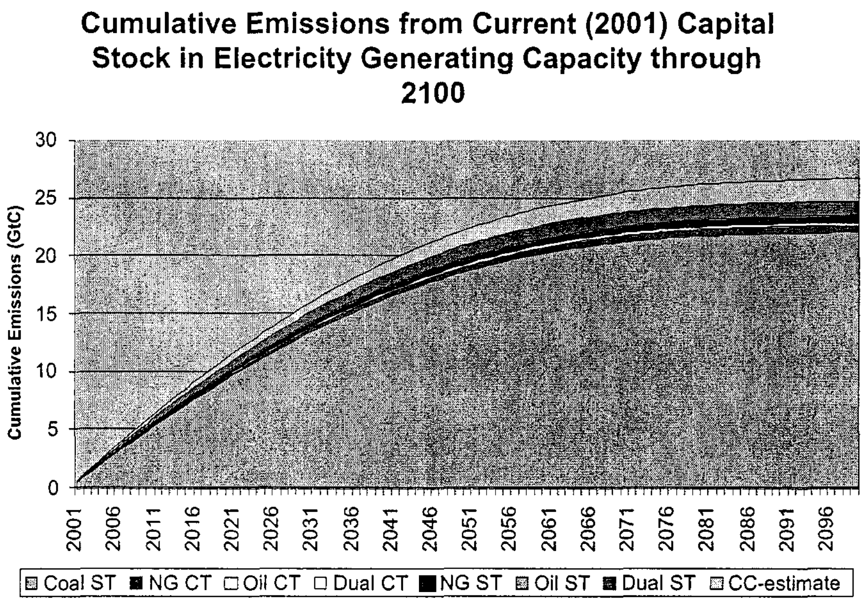

Figure ES1. Cumulative emissions (GtC) from electricity capacity technologies operating as of 2001 through 2100.

There is a contrast with the vehicle sector (Figure ES2) where most of the emissions that make up the carbon shadow come in the first 25 years of the century. Yet even with the shorter lifetime of vehicle stock the current U.S. vehicle fleet is projected to emit more than 4 gigatons of carbon. The bulk of the carbon shadow is equally divided among passenger vehicles, light duty trucks (including SUVs) and heavy-duty trucks.

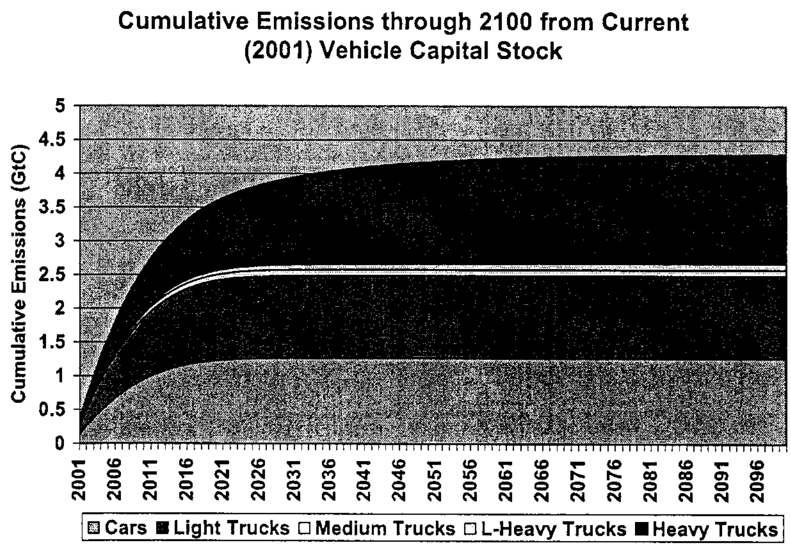

Figure ES 2. Cumulative emissions from current (2001) capital stock in vehicle capital stock through 2100.

Having analyzed electricity generation and ground transportation in detail, we have used those results to generalize the results to determine the carbon shadows for the entire U.S. capital stock. These results for the two analyzed sectors and the generalization to the rest of the U.S. capital stock are summarized in Table ES1. The definition of the carbon shadow as shown here is the amount of carbon that will be emitted by sector over the period from the present to dates indicated (2050 and 2100).

Sector	Carbon Shadow 2050 (GtC)	Carbon Shadow 2100 (GtC)
Electricity Generation	22.3	26.8
Ground Transportation	4.2	4.3
Other	13.4	16.1
Total Carbon Shadows	39.9	47.2

Table ES1. Total carbon shadows for the United States capital stock to 2050 and 2100 respectively.

Putting these carbon shadows in perspective requires the calculation of a budget for global carbon emissions under the constraint of some stabilization level. The level of 550 ppmv has been chosen as a reference case. The budget was calculated under some key assumptions. First, it used a reduced form carbon cycle model that has fairly standard assumptions about how the natural carbon cycle operates. Second stabilization was constrained to be completed by 2150 and the carbon reductions profile was constrained by a cost minimization approach of the type used by Wigley, Richels and Edmonds. Finally the base case for global emissions was a variant of the IPCC B2, scenario a moderate economic and population growth scenario. The resulting global carbon budgets are 460 GtC and 870 GtC to 2050 and 2100, respectively.

	2001 emissions	2050	2100
Emissions from Electricity Generation Capacity	0.6 GtC	22.0 GtC 4.8%	26.8 GtC 3.1%
Emissions from Ground Transportation	0.36 GtC	4.2 GtC 0.9%	4.3 GtC 0.5%
Emissions from other sources	0.6 GtC	13.4 GtC 2.9%	16.1 GtC 1.9%
Shadow in GtC As % of Global Carbon Budget		**39.9 GtC 8.7%**	**47.2 GtC 5.4%**

Table ES2. Global carbon budgets and their relationship to the carbon shadows of existing U.S. capital stock. The percentages of the global budgets are calculated on the basis a budget of 460 GtC to 2050 and 870 GtC to 2100.

The results are striking. The current U.S. capital stock in electricity generation alone is projected to consume 4.2% of the entire global carbon budget (550 stabilization) for the next 50 years and 3.1% of the 100-year budget. Currently installed coal fired steam turbines account for most of the carbon shadow of U.S. emissions, and are projected to consume 4.1% of the entire global carbon budget over the next 50 years and 2.6% over the next 100.

The situation is even more interesting when one considers what the situation will be in 2020, if the U.S. continues on a more or less "business as usual" path of the use of fossil fuels resources. A simple analysis suggests that by 2020 the combination of emissions from 2000 to 2020 with the carbon shadows of the capital stock existing in 2020 will lead to the U.S. having used or committed to use, 63.9 and 80.1 GtC, of the global carbon budget to 2050 and 2100, respectively. This corresponds to 13.9% and 9.2% of the global carbon budget (550 ppmv stabilization target), even if no further capital equipment utilizing fossil fuels were introduced into the U.S. economy after 2020.

It is useful to put the U.S. situation in a more specific context, by trying to estimate what might be an "appropriate" U.S. share of global emissions. We have taken five different approaches to such an estimate, which can be summarized as follows:

1. The U.S. share for the 21st century is based on maintaining an average emission of some benchmark year.

2. Estimating the U.S. share by claiming that the share of emissions in a given year would be the share in perpetuity of the global budget.

3. Indexing emissions to GDP and extrapolating the likely share of U.S. share of global GDP over the 21st century.

4. Using the current administration's goal of reducing carbon intensity by 18% per decade.

5. Having the relative shares of carbon emissions trend to a per capita distribution of shares by 2100.

Table ES3 summarizes these possible U.S. carbon budgets and provides a comparison with the various possible U.S. shares of the carbon budget noted above.

Basis of allocation		U.S. Budget to 2050 (GtC) with % of Global Budget	U.S. Carbon shadow to 2050 as a % of budget (550)	U.S. Budget to 2100 (GtC) with % of Global Budget	U.S. Carbon shadow to 2100 as a % of budget (550)
Maintain average emissions	Base Year 1990	66 14.3%	60.5%	132 15.2%	35.8%
	Base Year 2001	78 17.0%	51.2%	156 17.9%	30.3%
Maintain share of global emissions	Base Year 1990	99 21.5%	40.3%	187 21.5%	25.2%
	Base Year 2001	108 23.5%	36.9%	205 23.6%	23.0%
Share based on relative share of the global economy		126 27.4%	31.7%	213 24.5%	22.2%
18% per decade reduction in carbon intensity		76-117 16.5-25.4%	52.5-34.1%	122-182 14.0-20.9%	38.7-25.9%
Trend to share based on relative population in 2100		87 18.9%	45.9%	124 14.3%	38.1%

Table ES3. United States carbon budgets to 2050 and 2100 under the various assumptions described in the text. For perspective the U.S. budgets are also shown as a percentage of the global carbon budgets to 2050 and 2100, 460 and 870 GtC (550 stabilization) respectively. Also shown is the carbon shadow for the entire U.S. economy as a percentage of the U.S. budgets.

The various means of estimating U.S. shares give a wide range of possible U.S. budgets, yet the results are striking in any context. They suggest that existing capital stock has committed the U.S. to the use of 30-60% of a reasonable estimate of the allowance for a 550 ppmv stabilization to 2050 and 22-38% of the those allowances for the century. This analysis is extended in the main text of the report and further suggests that, if the U.S. continues a "business as usual" use of fossil fuels as described above, by 2020 it will have either consumed, or committed to consume (as carbon shadow) 50-95% of its share to 2050 and 35-65% of its share for the century.

Clearly if the U.S. continues on something that resembles its current emissions pathway, by 2020 it will be faced with the prospect of prematurely retiring some of its capital stock under some of these budget scenarios.

All analyses like the ones described above are subject to uncertainties and are sensitive to underlying assumptions. While other sensitivities and uncertainties need to be addressed, two deserve special mention because they have important policy implications. They are uncertainty in our understanding of the carbon cycle and sensitivity to the selection of a carbon stabilization goal. The calculation of a carbon budget helps put the carbon shadows in context. However our knowledge of the global carbon cycle is not perfect and one uncertainty in particular has a major impact on the stabilization budgets. This is the value for the long-term uptake of carbon dioxide by the oceans and terrestrial ecosystems. Similarly, while a reference analysis was done using a concentration of 550 ppmv for a CO_2 stabilization goal, this is not the only choice. 550 ppmv is a frequently used target value, simply because it represents a doubling of the pre-industrial concentration of carbon dioxide. Performing the analysis for other concentration targets, 450 and 650 ppmv shows the sensitivity of the results to the stabilization policy.

Table ES4 summarizes the impact of the carbon cycle and uncertainty and the stabilization level policy choice. The reference case is the amount of carbon that would be emitted under the base assumptions noted above, an IPCC B2-like scenario. Several points are worth noting. First, that for the 650 ppmv target, major reductions are not required until the second half of the century. For 450 ppmv stabilization there are not only severe reductions in allowable emissions in the next 50 years, the emissions allowed in the second half of the century are less than 200 gigatons. Next, it is important to note the impact of the uncertainty in the carbon cycle shown in the uncertainty range. While the large range of uncertainty is interesting, the policy ramifications of reducing the possibility of very much lower than expected budgets due to lower uptake of carbon dioxide is evident. The reduction of budgets would 10-20% through 2050 and 20-40% through 2100, which make them both much tougher targets.

	Stabilization at 650 ppmv	**Stabilization at 550 ppmv**	**Stabilization at 450 ppmv**	**Reference case**
Global carbon budget to **2050** (GtC)	505	460	373	500
Uncertainty range (GtC)	451 – 515	423 – 463	311 – 397	
Global carbon budget to **2100** (GtC)	1089	870	579	1345
Uncertainty range (GtC)	815 -1 176	663 – 973	331 - 655	

Table ES4. The global carbon budget, assumptions and uncertainties.

When we begin to compare the global budgets above to the U.S. carbon shadows and the analysis of U.S. likely future emissions, several key points emerge. As can be seen in Table ES5, current shares and likely near term emissions have greatest impact for concentration goals lower than 550 ppmv. Further, the impact is not linear, but skewed and 450 ppmv is far harder to reach relative to 550 ppmv than 550 ppmv is relative to 650 ppmv. It is important to note that for the lower target (450 ppmv), existing capital stock makes a significant impact even in the second half of the century.

	To 2050		**To 2100**	
Total U.S. Carbon Shadow in GtC	**39.9 GtC**		**47.2 GtC**	
As % of Global Carbon Budget		**Range**		**Range**
for 450 ppmv	**10.7%**	**10.1-12.8%**	**8.2%**	**7.2-14.2%**
for 550 ppmv	**8.7%**	**8.6-9.4%**	**5.4%**	**4.8-7.1%**
for 650 ppmv	**7.9%**	**7.7-8.8%**	**4.3%**	**4.0-5.8%**

Table ES5. The U.S. carbon shadows to 2050 and 2100 shown as a percentage of the corresponding global carbon budgets.

Finally, when we look at how current capital stock and near term emissions might impact the U.S. share of the budget, the difficulty with trying to meet lower targets is even more obvious. This is highlighted by looking at Table ES6, which looks at the impact U.S. near term emissions and likely future carbon shadows have on U.S. shares of the global carbon budget in 2020.

	U.S. share of total global budget (percentage of global budget)	U.S. budgets and carbon shadow as a percentage of the budget to 2050		
Assumptions about U.S. share of global carbon budget		450	550	650
Maintain share (2001)	23.5%	88	108	119
		72.9%	59.1%	53.8%
Maintain % of Global Economy	27.4%	102	126	138
		62.5%	50.7%	46.2%
Population Based	18.9%	70	87	95
		90.6%	73.5%	66.9%
		U.S. budgets and carbon shadow as a percentage of the budget to 2100		
		450	550	650
Maintain share (2001)	23.5%	136	204	256
		58.9%	39.2%	31.3%
Maintain % of Global Economy	24.5%	142	213	267
		56.5%	37.6%	30.0%
Population Based	14.3%	83	124	156
		96.7%	64.4%	51.4%

Table ES6. The consumption of and committed consumption (carbon shadow) of the U.S. share of the global carbon budget in 2020 under a range of target concentrations and for three U.S. policy options that are referenced to the emissions in the rest of the world and a continuation of business as usual use of fossil fuels by the U.S.

The results of these analyses lead to the following conclusion and observations:

- The concept of a global carbon budget associated with particular stabilization levels for atmospheric carbon dioxide is a useful method for putting future emissions in context.
- For the globe global carbon budgets to 2100 range from 579 GtC for 450 ppmv target to 1089 GtC for a 650 ppmv target. The uncertainties in these budgets due to knowledge of the carbon cycle are only 10-15% for the next 50 years and climb to 20-25% for the century
- It is possible to analyze the U.S. capital stock in transportation and electricity generation and estimate future emissions from these existing sources by estimating future retirement rates based on past experience. It is also possible to generalize the results for these two sectors to the entire U.S. capital stock. This

analysis suggests that current capital stock will release approximately 39.9 GtC over the next 50 years and 47.2 GtC over the next century.

- An analysis of possible future emissions by the U.S. suggest that by 2020, on a business as usual trajectory, the U.S. will have consumed or committed to consume 63.9 and 80.1 GtC of the global budgets to 2050 and 2100 respectively.

- Based on an analysis of a wide variety of possible U.S. shares of global carbon budgets of between 14% and 28% of global emissions, we find that existing capital stock has committed the U.S. to the use of 30-60% of its possible allowance for a 550 ppmv stabilization to 2050 and 22-38% of the possible allowance for the century. If the U.S. continues a "business as usual" use of fossil by 2020 it will have either consumed, or committed to consume (carbon shadow) 50-95% of its share to 2050 and 35-65% of its share for the century.

- The impact of current U.S. capital stock on global carbon budgets, and the corresponding U.S. share of that budget, is greatest for lower desired carbon dioxide concentrations. Under some scenarios for these low concentrations targets, current capital stock has consumed a higher fraction of the 100 year budget than of the 50 year budget, suggesting future pressure for premature retirement of capital stock.

By 2020 the U.S. may be in a position that it has little if any option to create new capital stock that freely vents carbon dioxide to the atmosphere if a global goal of 450 ppmv is to be achieved. Further even if the concentration goals are higher there will be severe constraints on deploying such resources as well.

1. Introduction and Background

Developing policy for the mitigation of greenhouse gas (GHG) emissions is a major challenge. The challenge arises from several perspectives.

First, GHG mitigation is a long-term task. Whatever policy, or succession of policies are developed, they must be sustained over the period of time necessary to stabilize greenhouse gas concentrations. All analyses suggest that the time period is at least a century.

Second, every policy has both benefits and costs. Problematically, the cost benefit profile of GHG mitigation is contrary to the preferred policy approach. Policymakers prefer to provide immediate benefits, with costs deferred to a later time. For GHG mitigation however, even if the policy is effective, and the change in emissions is exactly what is desired, it may not be possible to see the impact of actions on total emissions for several decades. Further, GHG mitigation does not reverse climate change, it only stops the anthropogenic component of that change and climate stabilization will only be achieved after the end of the stabilization process. On the other hand, the costs are far more immediate – essentially, beginning now.

Third, the costs can appear to be very large. The total global costs of most mitigation scenarios are measured in trillions of dollars. If one puts these costs in perspective by either comparing them to global GDP or to total investment that will be made in energy generation and consumption technology over this century, the costs look relatively modest. However, the total cost is intimidating, particularly when advocating action now, while there remains some uncertainty in the science.

Fourth, the scale of the systems that need to be changed is massive. The goal is to make a dramatic change in the nature of global energy production and use. Currently, the annual global waste stream from fossil fuel combustion, measured in billions of tons of carbon emitted, is six times larger than the annual global production of iron and steel. It is not just the existing energy system that must be transformed. Concurrently, it will be necessary to provide an energy infrastructure for developing nations that both provides adequate energy for development and does not drive their technological infrastructure into a dependence on fossil fuels and the free venting of carbon dioxide to the atmosphere.

Finally, the United States must be a significant player in the eventual mitigation of GHG emissions. It is currently the largest national emitter of carbon dioxide. There is a real question of how the U.S. should view itself within the context of this global challenge, particularly in light of the growing emissions from the developing world.

In this paper we suggest that the key to near term actions is an understanding that there is not only the issue of current emissions, but also the issue of current capital stock that will continue emitting into the future. An important cost of future mitigation is the loss of economic value of existing capital stock through premature retirement. The current stock of energy generating and consuming technologies, for example in the transportation and electricity generating sectors, cast a carbon shadow into the future. When the shadow of the existing capital stock, as well as current construction and manufacture of fossil fuel dependent technologies, is calculated, one realizes the extent to which we have already committed to consuming this century's global budget of carbon dioxide emissions. This carbon shadow highlights the potential need for both an accelerated deployment of non-carbon emitting technologies and a policy approach that addresses the problem of current capital stock.

In what follows we will:

1. Describe how the desire for stabilizing carbon dioxide concentrations at a particular level leads, because of the nature of the carbon cycle, to a global budget for carbon dioxide emissions.

2. Discuss the variety of ways that a carbon shadow can be important, motivating the focus of this report on U.S. electricity generation and transportation vehicles.

3. Examine the ways in which one might determine the lifetime of a particular piece of technology, drawing a distinction between the capital cycle and actual retirement.

4. Describe the process for calculating the retirement rates for U.S. electricity generation and transportation capital and derive the carbon shadows for the technologies based on their inferred retirement rate.

5. Generalize the carbon shadows for the U.S. beyond electricity generation and ground transportation, and put these in the context of various assumptions about appropriate U.S. shares of the global carbon budget.

6. Describe how various factors such as carbon cycle uncertainties, choice of stabilization level, and specific technology characteristics affect the basic results.

2. Budgets and Shadows

2.1 Carbon Budgets

There are a variety of ways to think about the transition from the current situation of increasing concentrations of atmospheric greenhouse gases to a stabilization of those concentrations. For the current work we are putting that transition into perspective by looking at the amount of carbon that can be emitted between now and a future time along a particular projected emissions path that would achieve a stabilization of the atmospheric concentration of carbon dioxide. The cumulative carbon emissions leading to stabilization is what we will refer to as an "allowable carbon budget."

The allowable carbon budget for stabilization is largely a function of two considerations. The first is the concentration at which one might wish to achieve stabilization: the lower the stabilized concentration the lower the allowable budget. Second, it is a function of the behavior of the Earth's carbon-cycle. If terrestrial and oceanic carbon reservoirs take up carbon at a greater rate, then the allowable budget for anthropogenic emissions will be larger. The shape of the path toward stabilization and the exact time of stabilization have some effect on the size of the allowable carbon budget, but are much less important than the target value and carbon-cycle parameters. A detailed discussion of how these various factors determine the allowable carbon budget is contained in Appendix A.

In Appendix A the trajectory for stabilization is of a type that has become to be known as a WRE trajectory. This trajectory, first elucidated by Wigley, Richels and Edmonds in 1996 is determined by minimizing the cost of achieving a particular stabilization level. As noted above, the exact trajectory is not critical to the allowable budget. Table 1 presents the allowable carbon budget for fossil emissions (fossil fuels plus cement production) for a trajectory that would achieve a 550 ppmv concentration target by 2150. The allowable carbon budgets up to the years 2050 and 2100 are 460 and 870 GtC, respectively.

The results in this section will be presented for a concentration target of 550 ppmv. A discussion of the impact on the analysis of selecting alternate target concentration is discussed later in the paper and in Appendix A.

	Allowable cumulative emissions under a 550 ppmv atmospheric concentration target by 2150 (GtC)
2050	460
2100	870

Table 1 Allowable cumulative emissions, in gigatons of carbon (GtC), from 2000 to 2050 and 2100 along a trajectory that would achieve a 550-ppmv atmospheric concentration target by 2150.

With the "allowable" carbon budget established, we can now turn to the question of how much of budget is already "committed to" because of the existing capital stock.

2.2 Carbon Shadows

The idea of a "carbon shadow" is a concept that attempts to capture quantitatively the impact of the current capital stock of fossil fuel generating and consuming technology as they continue to produce carbon emissions until they are retired. Specifically, the concept can be used in conjunction with the "allowable" budgets, discussed previously, to indicate the extent to which current capital stocks limit future flexibility in carbon emissions. It is possible to compute these shadows because the rate at which capital stock produces carbon emissions is a property of the technology itself, reflected in the efficiency of a fossil-fired fuel plant or of a motor vehicle. Therefore, if one understands how long the technology will be in use and how much it will be used, it is possible to calculate how much carbon dioxide will be emitted by an individual plant or vehicle.

By itself the carbon shadow cast by existing capital stock is interesting but lacks context. The context comes when one understands that stabilization at any particular concentration of atmospheric carbon dioxide implies a global budget for emissions over the course of this century. Therefore, it is possible to understand what fraction of this global budget is "spoken for" by the existing capital stock. This fraction we will refer to as the carbon shadow index, or share committed to, of the current capital stock. The capital stock, and therefore the carbon shadow, can be disaggregated by sector, specific technology or by country, providing context at a variety of levels.

Current capital stock leads to future emissions in three ways, direct conversion, energy utilization technologies, and structural consumption. This report focuses on only the first class of technologies, but as one contemplates the problem of stabilizing the concentrations of greenhouse gases it is important to realize that there are other technological shadows that impact carbon emissions, largely through their consumption of energy.

1. Direct conversion technologies: These technologies directly convert fossil fuels into energy services. This report will focus on the two largest of these technologies, electricity generation and vehicle transport. There are other technologies that fall into this class, such as cement production, some forms of steel production, and the use of natural gas for home heating. The basic characteristic of these technologies is that the individual plant or vehicle is characterized by a direct relationship between the energy service and the consumption of fossil fuels. This relationship is a property of the capital stock itself and is not readily changed. An example is automotive efficiency measured in miles per gallon.

2. Energy utilization technologies: These technologies are characterized by a direct relationship between an energy service and the consumption of some energy

carrier. Examples include many end use technologies, such as refrigerator and air conditioners. Like the direct conversion technologies the relationship between the energy service and the consumption of, for example, electricity is a property of the technology and not easily changed over the lifetime of its usage. The degree to which these technologies create a carbon shadow is a function of the extent to which the energy carrier generates carbon emissions and the turnover rate of the technologies.

3. Structural consumption: Some demand for energy services is structural and embodied either in a capital infrastructure or other societal factors. These range from buildings to highways to zoning decisions. Each has a certain degree of mutability as a function of time, but the basic structure implies a demand for energy services. For example tall buildings require elevators, and housing and employment being separated by large distances creates a demand for surface transportation. The impact of these demands on carbon emissions can be modified through changing the technologies that provide the services. However, the structural demand places limits on the benefits that energy efficiency or carbon intensity improvements can achieve. These limits are in turn embodied in a long-lived capital stock.

The key point about all three of these sources of carbon shadows is their embodiment in capital stock. Further, the currently existing capital stock limits the possible alternatives for the future. Retiring capital stocks before their useful life has run out incurs costs on society by shifting resources from capital expansion to capital replacement, with a concomitant loss of the economic value of the prematurely retired asset. This cost therefore suggests that, absent any policy, existing capital stocks will still be used until their retirement.

3. Carbon Shadows of U.S. Transportation and Electricity Generation Sectors

3.1 Capital Cycles vs. Retirement

The calculation of a carbon shadow for a direct conversion technology is based on three factors. They are the rate of carbon emissions per unit of service provided (e.g. carbon emissions per kilowatt), the average rate utilization of the services provided (kilowatts produced per year) and the lifetime of the technology (years before retirement). There are a number of timescales that could be used, and have been used, to estimate time of retirement. Because we are discussing capital stock and the financial consequences of premature retirement, it is tempting to use financial measures to determine the age of the asset at retirement. Such measures include the time to pay off funds borrowed for construction of the asset, to the time to depreciate the capital stock for tax purposes. These two are some times referred to as capital cycles. Capital cycles analysis assumes that characteristics such as lifespan, time to retirement, of capital investments are a fixed characteristic of capital itself.

A recent report by Lempert, Popper, Resetar and Hart[1] has examined the question of capital cycles in the climate change context. They conclude, "Capital has no fixed cycle". That is to say that financial considerations alone do not determine when one piece of capital stock is replaced with another. They highlight this by also concluding "equipment lifetime and more efficient technologies are not significant drivers in the absence of policy or market drivers".

Clearly, the useful life of capital can be extended well beyond its "normal" financial lifespan; coal plants, in particular, are still economically viable for decades after all capital costs have been paid.

The depreciation approach assumes that the useful output of a capital stock is reduced by a constant percentage each year. The data, however, (see model description below) suggests that capital retirement proceeds more slowly in early years and most quickly in the middle years of capital life, not at the constant rate assumed by depreciation. The retirement of capital stock appears rather to be driven by a combination of engineering factors, such as efficiency, breakdown, and repair costs, which in turn are driven by age and non-age-related factors, such as economic conditions, fuel prices, and the prices and/or the availability of alternative technologies.

The following analysis is based on third approach, an historical analysis of the actual retirement (removal from service) of direct conversion technologies used for electricity and vehicle transportation.

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[1] "Capital Cycles and the timing of climate change policy" Pew Center for Global Climate Change, October 2002.

Before beginning the historical analysis of retirement it is worth noting the reasons for selecting electricity production and highway transportation. The basic numbers are quite compelling:

- Electricity generation accounted for 39% of 2001 U.S. carbon emissions
- Highway transportation (cars and trucks) accounted for 23% of 2001 U.S. carbon emissions
- Together, these two capital stocks represent 62% of U.S. emissions, and roughly 15% of global carbon emissions for 2001.

These sources do have some important differences. The capital stock in electricity production sector has a long life (30-70 years) and a correspondingly longer carbon shadow. The sector is composed of a small number of large emitters and some units (especially steam turbines) can be used almost indefinitely. On the other hand ground transportation is characterized by a relatively short life (10-15 years) and thus, a shorter carbon shadow. It is composed of a large number of small-scale emitters and vehicles are used more intensively when younger than when older, leading to a more rapid drop-off in the carbon shadow as the stock ages.

Once we have completed the analysis for these two sectors we will generalize the results in order to estimate the entire U.S. carbon emissions shadow.

3.2 Electricity Generation

Three fossil fuels —coal, natural gas, and oil— are used in four different electricity production technologies —steam turbine, combustion turbine, internal combustion, and combined-cycle— to produce most of the electricity consumed in the United States.[2] Appendix B contains a more detailed description of nature of each of these electrical generation technologies. Appendix B also contains the details of the methodology used to calculate the carbon shadows.

Briefly, the base methodology employed for the analysis proceeds in three steps. First is the calculation of a retirement rate. The methodology for this is adopted from a Federal Reserve analysis due to Greenspan and Cohen. Their approach[3] considers two factors in retirement, age and a collection of financial terms cyclical scrappage.

The second step is to assess the capacity factor for the plants – how much the plant runs in a given year. Both the retirement rate and the capacity factor were estimated from historical data. The capacity factor is also a function of the age of the plant with older plants having a lower capacity factor. The final term in the analysis is the heat rate term,

[2] Other fuels include biomass and wastes, while other technologies include renewable energy sources such as wind turbines, hydro turbines, and geothermal steam turbines. As these fuels and technologies are either carbon neutral or at least very low carbon emitters, they are ignored in this study.
[3] http://www.federalreserve.gov/Pubs/FEDS/1996/199640/199640pap.pdf

which is used to calculate how much carbon dioxide is emitted by the plant when operating.

Since each electrical generating technology has a slightly different history, separate calculations were carried out for each technology-fuel combination. As shown in Figures 1 and 2, coal-fired generators dominate the carbon shadow of the electricity-generating sector. By 2050, the cumulative total coming from non-coal generators is 3.6 GtC, as compared to coal's 18.6 GtC, giving non-coal technologies approximately 16% of the sector's cumulative emissions. By 2100, this total increases to 4.7 GtC, compared to coal's 22.1 GtC, increasing non-coal technologies' share of cumulative emissions to 17.5%. This reflects the youth of the combined cycle generator stock, which continues to churn out carbon well into the 21st century, even after most of today's coal plants have been retired.

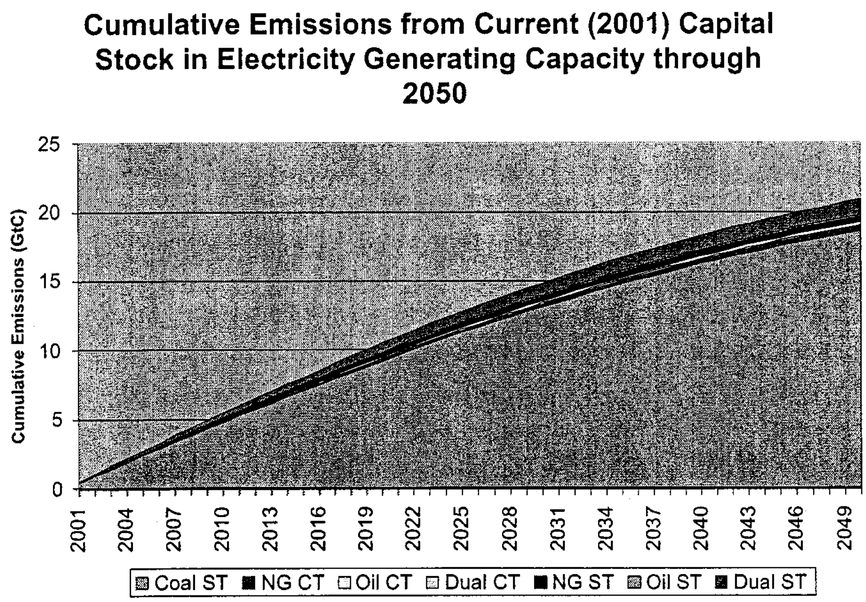

Figure 1. Cumulative emissions (GtC) from electricity capacity technologies operating as of 2001 through 2050. In the legend ST=steam turbines; CT=combustion turbines; NG=natural gas; and, dual refers to Steam turbines capable of being fired by either oil or natural gas.

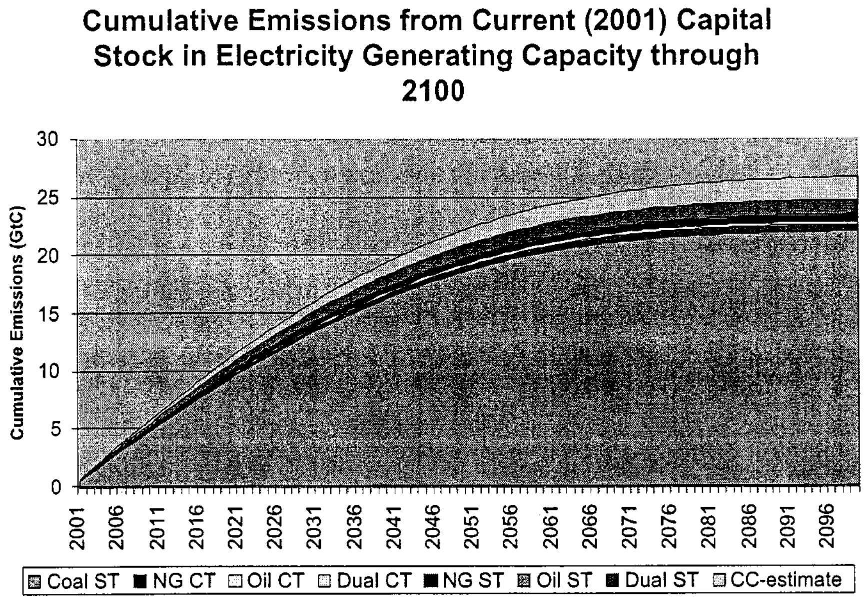

Figure 2. Cumulative emissions (GtC) from electricity capacity technologies operating as of 2001 through 2100. In the legend ST=steam turbines; CT=combustion turbines; NG=natural gas; and, dual refers to Steam turbines capable of being fired by either oil or natural gas.

The relatively long life of electricity generating capital stocks is highlighted in Table 2. In this table we show what the emissions would be if there were no retirements of capital stock as well as the projected emissions with retirement. Over the next 50 years there will a less than 25% reduction in cumulative emissions if the historical retirement rate of electrical generating capacity is maintained. Alternatively, existing capital stock is not very much of a factor after 2050.

While the carbon shadow diminishes for electrical generation, it should be noted that new fossil generation capacity will have an impact over much of the coming century and decisions how to replace retiring units will be critical to managing future commitments to carbon emissions.

Emissions from Electricity Capacity in year:	Cumulative emissions without retirement but with 2001 capital stock emissions constant for 50 or 100 years (GtC)	Cumulative emissions under expected retirement of 2001 capital stock (GtC)
2001	0.6	0.6
2050	30.1	22.3
2100	60.2	26.8

Table 2. Cumulative Emissions from electricity capacity under expected retirement of 2001 capital stock and with 2001 level emissions kept constant for 50 or 100 years.

3.3 Ground Transportation

The U.S. transportation sector accounted for 33% of national annual carbon emissions in 2001[4] , a significant source of emissions and potentially major contributor to U.S. carbon shadow. However, unlike power plants, data concerning vehicles is much harder to come by—the sheer number of vehicles makes reliable data difficult to find or expensive to obtain. For this reason, our model of transportation carbon shadows has been restricted to highway vehicles: cars, medium (GVW 10,001-16,000), light-heavy (GVW 16,001-26,000) and heavy-heavy (GVW 26,001+).light trucks, and heavy trucks.[5] Contributing approximately 76% of total transportation emissions, roughly a quarter of U.S. carbon emissions were attributable to these vehicles. This means that our more restricted model captures the lion's share of transportation-related carbon emissions. We will discuss other emissions associated with for example air transport as part of our generalization of the U.S. carbon shadow in the next section of the paper.

The detailed calculation of the ground transportation carbon shadow is contained in Appendix C. The model for this sector, like the electricity generator models, has three components. First, a retirement model calculates the total number of vehicles of each age group surviving into the next year. Second, a usage model determines how many vehicle miles are driven for each age cohort. The third component assigns the appropriate efficiency (measured in miles per gallon (mpg)) to each vehicle type and age group to obtain a total amount of fuel consumed and the associated carbon emissions.

Figures 3and 4 show the results of the calculations of the carbon shadow for the existing U.S. ground transportation fleet. There are several key features of these figures. First, unlike electricity generation where one technology dominates the carbon shadow, for ground transportation, passenger cars, light trucks and heavy trucks represent almost identical portions of the carbon shadow. Second, heavy trucks dominate the long-term component of the ground transportation shadow. Finally, practically all of the existing fleet will be retired before 2050.

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[4] Information on total 2001 carbon emissions from EIA's 2001 AEO.
http://www.eia.doe.gov/oiaf/aeo/results.html

[5] Polk, a data collection company, has extensive (but expensive) data on these classes of vehicles. There are some data available on publicly-owned transportation (buses and rail systems) and some information on the number of planes, but the historical data and usage data necessary to create a reliable vintage capital model is lacking.

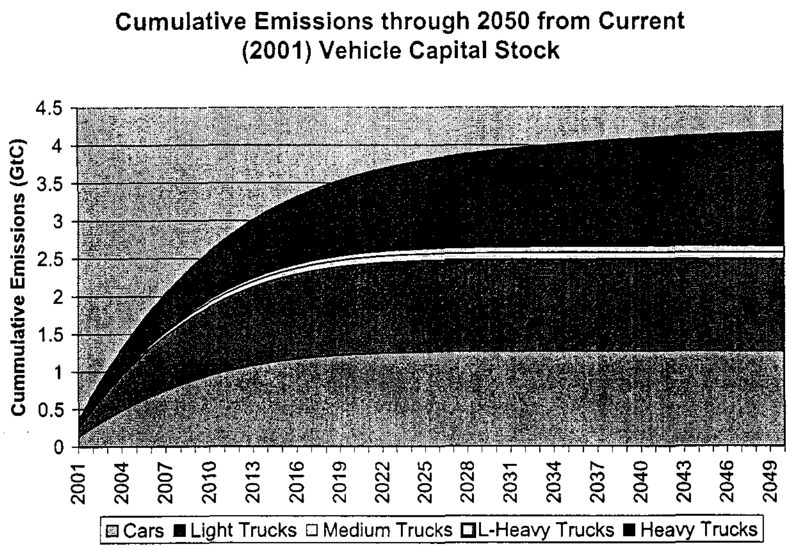

Figure 3. Cumulative emissions from current (2001) capital stock in vehicle capital stock through 2050.

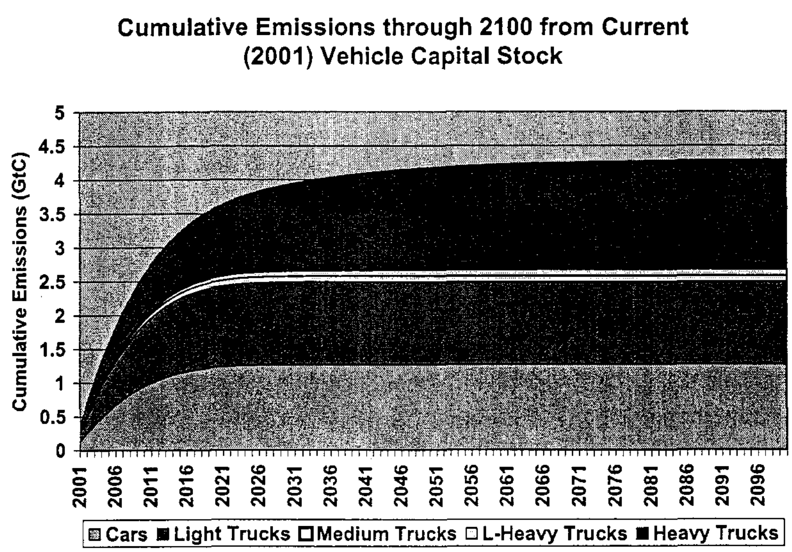

Figure 4. Cumulative emissions from current (2001) capital stock in vehicle capital stock through 2100.

This latter point is highlighted in Table 3. This table is the ground transportation equivalent of Table 2. Unlike electricity generation, the ground transportation stock only accounts for less than 25% of the emissions that would come from a constantly emitting fleet of surface transportation vehicles with comparable carbon emissions to the current U.S. fleet. Further, less than 3% of the carbon shadow of the current fleet will be emitted after 2050, in contrast to almost 17% of the shadow of the electrical generation sector coming from post 2050 emissions.

The results in Tables 2 and 3 highlight an important point about technological change. Specifically, a technology with relatively rapid turnover, like ground transportation, can see the effect of the introduction of new technology fairly quickly. As a result, the rapid turnover technology is not likely to be driven to early, uneconomic retirement by carbon emission policies. For longer-lived technologies, such as those found in electricity generation, premature retirement, and/or retrofit technologies maybe required to meet carbon emission targets.

Emissions from ground transportation in year:	Cumulative emissions without retirement but with 2001 capital stock emissions constant for 50 or 100 years (GtC)	Cumulative emissions under expected retirement of 2001 capital stock (GtC)
2001	0.36	0.36
2050	18.11	4.17
2100	36.23	4.29

Table 3. Cumulative emissions from U.S. ground transportation under expected retirement of 2001 capital stock and with 2001 level emissions kept constant for 50 or 100 years.

3.4 Projecting balance of the U.S. emissions shadow

The combined carbon shadows of the electrical generation and ground transportation technologies considered above are 26.4 and 31.0 GtC, for 2050 and 2100 respectively. However, as noted at the outset of the discussion, these sources, while making up most of the U.S. emissions, are not all of the emissions. The two sectors that we have analyzed make up approximately 62% of the total emissions. Table 4 summarizes the other sources of the other 38% of carbon emissions in the U.S.

Source	MtC (% of U.S) 2001	Nature of emissions (primary energy services)
Other transportation	447 (7.8%)	Aircraft, shipping, rail, buses
Industrial	1048 (18.2%)	Process and boiler heat
Commercial	227.2 (4.0%)	Space conditioning
Residential	366.2 (6.4%)	Space and water heating; cooking
Other	112.8 (2.0%)	Cement; gas production; waste combustion

Table 4. Carbon emissions in MtC in 2001 from sectors other than electricity generation and the ground transportation discussed earlier. Source AEO 2004 (DOE/EIA-383(2004)) and Emissions of Greenhouse Gases in the United States (DOE/EIA-0573(2002)).

An approach to estimating the rest of the U.S. carbon shadow is to use these numbers and the very different retirement characteristics of the two detailed analyses already completed as the basis of the estimate. Specifically, the ratio of the current annual emissions to the carbon shadow for a particular technology could be a measure of an "effective lifetime" of the technology. By this we mean if all of the emissions in a period were to be released to the atmosphere at a constant rate and all of the sources were to retire at the same time how long would they emit? Table 5 gives the effective lifetime for the electricity generation and ground transportation sectors calculated from the data in Tables 2 and 3.

	Effective Lifetime in Years
Electricity Generation – 2050	37.1
Electricity Generation – 2100	44.6
Ground Transportation - 2050	11.6
Ground Transportation - 2100	11.9

Table 5. Effective lifetimes of the capital stock in the electricity generation and ground transportation sectors based on the data in Tables 2 and 3.

End-use sector		Transport	Electricity		Transport	Electricity	
	2001	2050			2100		
Transportation	0.12	1.4	4.4	1.8	1.4	5.3	1.8
Industry	0.29	3.4	10.8	8.1	3.5	12.9	9.7
Commercial	.062	0.7	2.3	0.9	0.7	2.8	1.0
Residential	0.10	1.2	3.7	1.4	1.2	4.5	1.5
Other	.031	0.4	1.1	1.2	0.4	1.4	2.1
Total	0.60			13.4			16.1

Table 6. Estimating the carbon shadows for the rest of the U.S. economy. This table shows the 2001 emission in GtC for the end-use sectors not previously analyzed and summarized in Table 4. In the third and fourth columns the carbon shadow to 2050 is shown if the carbon emitting capital stock in each end-use sector had the same effective lifetime. The "other" end-use sector data comes from Table 7.

Considering each of these end-uses in turn we can use the data in Table 6 to estimate their carbon shadows.

> Other transportation: From Table 4 we can see that the previously not considered elements of the transportation sector are largely aircraft, rail and shipping. The base technologies probably have a longer lifetime than the average for ground transportation, which is dominated by passenger cars and light duty trucks. If we look at the carbon shadow for heavy trucks alone, we can calculate an effective lifetime to 2050 and 2100, of 17.6 an 18.9 years[6]. In Table 6 we have adopted an intermediate value for the balance of the transportation sector that is the average of the ground transportation and the heavy truck effective lifetime of 14.6 and 15.4 years giving carbon shadows of 1.4 and 1.8 GtC.
>
> Industry: The mix of end-uses associated with the industrial sector appear to be more durable than that associated with the transportation sector, but may not be as durable as the electricity generation sector. For present purposes we are estimating that these end-uses have a similar retirement profile to the electricity sector, but with a shorter effective lifetime. For present purposes we are estimating that this sector will have an effective lifetime 75% of the electricity generation sector.

[6] For U.S. heavy trucks the 2001 carbon emissions were 85.8 MtC and the retirement analysis in Appendix C gives a carbon shadow of 1.51 and 1.62 GtC for 2050 and 2100 respectively.

Commercial: We expect the commercial sectors carbon emissions to be greater than ground transportation and to be more in keeping with the balance of the transportation sector described above. While buildings themselves are relatively durable the heating infrastructure is replaced more often than the shell is raised and we estimate the durability of this capital to be comparable to that of the "Other Transportation" sector and will adopt its effective lifetimes for this calculation.

Residential: Space and water heating are the dominant end-uses and we are estimating that these systems have retirement rates comparable to their commercial counterparts.

Other U.S. Carbon Emissions: These emissions are difficult to estimate for several reasons. Looking at the five major sources in turn, we note that:

Cement production: The emissions from cement production are a function of the process not the capital stock. The emissions are therefore a product of the production of cement, which is in fact growing.

Natural Gas Flaring: This is a practice that is in heavy decline, having dropped nearly by a factor of 2 in the last decade. As a rapidly disappearing practice one cannot expect much of a shadow.

CO_2 in Natural Gas: The emissions here are a product of the natural gas being recovered and the demand for the CO_2 for other purposes that might sequester it. This source has increased with time.

Waste Incineration: These emissions are tied to a capital stock that likely has an industrial retirement schedule.

Other industrial: These include emissions from smelting and the use of limestone in desulphurization. The associated capital stock will have a characteristic industrial time scale.

Source	2001	Assumption	ELT 2050	ELT 2100	Shadow 2050 (GtC)	Shadow 2100 (GtC)
Cement	11.3	Constant	50	100	0.56	1.13
NG Flaring	1.4	Zero	0	0	0	0
CO2 in NG	5.1	Constant	50	100	0.25	0.52
Waste	5.4	Industrial	27.8	33.4	0.15	0.18
Other	7.6	Industrial	27.8	33.4	0.21	0.25
Total	30.8				1.18	2.07

Table 7: Estimates of the Carbon Shadow for other industrial sources. Column 3 contains the assumption made to estimate the effective lifetime (ELT) for the associated capital stock. Constant implies that the source is a product of the process not the capital equipment and the assumption is that there is constant use of the resource. Industrial means that the industrial effective lifetime (75% of the electricity sector has been used. Zero has been assumed for natural gas flaring which is a sharply diminishing practice.

We can now estimate the total carbon shadow for the United States, which is summarized in Table 8.

Sector	Carbon Shadow 2050 (GtC)	Carbon Shadow 2100 (GtC)
Electricity Generation	22.3	26.8
Ground Transportation	4.2	4.3
Other	13.4	16.1
Total	39.9	47.2

Table 8: Total carbon shadows for the United States to 2050 and 2100 respectively.

4.0 U.S. Emissions in Perspective

The key question now is, "what are the ramifications of capital lifetimes on future options for carbon dioxide emissions mitigation strategies in the United States?" Specifically, this can be looked at from four perspectives:

1. If the U.S. were to continue its emissions at present levels over the next century, how much of the global budget of emissions would it consume?

2. How much of the global carbon budget does the existing U.S. capital stock of carbon emitting facilities consume of the global budget?

3. If we estimate a range of values for the "share " of the century's global carbon budget that could be assigned to the U.S. how much of those budgets will the existing capital stock consume?

4. Since it takes time to make a transition to new energy systems, can we estimate the U.S. situation with respect to possible carbon budgets 20 years hence?

Many policy proposals start with stabilizing emissions as an interim goal on the path to carbon emissions reduction. Table 9 summarizes what the U.S. emission would be if they average 2001 emissions for the next 50 and 100 years respectively. There are several points worth noting in the context of Table 9:

- Maintaining average 2001 emissions over the next 50 and 100 means that the U.S. would use less than its current annual percentage of global emissions (Currently the U.S. is 24% of global carbon emissions.). This reflects the impact of the projected growth of carbon emissions in the rest of the world, most notably developing countries.

- For reference, it should be noted that the U.S. emissions in 2001 (1.56 GtC) have grown from 1990 levels (1.32 GtC). If the U.S. were to average 1990 emission levels for the next 50 and 100 years, those emissions would constitute 14.3% and 15.2% respectively of the global budget.

- Finally, Table 9 illustrates the impact of the stabilization trajectory that calls for less emissions in the second half of the 21st century than in the first, a reduction of 50 GtC.

	2001 U.S. Annual Emissions (GtC)	U.S. Emissions to 2050 and percent of the Global Carbon budget	U.S. Emissions to 2100 as a percent of the Global Carbon budget
Electricity Generation	0.60 GtC	30.1 GtC (6.5%)	60.2 GtC (6.9%)
Ground Transportation	0.36 GtC	18.1 GtC (3.9%)	36.2 GtC (4.1%)
Other Carbon Emissions	0.60 GtC	30.0 GtC (6.5%)	60.0 GtC (6.9%)
Total	1.56 GtC	17.0%	17.9%
Global Carbon Budget (GtC) for 550 ppmv stabilization		460 GtC	870 GtC
Global Carbon Emissions in 2000	6.61		

Table 9: Projection of U.S. emissions to 2050 and 2100 under the assumption of constant U.S. emissions. The results are shown both as total emissions in GtC and as a percentage of the Global Carbon Budget. The calculations of the percentages are based on budgets to 2050 and 2100, for a 550 ppmv target concentration.

The second question is, in essence, "how significant is the U.S. carbon shadow in the context of a global carbon budget?" The bottom line (Table 10) is that the carbon shadow of the current U.S. carbon emitting capital stock represents 8.7% and 5.4% of the global carbon budget to years 2050 and 2100 respectively. For context, from Table 9 we note that the if U.S. emissions remained constant over the century that they would represent 17.0% and 17.9% of the 2050 and 2100 global budgets respectively. Table 10 shows further that in the electric utility sector, existing capital has committed the U.S. to almost 75% of the emissions it would have it continued to emit at a constant level over the next 50 years.

		2050		2100	
		Cumulative emissions without retirement but with 2001 capital stock emissions constant	Carbon Shadow (Carbon Shadow as a percent of constant emissions)	Cumulative emissions without retirement but with 2001 capital stock emissions constant	Carbon Shadow (Carbon Shadow as a percent of constant emissions)
Cumulative U.S. Emissions from Electricity Capacity		30.1 GtC	22.0 GtC (73.1%)	60.2 GtC	26.8 GtC (44.5%)
Cumulative U.S. Emissions from Ground Transportation		18.1 GtC	4.2 GtC (23.2%)	36.2 GtC	4.3 GtC (11.9%)
Cumulative U.S. Emissions from other sources		30.0 GtC	13.4 GtC (44.7%)	60.0 GtC	16.1 GtC (26.8%)
Total U.S Carbon Shadow	**Shadow in GtC**	**39.9 GtC**		**47.2 GtC**	
	As % of Global Carbon Budget	**8.7%**		**5.4%**	

Table 10: A summary of U.S emissions from tables 8 and 9 showing the relationship between carbon shadows of various sectors and the global carbon budget and emissions associate with a flat emissions profile. Global carbon emissions budgets are based on target of 550 ppmv atmospheric concentration by 2150 and are 460 GtC (to 2050) and 870 GtC (to 2100).

While the percentage of the global budget is instructive, it is also worthwhile to consider what impact the carbon shadow of the U.S. current capital stock may have on future carbon emissions mitigations options. One way to do this is to consider what range of global emissions might apply to the United States. The purpose of this is not to enter into a discussion of what might be the "fair share" of global emissions that might be allocated to the U.S., but rather to see the extent to which current "committed" emissions might constrain future U.S. policy. In order to estimate what plausible range of U.S. emissions budgets might be, we have hypothesized five "bases of allocation" of global emissions. Again, none of these are recommendations as the basis of allocation; they are simply heuristics for understanding U.S. policy options. The five used here are:

1. Set the U.S. budget for the 21st century based on maintaining an average emission of some benchmark year. Table 10 does this for a benchmark year of 2001, but one could imagine using 1990, the year of the signing of the UN Framework Convention on Climate Change. If the benchmark year is 2001 the cumulative U.S. budget to 2050 is 78 GtC and to 2100 156 GtC. If the benchmark year were

1990 the U.S. budgets would be 66 and 132 GtC to 2050 and 2100, respectively.

2. Another means of estimating a budget would to say that the budget for any given year would be the same fraction, in perpetuity, of the global budget. Again there is the question of establishing the benchmark year for the budget. In 2001 the U.S. accounted for 23.6% of global emissions and 1990 21.5%. Therefore with 2001 base year the cumulative U.S. budgets would be 108 and 205 GtC to 2050 and 2100 respectively. If the base year were 1990 the U.S. budgets would be 99 and 187 GtC.

3. Since emissions are tied to economic activity it may be useful to consider indexing emissions budgets to GDP. In 2000 the U.S. economy was about 31% of global GDP. Using the IPCC Special Report on Emission Scenarios and assuming that the current relative rates of growth of the global economy and the advanced economies persist, on average, over the next century, the U.S. economy would be about 18% of the global economy, that is a $40-95T economy for the U.S. in 2100. By assuming a linear transition to this share of GDP we get U.S. carbon budgets of 126 and 213 GtC to 2050 and 2100, respectively.

4. Another approach might be to set the share in terms of a policy aspiration. One example is the idea of using the current administration's goal of reducing carbon intensity by 18% per decade. Currently the U.S. emits about .16 tons of carbon per dollar of GDP. If the goal of reducing the U.S. carbon emissions by 18% per decade could be sustained over this century that number would reach .022 tons of carbon per $ of GDP in 2100. Using the 2100 U.S. GDP numbers above ($40-95T) and an assumption of linear GDP growth over the century, the U.S. emissions budgets would be in the range of 76-117 GtC to 2050 and 122-182 GtC to 2100.

5. Finally, there has been some discussion of having the relative shares of carbon emissions trend to a per capita distribution of shares. For the U.S this would be a 5% share of annual emissions in 2100. Presuming a linear transition from the current 23.6% share of annual emissions this would imply 87 and 124 GtC U.S. budgets to 2050 and 2100.

Table 11 summarizes these possible U.S. carbon budgets and provides a comparison with the various possible U.S. shares of the carbon budget noted above.

Basis of allocation		U.S. Budget to 2050 (GtC) with % of Global Budget	U.S. Carbon shadow to 2050 as a % of budget (550)	U.S. Budget to 2100 (GtC) with % of Global Budget	U.S. Carbon shadow to 2100 as a % of budget (550)
Maintain average emissions	Base Year 1990	66 14.3%	60.5%	132 15.2%	35.8%
	Base Year 2001	78 17.0%	51.2%	156 17.9%	30.3%
Maintain share of global emissions	Base Year 1990	99 21.5%	40.3%	187 21.5%	25.2%
	Base Year 2001	108 23.5%	36.9%	205 23.6%	23.0%
Share based on relative share of the global economy		126 27.4%	31.7%	213 24.5%	22.2%
18% per decade reduction in carbon intensity		76-117 16.5-25.4%	52.5-34.1%	122-182 14.0-20.9%	38.7-25.9%
Trend to share based on relative population in 2100		87 18.9%	45.9%	124 14.3%	38.1%

Table 11: United States carbon budgets to 2050 and 2100 under the various assumptions described in the text. For perspective the U.S. budgets are also shown as a percentage of the global carbon budgets to 2050 and 2100 (460 and 870 GtC respectively for a 550 ppmv stabilization target). Also shown is the carbon shadow for the entire U.S. economy as a percentage of the U.S. budgets.

It is important not to be caught up in the details of Table 11. The range of U.S. carbon budgets described above are 66-126 GtC to 2050 and 124-213 GtC to 2100. Thee are to be compared to the U.S. carbon shadows of 39.9 GtC and 47.2 GtC to 2050 and 2100 respectively. Even from this simple perspective, the results are fairly dramatic.

The biggest impact of carbon shadows is clearly in the next 50 years. Under the assumptions described in the text above the current U.S. capital stock, if retired at historical rates represents a commitment to consume between 30 and 60% of possible U.S. shares of the global carbon budget. Recall that this commitment is without the construction of another fossil fuel fired power plant or the construction of a single petroleum fueled vehicle. Perhaps just as striking is that the current U.S. capital stock represents a commitment to emitting an amount equal to 22-38% of possible U.S. budgets for the next 100 years. Clearly the carbon shadow of current U.S. capital stock is quite long.

The final task in our attempt to put U.S. carbon emissions in perspective is to estimate what might happen over the next twenty years if the U.S. does not make a significant transition to a much lower carbon intensity path. There are two parts to the question. First what will happen to the U.S. carbon shadow as various elements of the carbon emitting capital stock are retired and replaced? Second how what will the emissions over the next 20 years look like and how much of the U.S. carbon budget will those emissions consume?

Two factors control estimate of what happens to the shadow over the next 20 years.

- What kind of capital stock replaces retired capital stock?
- What capital stock is added over and above replacement?

The answers to these two questions probably have an opposite impact on the carbon shadow of the resulting capital stock. We would expect that new capacity would produce energy services at higher efficiency and therefore lower carbon intensity. Alternatively, the addition of capacity would simply increase the carbon shadow. New capital equipment may have a longer lifetime than the equipment it replaces (the tendency for motor vehicles), which would add to the carbon shadow. Similarly, if the replacement capital equipment has a shorter lifetime, e.g. a combustion turbine versus a pulverized coal plant, the shadow would be smaller. For present purposes, we will take a conservative (lower carbon shadow assumption that the carbon shadow in 2020 would be equal to the current carbon shadows, 39.9 and 47.2 GtC to 2070 and 2120 respectively. Following the previous analyses, we estimate the carbon shadow to be 29.9 GtC from 2020 to 2050 and 46.1 GtC to 2100.

The next question is what might the expected emission for the U.S. over the next 20 years. Over the past decade the annual U.S. carbon emissions have increased at about 1.7% per year. For present purposes we estimate U.S. increases at half this rate for the next 20 years. Under this assumption, the U.S. would emit approximately 34 GtC over the 20-year period. Therefore by 2020 the U.S. has emitted and committed to emit 63.9 GtC and 80.1 GtC to 2050 and 2100, respectively.

Table 12 summarizes the impact of these assumptions on the various U.S. shares of the global carbon budget as described in Table 11 and the associated text. There are several key points. First, even for the most generous U.S. share of the global carbon budget, one based on GDP, by 2020 the U.S. has either emitted or committed to emit, in the form of its carbon shadow more than 50% of its budget to 2050 and almost 38% of the budget to 2100.

Basis of allocation		U.S. Carbon shadow in 2020, plus 2001-2020 emissions (63.9GtC) to 2050 as a % of budget (550)	U.S. Carbon shadow in 2020, plus 2001-2020 emissions (80.1GtC) to 2100 as a % of budget (550)
Maintain average emissions	Base Year 1990	96.8%	60.7%
	Base Year 2001	81.9%	51.3%
Maintain share of global emissions	Base Year 1990	64.5%	42.8%
	Base Year 2001	59.2%	39.0%
Share based on relative share of the global economy		50.7%	37.6%
18% per decade reduction in carbon intensity		84.1-54.6%	65.7-44.0%
Trend to share based on relative population in 2100		73.4%	64.6%

Table 12: Use and committed use of the United States carbon budgets to 2050 and 2100 by 2020 following the assumptions in the text. The basis for determining the U.S. budgets is the same as for Table 11.

As above rather than focusing on the detailed results in the table we can consider the ranges consumption of the possible U.S. carbon budgets. Doing that we note that to 2050, the combination of twenty years of "business as usual" consumption, and the carbon shadow of the evolved capital stock implies consumption of 51-97% of the possible U.S. budgets to 2050. To 2100, we may have consumed and committed to consume 38-65% of the range of U.S. budgets considered here.

What does it mean to have emitted or committed to emit 100% of the nation's budget? If we were speaking to the entire period, from a given time forward to the stabilization date of 2150, it would imply that the nation in question could not build any more carbon emitting technologies, even to replace those that have retired. In the current context using 100% of the budget to an intermediate point in time, implies that the changing emissions profile will not stay on a cost minimization WRE-like trajectory and that future emissions reductions may require premature retirement of capital stock in order to meet the final budget.

4.1 Impacts of policy goals

The previous results and discussion are even more powerful when put in the context of the policy options related to managing the concentration of atmospheric carbon dioxide. The analysis in Appendix A, which discusses both the budget for different levels but also the impacts on those budgets of uncertainties in our understanding of the carbon cycle, gave the following budgets (Table 13) for global carbon dioxide emissions over the next century.

	Stabilization at 650 ppmv	**Stabilization at 550 ppmv**	**Stabilization at 450 ppmv**	**Reference case**
Global carbon budget to **2050** (GtC)	505	460	373	500
Uncertainty range (GtC)	451 – 515	423 – 463	311 – 397	
Global carbon budget to **2100** (GtC)	1089	870	579	1345
Uncertainty range (GtC)	815 -1176	663 – 973	331 - 655	

Table 13: The carbon budget, assumptions and uncertainties (from Appendix A). As described in the appendix, the uncertainty range is due to our current uncertainty in the carbon cycle, largely related to the long-term uptake of carbon in the oceans.

The values in Table 13 have been used to calculate the consumption of global carbon budgets by current U.S. capital stock (Table 14). There are two points to be noted from Table 14. First, the impact of a 450 ppmv target on the fraction of the global budget consumed by existing U.S. capital stock is greater than for the 650 ppmv policy case. This reflects the fact that as one lowers the target concentration and future emissions are more severely constrained, the impact of existing capital stock is correspondingly greater. The second point is that carbon cycle uncertainties are important, but primarily for the 450 policy case on the 100 year time scale. For the 450 case, in the long term, the existing capital stock could have an even greater impact on global budgets in the second half of the 21st century than in the first half.

		To 2050		To 2100	
Total U.S. Carbon Shadow in GtC		**39.9 GtC**		**47.2 GtC**	
As % of Global Carbon Budget			**Range**		**Range**
for 450 ppmv		**10.7%**	**10.1-12.8%**	**8.2%**	**7.2-14.2%**
for 550 ppmv		**8.7%**	**8.6-9.4%**	**5.4%**	**4.8-7.1%**
for 650 ppmv		**7.9%**	**7.7-8.8%**	**4.3%**	**4.0-5.8%**

Table 14. The U.S. carbon shadows to 2050 and 2100 expressed as a percentage of the corresponding global carbon budgets. These are the shadow calculated from 2000 and correspond to the values in Table 10.

What do the 450 and 650 ppmv cases imply for the U.S. with respect to possible allocations of shares of the global carbon to U.S. and the corresponding consumption of those budgets by existing capital stock? Because of the differing ways in which the U.S. shares were determined, there are two different impacts.

For two cases, previously discussed, we have assumed a U.S. share based on policy targets that are not indexed to anything else going on in the world. In these two cases, holding U.S. emissions to an average of the emissions in some reference year and setting a targeted reduction in the intensity of carbon emissions, the absolute carbon budget, and therefore the percentage of the U.S. budget consumed by current capital stock does not change. However, the U.S. share of the global budgets changes. These results are shown in Table 15 and they raise two issues. First, note that for both of these options existing capital stock already consumes a significant fraction of these budgets. Second it is clear again that targets as low as 450 will make it increasingly difficult for the U.S. to maintain these budgets in view of global competition for emissions budgets. It is also instructive to refer back to Table 12, where we note that the continuation of U.S. emission patterns suggests that for these cases the U.S. carbon shadow in 2020 will have consumed 60-80% of the U.S. budget to 2050 and nearly half of the U.S. budget to 2100.

Global Budget to 2050	Maintain U.S. average at 2001 emission levels with Carbon Shadow (%) of U.S. budget	U.S. Budget as a Percentage of Global Budget	Reduce carbon intensity 18% per decade with Carbon Shadow (%) of U.S. budget	U.S. Budget as a Percentage of Global Budget
U.S. Budget	78 (51.2%)		76-117 (52.5-34.1%)	
450		20.9%		20.4-31.4%
550		17.0%		16.5-25.4%
650		15.4%		15.0-23.2%
Global Budget to 2100				
U.S. Budget	156 (30.3%)		122-178 (38.7-25.9%)	
450		26.9%		21.1-30.7%
550		17.9%		14.0-20.5%
650		14.3%		11.2-16.3%

Table 15. The U.S. share of the global carbon budget under a range of target concentrations and for two U.S. policy options that represent unilateral U.S. policies, without reference to the rest of the world's emissions.

The other possible U.S. budgets are more closely tied to the rest of the world, indexed to (1) shares of global emissions, (2) shares based on global GDP and (3) shares based on population. For these three estimates changing the stabilization goal will change the proportion of the U.S. share consumed by current capital stock. The results are shown in Table 16. Again, the results are striking. Several points emerge, the most prominent of which is that for lower stabilization targets (450 ppmv) current capital stock consumes a substantial fraction of the U.S. share both in the first half of the 21st century and for the second half of the century as well.

	U.S. share of total global budget (percentage of global budget)	U.S. budgets and carbon shadow as a percentage of the budget to 2050		
Assumptions about U.S. share of global carbon budget		450	550	650
Maintain share (2001)	23.5%	88	108	119
		45.5%	36.9%	33.6%
Maintain % of Global Economy	27.4%	102	126	138
		39.0%	31.7%	28.8%
Population Based	18.9%	70	87	95
		56.6%	45.9%	41.8%
		U.S. budgets and carbon shadow as a percentage of the budget to 2100		
		450	550	650
Maintain share (2001)	23.5%	136	204	256
		34.7%	23.1%	18.4%
Maintain % of Global Economy	24.5%	142	213	267
		33.3%	22.1%	17.7%
Population Based	14.3%	83	124	156
		57.0%	37.9%	30.3%

Table 16. The U.S. share of the global carbon budget under a range of target concentrations and for three U.S. policy options that are referenced to the emissions in the rest of the world.

The results in Table 16 are amplified in Table 17 where we have taken the previous analysis of what the consumption over the next 20 years might be and estimated the carbon shadow in 2020 (Table 11) and looked at the corresponding consumption of the carbon budget as of 2020. In this case, a business as usual use of fossil fuels by the U.S. for the next 20 years has dramatically limited options. Specifically with respect to the 450 ppmv stabilization goal the U.S. has either consumed or committed to consume 60-90% of its "share" of global emissions not only to 2050 but also to 2100. For higher stabilization levels, the picture is similar but not as severe. For 550 ppmv, consumed plus committed emissions represents 50-75% of possible budgets to 2050 and 40-65% of budgets to 2100. Even for a 650 ppmv goal, consumed plus committed emissions have consumed 45-65% of the 2050 budget and 30-50% of the budget to 2100. These shadows are profound and are cast well into the second half of the 21st century. The implications are just as compelling when one considers that these correspond to consuming 17.1%, 13.9% and 12.7% of global budgets to 2050 and 13.8%, 9.2% and 7.4% to 2100, for targets of 450, 550 and 650 ppmv, respectively.

	U.S. share of total global budget (percentage of global budget)	U.S. budgets and carbon shadow as a percentage of the budget to 2050		
Assumptions about U.S. share of global carbon budget		450	550	650
Maintain share (2001)	23.5%	88	108	119
		72.9%	59.1%	53.8%
Maintain % of Global Economy	27.4%	102	126	138
		62.5%	50.7%	46.2%
Population Based	18.9%	70	87	95
		90.6%	73.5%	66.9%
		U.S. budgets and carbon shadow as a percentage of the budget to 2100		
		450	550	650
Maintain share (2001)	23.5%	136	204	256
		58.9%	39.2%	31.3%
Maintain % of Global Economy	24.5%	142	213	267
		56.5%	37.6%	30.0%
Population Based	14.3%	83	124	156
		96.7%	64.4%	51.4%

Table 17. The consumption of and committed consumption (carbon shadow) of the U.S. share of the global carbon budget in 2020 under a range of target concentrations and for three U.S. policy options that are referenced to the emissions in the rest of the world and a continuation of business as usual use of fossil fuels by the U.S.

Highlighting a point made earlier, for some of these approaches to determining a U.S. share, these results suggest that by 2020 the U.S. may be in a position that it has little if any option to create new capital stock that vents carbon dioxide to the atmosphere if a global goal of 450 ppmv is to be achieved. Further even if the concentration goals are higher there will be severe constraints on deploying such resources in those cases as well.

5.0 Conclusions

This report has examined both current emissions from the United States and the likely persistence of some of those emissions into the future. These emissions are put in the context of a global budget for carbon dioxide for a variety of stabilization levels. The primary results and observations are as follows:

- The concept of a global carbon budget associated with particular stabilization levels for atmospheric carbon dioxide is a useful method for putting future emissions in context.

- For the globe global carbon budgets to 2100 range from 579 GtC for 450 ppmv target to 1089 GtC for a 650 ppmv target. The uncertainties in these budgets due to knowledge of the carbon cycle are only 10-15% for the next 50 years and climb to 20-25% for the century

- It is possible to analyze the U.S. capital stock in transportation and electricity generation and estimate future emissions from these existing sources by estimating future retirement rates based on past experience. It is also possible to generalize the results for these two sectors to the entire U.S. capital stock. This analysis suggests that current capital stock will release approximately 39.9 GtC over the next 50 years and 47.2 GtC over the next century.

- An analysis of possible future emissions by the U.S. suggest that by 2020, on a business as usual trajectory, the U.S. will have consumed or committed to consume 63.9 and 80.1 GtC of the global budgets to 2050 and 2100 respectively.

- Based on an analysis of a wide variety of possible U.S. shares of global carbon budgets of between 14% and 28% of global emissions, we find that existing capital stock has committed the U.S. to the use of 30-60% of its possible allowance for a 550 ppmv stabilization to 2050 and 22-38% of the possible allowance for the century. If the U.S. continues a "business as usual" use of fossil by 2020 it will have either consumed, or committed to consume (carbon shadow) 50-95% of its share to 2050 and 35-65% of its share for the century.

- The impact of current U.S. capital stock on global carbon budgets, and the corresponding U.S. share of that budget, is greatest for lower desired carbon dioxide concentrations. Under some scenarios for these low concentrations targets, current capital stock has consumed a higher fraction of the 100 year budget than of the 50 year budget, suggesting future pressure for premature retirement of capital stock.

- By 2020 the U.S. may be in a position that it has little if any option to create new capital stock that freely vents carbon dioxide to the atmosphere if a global goal of 450 ppmv is to be achieved. Further even if the concentration goals are higher there will be severe constraints on deploying such resources as well.

In conclusion, the concepts of global carbon budgets and carbon shadows provide two insights. First it shows the extent to which current practices and technologies are not only responsible for current but for future emissions. Second, it shows how existing capital stock may restrict the ability to cost effectively achieve low carbon dioxide stabilization levels. With these broad insights, we can see the challenge ahead for the U.S. Not only do we need to be concerned about reducing emissions, but we need to be mindful of the fact that decisions made today will cast shadows into the future, just as past decisions are affecting our flexibility now.

Appendix A: Carbon Cycle and Carbon Budgets

The concentration of carbon dioxide in the Earth's atmosphere is a consequence of the flows of carbon among a variety of different stocks of carbon. The movement among these stocks is controlled by a variety of geophysical process, each of which has a different characteristic time scale associated with it.

The time scales associated with the key processes affecting carbon dioxide concentrations can be ordered from fast to slow. There are two important fast processes. The first is the annual cycle of growth of plants associated with the change of the seasons. This cycle is driven in temperate climates mainly by spring and summer uptake of carbon dioxide due to net photosynthesis and release of carbon back to the atmosphere in the fall and winter when decay processes break down plant material. This process is large enough to be seen in the annual global variation of carbon dioxide concentration, such as that observed at Mauna Loa. The second fast process is the equilibrium that is established between the atmosphere and the mixed layer of the ocean.

The intermediate time scale is tied to these first two processes. In the case of the terrestrial component, there is a gradual net addition of carbon to standing biomass, perennial organisms like trees, and the soil. Second, in the ocean, the waters in the mixed layer, the top few hundred meters of the ocean, are gradually mixed by ocean circulation into the deep ocean, which is out of contact with the atmosphere. These two processes operate on timescales of decades to centuries. Finally, there is a geologic scale, operating over periods with characteristic times of millennia to millions of years where carbon is incorporated in geologic formations such as fossil fuels. It is the intermediate timescale processes, which are most relevant to the removal of carbon dioxide in the timeframe, that this project is concerned with (50-100 years).

When society mines the geologic repositories of carbon to generate energy through combustion or to make cement, an excess of carbon dioxide is emitted into the atmosphere. The ability of plants and the the ocean to absorb these emissions is limited, and, on an annual basis, this results in only about half of the carbon dioxide emitted being removed annually. The remaining carbon dioxide, in excess of the natural removal processes, leads to an increment in the atmospheric carbon dioxide concentration.

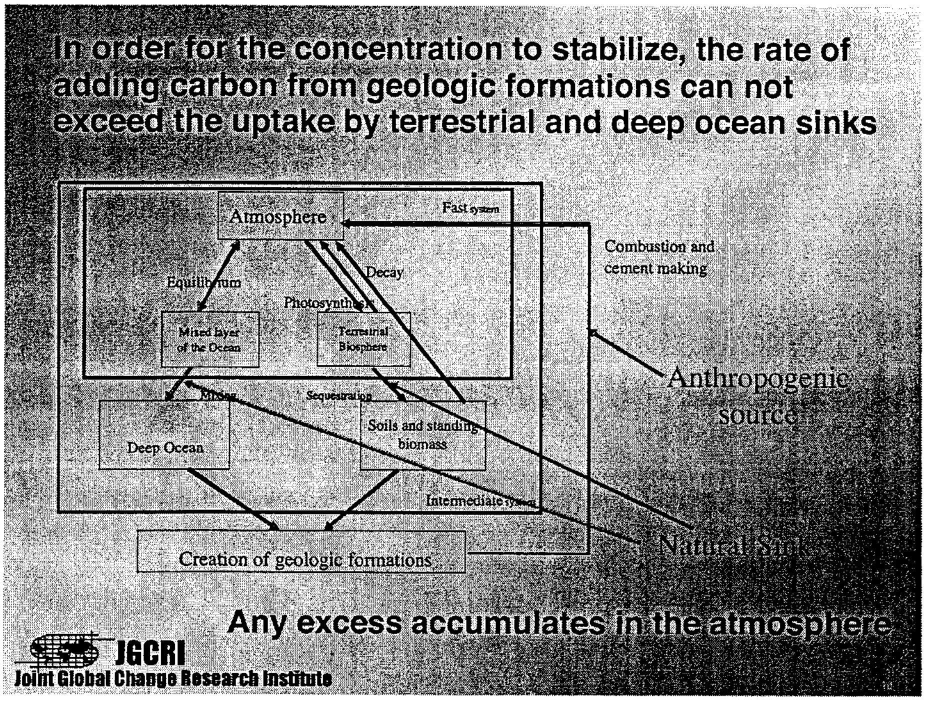

Figure A1. Overview of the carbon cycle

To be in equilibrium, the carbon fluxes, emissions and sink processes, must balance one another. For that to occur, each year we could only emit an amount of carbon equal to the amount of uptake by the deep-ocean and terrestrial systems without causing an increase in the atmospheric carbon dioxide concentration. Alternatively, we can budget an amount of emissions beyond this level by accepting a given increment in the atmospheric concentration of carbon dioxide. Thus, if we choose a given concentration as our target for stabilization, we can determine future annual carbon budgets that exceed annual uptake and increment the concentration towards the target. Once the stabilization level is reached, however, in order to be maintained, our emissions budget is limited to the equilibrium budget, meaning that the annual release of geologic carbon cannot exceed the rate at which the deep ocean and the terrestrial carbon pools are taking up the carbon dioxide.

When we speak of "allowable" emissions, we are referring to this type of future annual carbon budgets. The difference between current concentrations and stabilization target concentrations tells us what the total incremental increase in concentration can be. This total is distributed over time by constraining carbon emissions to an "economically efficient" path, in the sense of the work of Wigley, Richels and Edmonds – the WRE curves. That is, the amount of incremental increase allocated to each annual budget between now and the target year is determined by a least cost path to reach stabilization concentration in that year.

The results presented for allowable emissions are the integrated results from three JGCRI models: the Second Generation Model (SGM), the Mini-Climate Assessment Model

(MiniCAM), and a new global optimization model. Additionally, the optimization model uses the Model for the Assessment of Greenhouse gas Induced Climate Change (MAGICC), developed by Tom Wigley and collaborators.

The MiniCAM and the SGM are extensively described in model documentation (Brenkert *et al.* 2003a,b). These models were used to provide cost curves that were input into the global optimization model. The SGM contains an explicit representation of energy producing capital stock with vintaging in a computable general equilibrium framework. These features make the SGM the appropriate model to provide estimates of the cost of near-term reductions in global carbon dioxide emissions. The SGM has been used for this purpose in numerous national and international studies.

The MiniCAM is a flexible model with numerous technological options that runs on a global scale with a resolution of 14 world regions. The MiniCAM incorporates socio-economic changes over a century time scale such as improvements in energy technologies, demographic changes, economic development, and fossil resource depletion. These characteristics make the MiniCAM the appropriate tool for examining the costs of carbon policies over a century time scale. The MiniCAM was used to provide estimates of the cost of emissions reductions from 2050 onward. The cost curves from these two models were extrapolated for intermediate periods.

The global optimization model used here is a new model developed at JGCRI. This model uses a genetic optimization algorithm to produce globally optimized, cost-minimizing pathway to a specified climate target. The key input parameters are the value of the climate target (for example, stabilization at 550 ppmv) and the cost of emissions reductions. Cost curves from the two models above were used to determine emissions reduction costs. The program finds an emissions pathway that meets the specified target with the lowest total discounted cost. The discount rate used in the present calculations is 8%. Both the cost of emissions reductions and the constraints imposed by the carbon-cycle in order to achieve stabilization affect the shape of the resulting emissions curve. Because costs are discounted over time, emissions reduction costs are the most important factor for the early portion of the curve and the behavior of the carbon-cycle is more important at later times. Ultimately, however, it is the behavior of the carbon-cycle that largely determines the emissions budget allowed for a given stabilization level. This will be discussed at greater length in the section on sensitivity analysis.

The global optimization model uses MAGICC to translate carbon dioxide emissions into concentrations. MAGICC is a widely used "simple climate model" (Harvey et al. 1997) that includes the effects of all the major greenhouse gases (CO_2, CH_4, N_2O, halocarbons, ozone) and the effects of aerosol compounds (sulfur dioxide and black carbon). The carbon-cycle used in MAGICC is represented on a global scale as a terrestrial and an ocean component. The ocean component of the carbon cycle is an expanded version of the Maier-Reimer and Hasselmann (1987) model. The terrestrial carbon-cycle represents carbon flows between living biomass, liter, and soil carbon stock taking into account anthropogenic deforestation (Wigley 1991).

Figure A2 presents the allowable carbon budget for fossil emissions (fossil fuels plus cement production) for a 550 ppmv concentration target by 2150. The carbon budgets for the years 2050 and 2100 amount to 460 and 870 GtC, respectively.

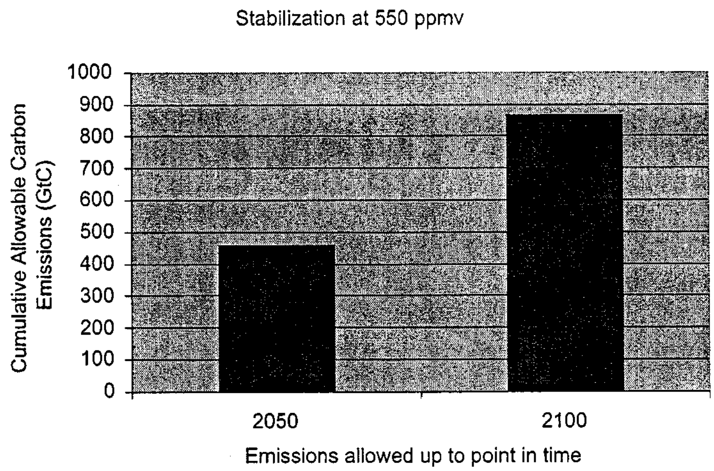

Figure A2. Carbon budgets for stabilization of carbon dioxide concentrations at 550 ppmv cumulative to the years 2050 (460 GtC) and 2100 (870 GtC). Budget figures are relative to the year 2000. Figures are shown for the central reference case of the carbon cycle model.

Appendix B: Retirement Models for Electricity Generations

Three fossil fuels —coal, natural gas, and oil— are used in four different electricity production technologies —steam turbine, combustion turbine, internal combustion, and combined-cycle— to produce most of the electricity consumed in the United States.[7] In order to understand the carbon shadow model at the core of this paper, it is necessary to outline the characteristics of these technologies and corresponding fuels that are relevant to the model.

B.1 Characteristics of electricity conversion systems

B.1.1 Steam Turbines

A steam turbine generator consists of three main parts. A boiler system burns one of the fossil fuels, using the generated heat to boil a large supply of water. This water is then moved, under great pressure, into the steam turbine itself, where it is allowed to expand. This expansion of gases pushes against rotor blades in the turbine, turning a drive shaft. This drive shaft is connected to the third part, the generator, where a large magnet spins inside a coil of wires, producing an electric current. This current is the output of the electrical plant. In the U.S. these units use primarily coal as a fuel, though there are a number of such generators that burn either oil or natural gas. The efficiency of steam generation is largely determined by the size of the unit, so these plants tend to be very large (many of the coal burning units built in the 70s and 80s are over 1000 MW capacity).

Two characteristics of these units are important for modeling purposes. First, the large amount of water that needs to be heated in the generation process means that these units take a large amount of energy and a long time to get going from a cold start. For this reason, steam turbines tend to be used as what are known as baseload units, meaning that they provide the constant minimum level of electricity that is demanded on the grid. Although very expensive in terms of capital to build, these units can be run on cheap fuel (such as coal) and are run almost continuously. Second, the parts of steam turbine units are very durable, and with proper maintenance can last several decades beyond their rated lifespan. This means that retirement decisions will likely be dominated by considerations other than serviceability.

B.1.2 Combustion Turbines

A combustion turbine has only two primary components. First, inside the turbine itself, natural gas and/or petroleum products are burned to create very high temperatures and pressures. The high pressure of the gases created pushes the turbine blades inside the turbine, turning a drive shaft that drives the generator.

[7] Other fuels include biomass and wastes, while other technologies include renewables such as wind turbines, hydro turbines, and geothermal steam turbines. As these fuels and technologies are either carbon neutral or at least very low carbon emitters, they are ignored in this study.

These units are the opposite of steam turbines for modeling purposes. First, unlike steam generators, these units have very low startup times and costs. Thus, instead of being run continuously, these units are brought online during periods of high demand to provided electricity for the higher cost "peak" periods. This allows them to use higher cost fuel than steam turbines (piped-in natural gas and petroleum), as owners are able to sell the generated electricity at a much higher price. Their role as "peaking" units means that these units are usually operational less than 10% of the time. Secondly, the significantly higher temperatures and pressures inside the turbine, relative to a steam turbine, means that the moving parts are exposed to much harsher conditions. Thus, these units tend to have a shorter lifespan.

B.1.3 Internal Combustion Generators

Internal combustion (IC) generators burn either natural gas or petroleum products inside a large engine (not unlike a truck engine), where the explosion of the fuel pushes pistons that turn a drive shaft. This drive shaft in turn rotates a generator that produces an electrical current in the same way as the above units.

For the purposes of modeling, IC generators are fairly analogous to combustion turbines. On the one hand, they have very low capital costs and startup costs, and thus make excellent peaking units. On the other hand, the internal explosions that drive the IC engine also put it under considerable strain, meaning that these units have a short, relatively constrained useful lifetime.

B.1.4 The Combined Cycle

Combined cycle plants are a fairly recently introduced hybrid of steam and combustion turbine units that produce electricity in two stages. In the first stage, a group of combustion turbines each turn a generator unit, creating electricity in the same process as normal combustion turbines. The exhaust heat from these units is then applied to a boiler unit, heating up water, which is then used to run a large steam turbine. This turbine turns a different generator, producing more electricity. By capturing and using the "waste" heat from the combustion turbines, these units are able to achieve much higher efficiencies than steam turbine or combustion turbines alone.

By combining the features of combustion and steam turbines, these units are not only difficult to model, but also difficult to keep accurate data on.[8] First, the inclusion of a steam turbine and boiler units does make the whole process difficult to start up, and thus these units are expected to play a role as baseload units. Secondly, however, it is difficult to say how the retirement aspects of these units will play out. On the one hand, the steam components will last near indefinitely, while on the other hand the combustion turbine components will experience shorter lifespan. This may result in combustion components

[8] The EIA has yet to introduce a standardized system of recording information about combined-cycle units, resulting in data that is very hard to make use of. Since data is recorded by individual generator and combined cycle "units" typically consists of 3-14 generators, how they get recorded, and how power production is divided among them is not clear at all. Thus, some combined-cycle units are listed as normal combustion turbines, while others appear as "combustion turbine components of combined cycle units," while still others are labeled "combined cycle" units.

being replaced regularly throughout the life of the steam turbine and thus giving these units a projected lifespan more akin to steam turbines. On the contrary, retirement decisions may be dominated by the combustion turbine components, meaning that combined-cycle units would have shorter service lives. Although the higher costs of steam units relative to combustion units seems to speak towards the first of these hypotheses, no data yet exists on the retirement decisions of combined-cycle owners as no combined-cycle plants have been retired.

B.2 Coal Generators

Projecting the currently existing coal power generators forward 50 and 100 years to obtain estimates of committed carbon emissions required a three step process. First, we developed a retirement model based on historic data to be able to project the amount of coal generation capacity remaining in use in each future year (see Figures B1 and B2). Second, a capacity factor model that ties usage to generator age was developed to adjust for the fact that older generators are generally used less intensively than newer units. Finally, generator usage had to be translated into a level of emissions for each future year. This necessitated, first, an efficiency (heat rate) model that could determine the amount of coal necessary to produce the electricity generated, and secondly, a carbon coefficient that could convert coal burned into carbon emitted. The following sections outline each of these model components and the results, in the form of emissions predicted by the model.

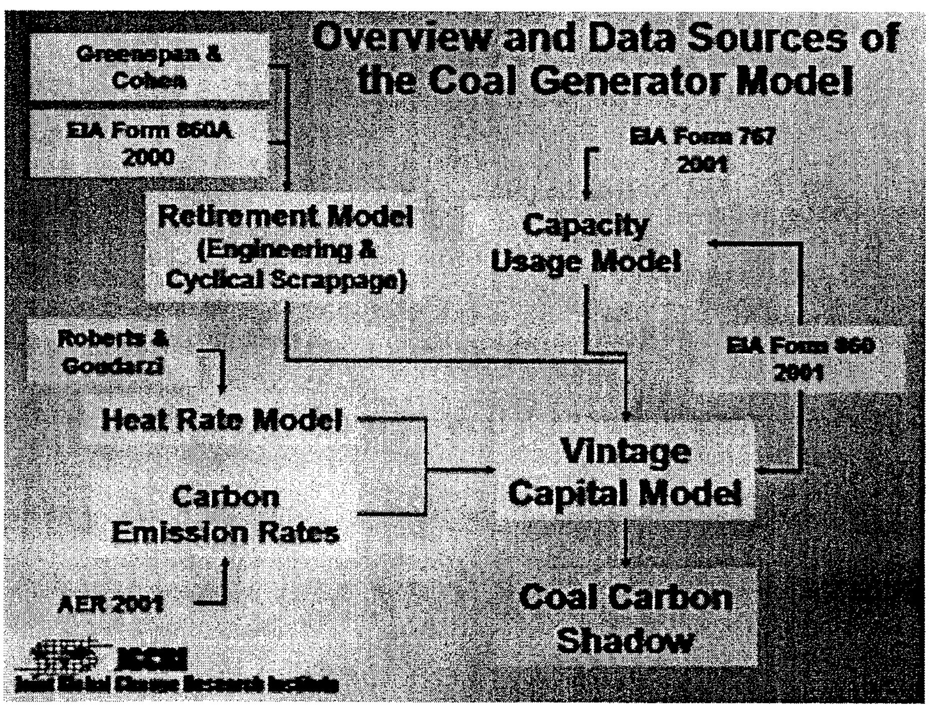

Figure B1 Overview and data sources of the coal generator model

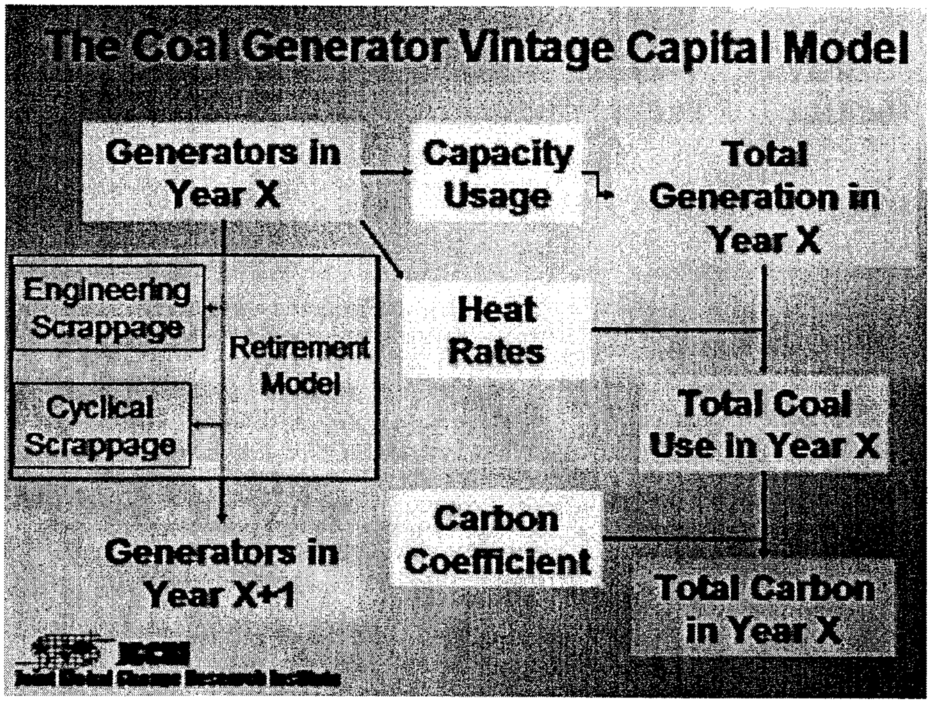

Figure B2. Overview of the coal generator vintage capital model

B.2.1 The Coal Generator Retirement Model

B.2.1.1 The data

The dataset used for determining the retirement model for coal power generators is the Energy Information Administration (EIA) Form 860a for the year 2000.[9,10] This database contains information on every utility-owned electric generator operated in the United States since 1970, including the rated summer capacity (the maximum producible electricity under average summer ambient conditions, in MW), year of initial operation, operation status, and year of retirement that was used in constructing the retirement model. Unfortunately, there is not a corresponding EIA database that contains information on non-utility generator retirements over the past 30 years. As such, we are forced to work under the assumption that all power generators face similar retirement patterns regardless of whether they are utility-owned.[11]

[9] Generators are the basic unit of this model, rather than plants, due to the fact that generators have a single build year associated with them allowing for calculations of the age of the generator. Plants, insomuch as they often contain multiple generating units cannot readily have a single age applied to them.

[10] http://www.eia.doe.gov/cneaf/electricity/page/eia860.html.

[11] This assumption is not likely to be all that influential in terms of the model's findings given that most of the large coal power units are owned and operated by utility companies. Furthermore, it should be mentioned that although the derivation of the retirement model relies on the utility database, the application of the model to the data uses a dataset that contains non-utility generators as well.

From this dataset, we extracted those power generators whose primary fuel is coal, waste coal, or synthetic coal derivatives and that have a rated summer capacity of 10 Megawatts (MW) or greater.[12] Using the "first-service" (the year the generator came on line) and retirement years, the total number of coal generators existing in the years 1970-2000 was extrapolated and divided up by age of the generators. This allowed us to compute a figure for the total fraction of generators of a given age that survive another year. Looking at every year from 1970-2000, the total the number of generators of age X was determined and how many of these survived to age X+1 was computed. This technique yielded an aggregated survival rate for each generator age (1 through 60). This was transformed into the data needed for regression by assuming an initial 100% stock level at age zero and then applying the derived survival rate for each year of age through 60 to find the fraction of the stock remaining at each age.

B.2.1.2 The Regression Model

The regression model itself is based on a model for the retirement of automobiles developed by Greenspan and Cohen.[13] They assumed two different types of scrappage, termed "engineering scrappage" and "cyclical scrappage," which refer, respectively, to age-motivated scrapping decisions and economically-motivated capital scrappage.[14] They assumed that a certain fraction of the capital stock, the engineering scrappage rate, is retired in any given year due to age considerations alone. The model we use for coal generators reproduces in part their methodology for the derivation of this engineering scrappage rate. It is important to note that this assumes homogeneity within the capital stock, meaning in our case that power generators are treated the same regardless of their geographic location, ownership, or profitability. This limits the model from being an accurate gauge of *which* generators will be scrapped in any given year. However, insomuch as the model builds up from aggregated data, it should still be a reliable guide to *average aggregate* retirements, which is all that is required to measure the aggregate committed carbon emissions of the stock of generators as a whole.

In the Greenspan/Cohen model, a shorter capital lifespan and a much larger data set (almost 200 million vehicles as compared to roughly 1600 coal generators) allow for separate curves to be derived for each model year of vehicles. In our model, coal generator lifetime characteristics are assumed to be homogenous across vintage classes, meaning that power generators built in 1950 will have the same age-related retirement rates as those built in 1970. Little research exists that explicitly supports this assumption, but there is also little evidence that it is wrong either.[15]

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[12] Generators smaller than 10 MW represent roughly 16.6% of coal steam generators, but are an almost insignificant .4% of total capacity.
[13] http://www.federalreserve.gov/Pubs/FEDS/1996/199640/199640pap.pdf
[14] "Scrappage" is used here interchangeably with "retirement." Both are taken to refer to discontinuing the use of a particular unit of fixed capital.
[15] Since the generators built prior to 1950 are the only ones that can give us information on the retirement of units older than 50 years of age, leaving them out would force us to extrapolate the late-lifetime characteristics of generators from a much shorter pool of data. If, however, generator lives have been extended due to technological improvements in their design during the 60s and 70s, then this model will

The retirement model uses aggregate capacity, instead of individual generators, as the unit of analysis. This stems from the fact that the number of generators is fairly inconsequential from an aggregate point of view. For instance, knowing that 5% of generators are retired in a given year means less than knowing 5% of capacity is retired when the focus is on the need to provide a certain total capacity of electricity. Thus, the retirement model focuses on fractions of capacity rather than number of generators. Accordingly, survival of capacity follows an S-shaped curve through time such that little capacity is retired in the first several years after a vintage is built, more rapid retirement occurs in the middle range of generator lifetimes, and the fraction of capacity remaining levels off at a low level in the later years of the lifetime. Also, we assume that no capacity is retired in the first 10 years of operation.[16] In this coal generator retirement model, the curve is functionally approximated by the following regression:

$$\ln(Y) = \text{constant} + \beta * t^3 \qquad (1)$$

where Y is the fraction of originally built generator capacity remaining after 10 + t years.[17] Using the extracted data described above, the regression results of (1) were:

$$Y = \exp(.00863 - .00000273 * t^3) \qquad (2)$$

(t-statistic) (3.34) (-45.8) Adj. $R^2 = .9785$

Figure B3 shows how this model compares to the original data. As the graph shows, the log-cubic model fits the data extremely well for the first 60 years of generator lifetime. It should be noted that beyond sixty years of generator life, the data is very thin (there weren't many generators greater than 10 MW built before 1935 and even fewer survived to be reported in this dataset). This means that there is very little information on the structure of the tail of the lifetime curve—a thinner tail (like a logistic estimation) would mean that more generators retire sooner, while a thicker curve (the log-squared result mentioned in note 8) would mean generators were around even longer. The log-cubic functional form was chosen both because of its superior fit to the data we have and because it is between the other two forms in terms of tail thickness.

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understate the amount of generation coming from existing coal generators in the distant future. As such, these findings would constitute a lower bound for such predictions.

16 In reality .1% of generators are shut down within 10 years of operation, but ignoring this allows for a model that fits the data better by exhibiting a longer flat section with very minor scrappage.

17 The Greenspan/Cohen model has both a t^2 and t^3 term; in our results the t^3 term dominated the t^2 results, however, leading to the eventual dropping of the t^2 term from the model.

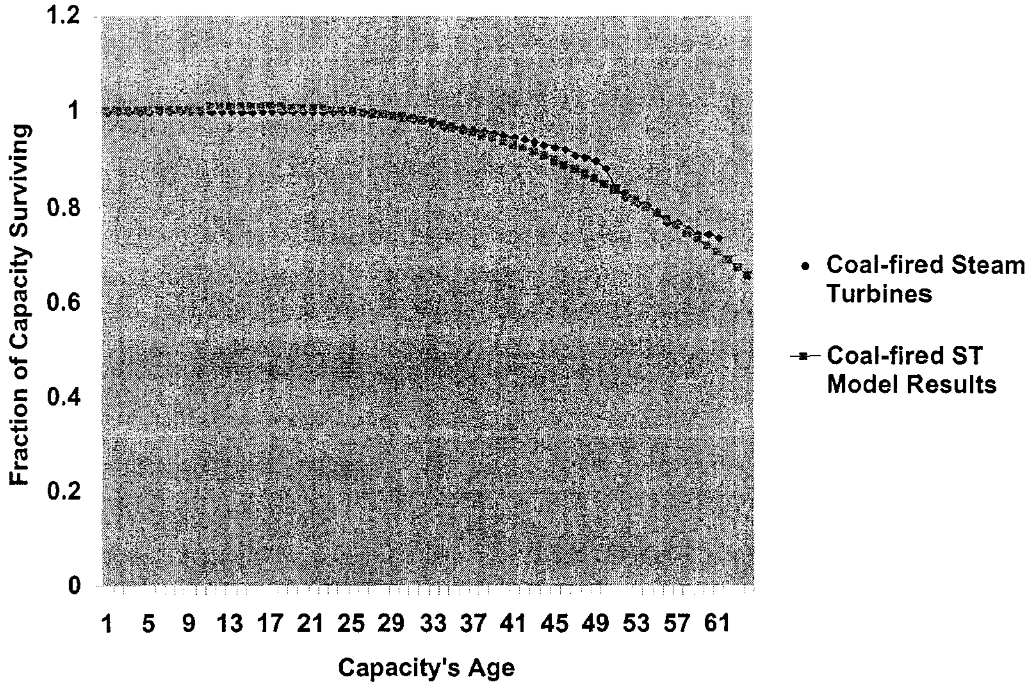

Figure B3 Coal-fired steam turbine electricity generating capacity surviving by age

Cyclical scrappage was then computed for each year 1970-2000 by subtracting the estimated engineering scrappage for each year (determined by the model described above) from the actual observed retirements in that year. This difference was then divided by the total capacity to yield the cyclical scrappage fraction. This change in actual scrappage above or below scrappage due to generator age was assumed to be dependent on the price of coal.[18] An initial model using just the logged price of coal, however, failed to explain a handful of years where retirement of coal generators was significantly above the retirements predicted by the engineering scrapping model and coal prices alone. It was discovered that these years (1981, 1985, and 1987) corresponded with years in which larger than average numbers of nuclear generators came on line.[19] Adding this information to the model yielded the following model of cyclical retirement as a fraction of total active capacity at a point in time:[20]

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[18] Different regressions also compared cyclical scrappage to the price of natural gas, petroleum, and the ratio of coal prices to each of these fuels. None of them proved significant, however. An attempt to include the historic price of electricity as an indicator of excess demand/supply also failed to yield significant results.

[19] Data on the number of nuclear reactors online used to compute the change in the number of reactors each year was obtained from: http://www.eia.doe.gov/emeu/aer/txt/ptb0901.html

[20] The price of coal is drawn from http://www.eia.doe.gov/emeu/aer/txt/ptb0708.html, and is in 1996 chain-weighted dollars per short ton.

$$\text{CycFrac} = -0.009863 + .0027388 * \ln(\text{coalprice}) + .0001709 * \text{deltanukes} \quad (3)$$
$$(-4.67) \qquad (4.24) \qquad (3.00) \qquad \text{Adj } R^2 = .642$$

B.2.1.3 Capacity Factor[21] Model

Information on generator usage was drawn from EIA Form 767[22], the steam generator report, from 2001. Using plant and generator ID codes, these data were matched up with generator summer capacities and first-service years from the EIA Form 860 from the same year. The resulting dataset was 1116 coal generators that were online in 2001. Capacity factor figures were calculated by dividing annual generation by summer capacity times 8760 hours (number of hours in a year). Figure B4 shows these fractions plotted against summer capacity for all 1116 units. Clearly, there is much wider variation of capacity factors among generators with summer capacity ratings less than 100MW than for those above 100MW. For this reason, generators rated at more than 100MW were treated separately from those less than 100MW in determining the relationship between capacity factor and age. Figure B5 plots capacity factors against age for generators over 100 MW summer capacity. There is clearly a linear trend downward through the data, which was estimated in an ordinary least square (OLS) regression as:

$$\text{CapFact} = 0.8343 - 0.004426 * \text{Age} \quad (4)$$
$$(\text{t-statistic}) \quad (54.79) \qquad (-9.90) \qquad \text{Adj } R^2 = .1100$$

where CapFact is the fraction of total possible output (summer capacity times 8760 hours) that is actually produced annually. The generators smaller than 100MW also exhibit a downward trend, though it is steeper than the larger units (Figure B6). The OLS result for the smaller units was:

$$\text{CapFact} = 0.8107 - 0.00755 * \text{Age} \quad (5)$$
$$(\text{t-statistic}) \quad (16.22) \qquad (-6.60) \qquad \text{Adj } R^2 = .1144$$

[21] "Capacity factor" is a measurement of usage intensity, and is equal to the actual annual generation (in kWh) divided by the total possible annual generation (8760 times the capacity of the generator; kW capacity times the maximum 8760 hours operations → kWh).
[22] http://www.eia.doe.gov/cneaf/electricity/forms/eia767/eia767.pdf

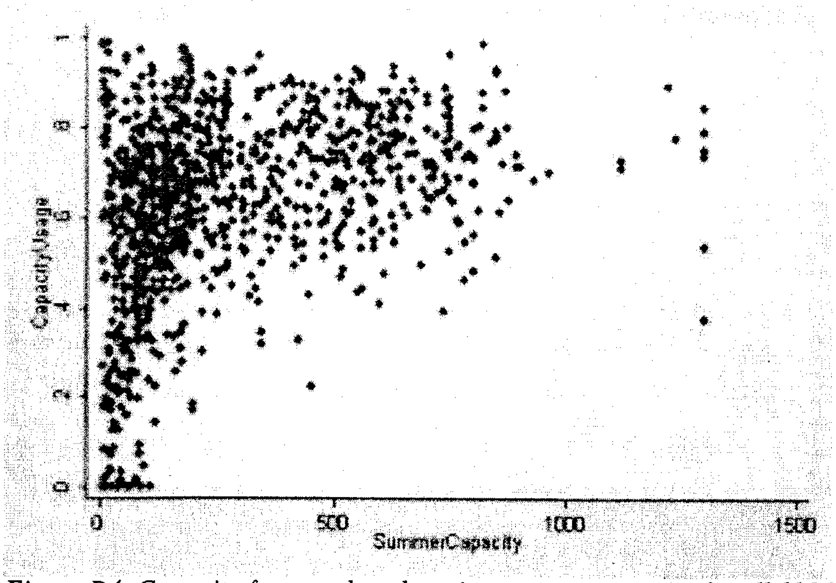

Figure B4. Capacity factors plotted against summer capacity for all 1116 coal-fired electric units operating in 2001

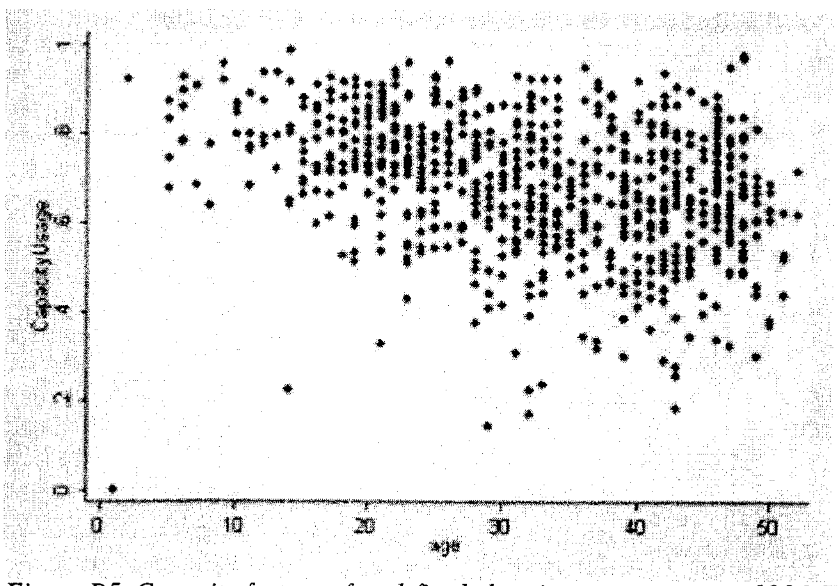

Figure B5. Capacity factors of coal-fired electric generators over 100 MW summer capacity operating in 2001 plotted against the generators' ages

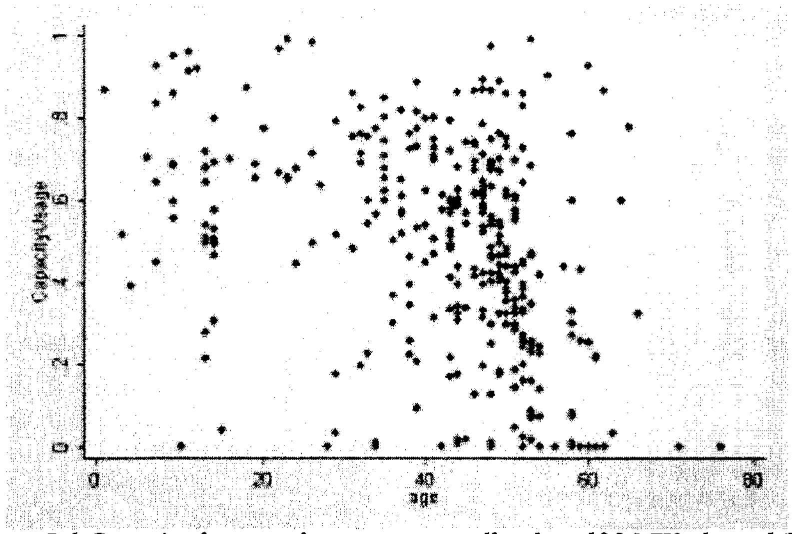

Figure B6 Capacity factors of generators smaller than 100 MW also exhibit a downward trend, though it is sharper than the larger units.

B.2.1.4 The Vintage Capital Model

EIA Form 860 from 2001 was used to find the total number of coal generators of each age that existed in 2001 and their associated rated summer capacity. The newest generators were built in 2000, while the oldest date from 1921. A separate age category is used for ages 0-80, with all generators older than 81 lumped together in an 82^{nd} category. Every generator in a given age category is assumed to have the same summer capacity as that age group's average summer capacity. This average capacity rating moves with the age group as the model advances through the years 2001-2100. A weighted average of the 80 and 81+ capacities in year X provide the average capacity of the 81+ category in year X+1.

Each year, the model computes engineering scrappage by applying model (2) to each age cohort and totaling the capacity that is projected not to survive. Cyclical scrappage is then computed according to (3) multiplied by the total capacity at the beginning of the year. These two figures are totaled to yield the total capacity retired during that year:

$$\text{Total Scrappage} = \Sigma_{(\text{age}=0\text{-}81+)} (\text{Capacity(age)} * (1 - \text{SurvFrac(age)})) + \text{CycFrac} * \text{Total Capacity} \quad (6)$$

where

$$\text{SurvFrac} = \text{Y(age+1)} / \text{Y(age)} \quad (7)$$

where Y is the calculated survival rate from (2). Retirements are then assigned, with the least efficient generators (as determined by the heat rate equation, (8), discussed below) being retired in turn until the total projected capacity retirement is met.[23]

[23] This approach is informed by the desire to produce a lower bound estimate for carbon emissions. Although geographic and economic considerations may not always lead to the least efficient generators

Next, the capacity factor models described above ((4) and (5)) are used to calculate capacity factors for each age group of generators in the model. Multiplying the capacities for each group by 8760 times the estimated capacity factor, total output in GWh by vintage cohort is estimated. These are then totaled to yield a total GWh output for each year.

B.2.1.5 Generator Heat Rates and CO_2 Emissions

The conversion of GWh electrical output to CO_2 emitted is a two-step process in this model. First, GWh must be converted to Btu of coal burned by means of heat rates in units of Btu/kWh. The number used for this conversion is dependent on the efficiency of the generator in question, expressed as heat rates, which ranges from 9500 Btu/kWh to 12500 Btu/kWh or more. Roberts and Goudarzi developed a model of coal generator efficiency based on the age, size, fuel, and abatement technology of the generator.[24] We draw on this model in determining the heat rate of the generators in our coal carbon shadow model. The heat rate of each vintage year of generators is determined, based on the age of the cohort and the average summer capacity of the generators as follows:

$$\text{Heat rate} = 13763.2*(\text{age}^{.07325025})*(\text{capacity}^{-.0932101}) \qquad (8)$$

This equation is used for the "average" case. It is increased by 9.548% in the "high" emissions case and decreased by 4.459% in the "low" emissions case. These adjustments are drawn from the original model, and represent lignite fuel with scrubbers in the "high" case and bituminous fuel with no scrubbing in the "low" case. The average case represents subituminous (or a mix of the three) fuel with no scrubbers.

The second conversion brings the model from Btu of coal burned to tons of CO_2 emitted. Carbon emissions from coal vary from 56 lbs/MBtu for Bituminous coal to 58.7 lbs/MBtu for Lignite coal (anthracite has a higher carbon value, but is not typically used for electricity production).[25] An average value (taken from the AER 2001) of 57.2 lbs/MBtu is used in the model for the average case, with the other values used in the low and high cases respectively.[26]

These two conversion factors are applied to the total generation values for each year to obtain an estimate of the total CO_2 emissions from coal generators for that year. In turn, a cumulative total of these emissions measures how much the generators existing in 2001 have emitted over the course of the model.

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being retired first, doing so in the model keeps us from over estimating emissions, and gives the benefit of the doubt to a "best-case scenario."

[24] The paper with this model is on http://www.econsci.com/euar9801.html.

[25] These conversion values are from http://www.eia.doe.gov/cneaf/coal/quarterly/co2_article/co2.html.

[26] AER, http://www.eia.doe.gov/emeu/aer/pdf/pages/sec13.pdf.

B.2.1.6 Cumulative Emissions of Coal-fired Electricity Generation and its Uncertainties due to the Quality of Coal used and Scrubbing Levels

Figure B7 shows the Low, Average, and High case paths of cumulative CO_2 emissions up to the year 2050 assuming no change in the number of large nuclear plants, and the coal price predictions published in the AEO (adjusted to 1996 dollars, with the 2025 prediction extended through to 2100).[27] Table B1 summarizes the results for 2050 and 2000. All three cases have begun leveling off by 2050, as the retirement of existing generators slows, given that most of the year-2001-generators have retired by that time. In the average case, the year 2001 coal generators have emitted 18.7 gigatons (Gt) of carbon by 2050. The high and low cases yield results of 20.9 Gt and 17.4 Gt of carbon respectively. By 2100, the emissions have leveled off at cumulative 20.6, 22.2, and 24.8 GtC for the low, average, and high cases respectively.

Emissions (Cumulative Giga ton Carbon) from Coal-Fired Electricity Generators Operating as of 2001 (GtC)			
Year	2001	2050	2100
Low carbon coefficient & high generation efficiency	0.47	17.4	20.6
Average case: average carbon coefficient and average generation efficiency	0.50	18.7	22.2
High carbon coefficient & low generation efficiency	0.56	20.9	24.8

Table B1 Cumulative emissions (GtC) from coal-fired electricity capacity operating as of 2001 through 2050 and 2100.

[27] Coal price predictions taken from the AEO: http://www.eia.doe.gov/oiaf/aeo/aeotab_3.htm

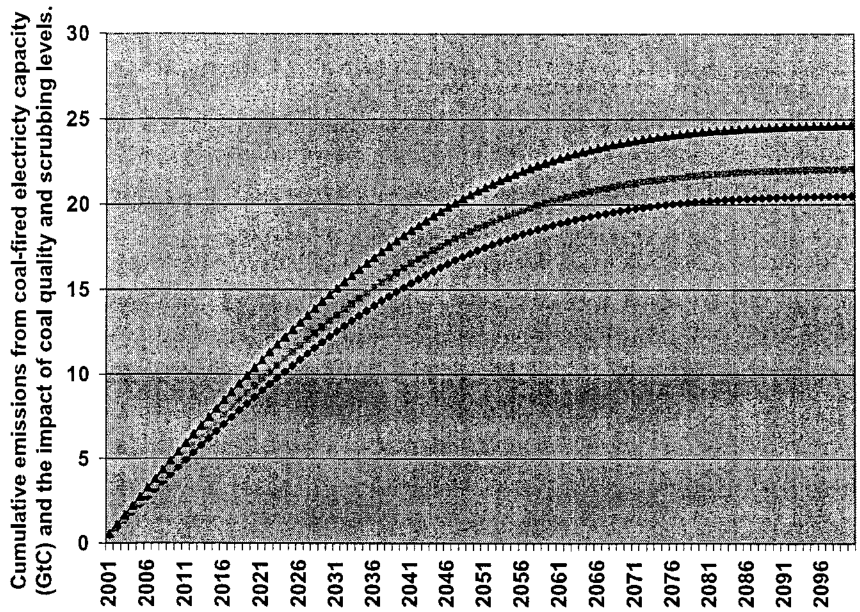

Figure B7. Cumulative emissions (GtC) from coal-fired electricity capacity operating as of 2001 through 2100 with high and low estimates due to the quality of coal used and scrubbing levels

B.3 Other than Coal-fired Electricity Generating Technologies

At 87% of carbon emissions from electricity production, coal comprises the lion's share of the U.S. electricity sector's emissions. Furthermore, as discussed above, coal generators are used for extremely long periods of time, causing coal to be the dominant contributor to that sector's carbon shadow. However, investigating the shadows of the other production technologies, despite their small share, would not only make our overview more complete, but also provide tools of analysis necessary for looking at futures that move away from the dominance of coal. Unfortunately, as these technologies are a much smaller share than coal in terms of generation and emissions, they receive less attention and thus the data on them is thinner. Although we use the same model framework developed for the coal steam turbines, the lack of data in some cases results in a number of limiting assumptions.

The following overview looks at, in turn,

- other steam turbines, with "other" referring to petroleum and natural gas steam generators, in contrast to coal steam generators discussed before,
- gas turbines,
- internal combustion generators, and
- combined-cycle generators.

Each section outlines the models used for each of these technologies, highlighting the differences between them and the coal model, and listing the regression equations for each fuel-technology combination. The data used for the retirement models are from the same sources as for coal, that is, from EIA Form 860 while the capacity factor and heat rate models draw from a different source in these models.[28] Within these models, the carbon coefficients for oil and gas are 47.4 and 31.9 lbs C/MBtu respectively, and are drawn from the 2001 AER. These sections are followed by a summary of the carbon shadow results of each of these models, and their comparison to the coal results above.

B.3.1 Other Steam Turbines[29]

B.3.1.1 Other Steam Turbine Retirement Components

Three types of steam turbines were looked at in this study:

- Oil only[30],
- Natural gas, and
- Dual oil-gas.

To account for the possibility of different usage characteristics based on type of fuel, these three were treated separately from one another, with a separate model developed for each. Engineering scrappage was computed for each in the same manner as for the coal steam turbines, identifying the percentage of generators reaching age X to pass on to age X+1 over the 30 years (1970-2000) of data contained in the EIA Form 860 data set. As with the coal, the functional form most closely approximating the retirement data was a log-cubic. The regression results for each fuel type are listed below.

Oil only:

$$Y = \exp(-.0038902 - .00000710 * t^3)$$

(t-statistic) (-.69) (-48.22) Adj. $R^2 = .981$

Gas only:

$$Y = \exp(.0124994 - .00000319 * t^3)$$

(t-statistic) (3.29) (-28.14) Adj. $R^2 = .948$

Dual Gas-Oil:

$$Y = \exp(-.0040379 - .00000574 * t^3)$$

(t-statistic) (.94) (-57.98) Adj. $R^2 = .986$

where Y is the fraction of originally built generator capacity remaining after 10 + t years.

[28] The total generation (used to calculate the capacity factor) and fuel usage (used to calculate the heat rate) are draw from EIA Form 759 from 2000. These data were matched up by generator ID to the capacity and age figures from EIA Form 860 from 2000, much in the same way that Form 767 and Form 860 were used for the coal model.

[29] "Other" here refers to petroleum and natural gas steam generators. Biomass and waste generators are ignored in this study as arguments can be made that they are carbon neutral or at least have lower *net* carbon emissions. Focus remains on the fossil fuel generators in the U.S.

[30] Oil-based generators are those that use residual fuel oil, distillate fuel oil, kerosene, waste oil, or jet fuel.

We have not been able to develop a cyclical model that fits with the data. Therefore, for the purposes of these models, cyclical scrappage is ignored for non-coal steam units, and engineering scrappage is assumed to dominate retirement decisions.

B.3.1.2 Other Steam Turbine Capacity Factors

The capacity factor for non-coal steam turbines was estimated using the age and size of the plants. As the regression results below show, capacity usage of non-coal steam generators is dominated by the size of the unit. Unlike coal, where age was the predominant variable, the capacity factor is linked most closely to summer capacity, with larger units seeing more usage than their smaller counterparts.[31] As with coal units, older generators are assumed to be used less intensively than younger ones, but the difference between older and younger ones' use is much smaller.

Oil Only:

$$CF = \underset{(4.51)}{.7196922} \; \underset{(-2.36)}{-.0004186 * summcap} \; - \underset{(-2.47)}{.0085659 * age}$$

Adj. R^2 = .0793

Gas Only:

$$CF = \underset{(1.87)}{.1391057} \; \underset{(5.37)}{+.0007092 * summcap} \; - \underset{(-0.01)}{.0000206 * age}$$

Adj. R^2 = .1866

Dual Gas-Oil:

$$CF = \underset{(6.38)}{.3117907} \; \underset{(4.57)}{+.0002554 * summcap} \; - \underset{(-2.87)}{.0030909 * age}$$

Adj. R^2 = .1312

B.3.1.3 Other Steam Turbine Heat Rates

Non-coal steam turbine heat rates were initially regressed against age and summer capacity. However, unlike coal turbines, age was not a statistically significant factor in determining heat rates. On the one hand, this is most likely related to similar findings for the capacity factors (if, for instance, heat rate is not dependent on age for these units, usage decisions could be explained as also not dependent on age). On the other hand, at this point, we have no explanation for this result, as we would expect these generators to physically behave like coal generators in terms of lifetime efficiency. The heat rate regression results are:

Oil Only:

$$\text{Heat rate} = 14358 * age^{(.0309015)} * capacity^{(-.0694145)}$$

(t-statistic) (20.81) (0.29) (-2.51) Adj. R^2 = .111

[31] The oil-only generators, however, exhibit considerably different statistical results. Capacity is negatively related to CF for them, and the regression on a whole has a much lower R-squared. This is possibly due to a low sample size (66) relative to the others.

Gas Only:

$$\text{Heat rate} = 14827 * \text{capacity}^{(-.0510657)}$$

(t-statistic) (164.53) (-3.75) Adj. $R^2 = .107$

Dual Oil-Gas:

$$\text{Heat rate} = 15360 * \text{age}^{(.0437232)} * \text{capacity}^{(-.0896352)}$$

(t-statistic) (47.78) (0.91) (-8.74) Adj. $R^2 = .233$

B.3.1.4 The Vintage Capital Models of Other Steam Turbines

The vintage capital model equations are combined in a similar fashion as for coal plants to yield annual carbon emissions for non-coal steam generators. An additional calculation, however, is required for determining how much oil and gas are used at dual-fueled plants. The lack of historical information on this share limits us to a static model (rather than one built on relative oil and gas prices) that uses the fuel ratio in dual-fired generators from 2000: 18.1% oil and 71.9% gas.[32] This fuel ratio is then used to determine the amount oil and gas respectively, which are then transformed into an amount of carbon emissions, using the appropriate carbon coefficient.

Figure B8 shows how the model results compare to the original data for "other" steam turbines.

[32] This ratio is express in terms of percent of total BTUs burned, and is drawn from the EIA Form 759 2000 database.

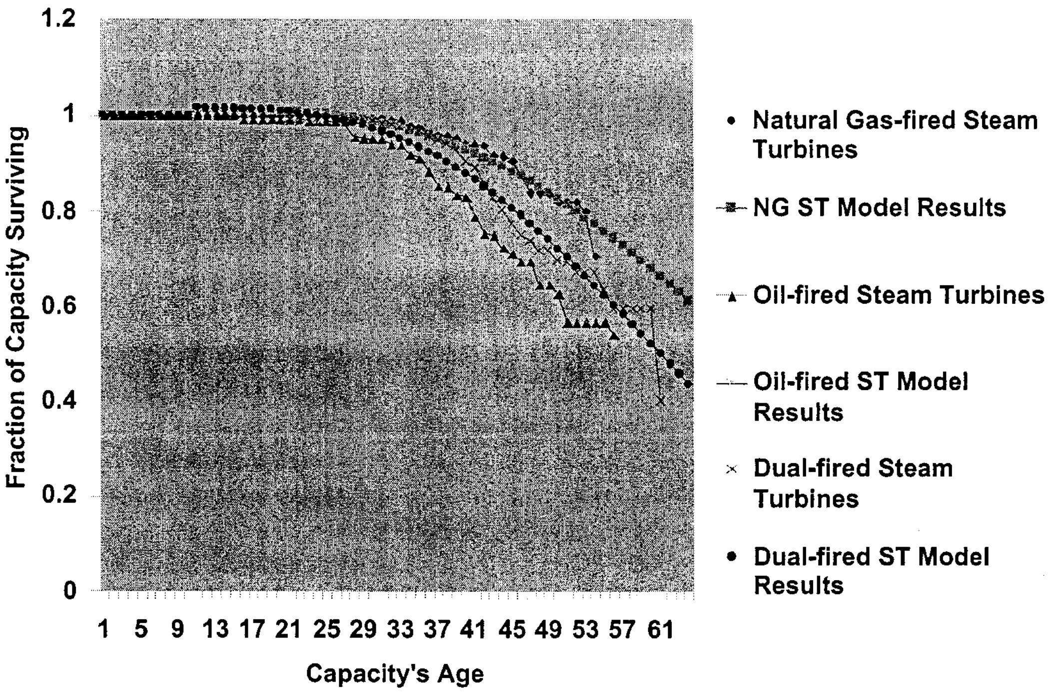

Figure B8. Other steam turbine capacity survival

B.3.2 Combustion Turbines

Gas turbines differ significantly from steam turbines (STs) in terms of both physical structure and use. In steam turbines, the movable turbine blades are exposed to high pressures and temperatures just over 100 degrees Celsius. In combustion turbines (CTs), however, as the burning occurs in the turbine, the same moving parts must be able to withstand significantly higher pressures and temperatures. As such, they have a shorter lifespan than steam turbines. Also, the facts that they are cheaper per kW to build and can be cold started much more quickly than steam turbines (as there is no water that must be heated up) lead combustion turbines to serve as peaking units rather than baseload. This means that while steam generators run most of the time to provide the constant, or baseload, supply of electricity used 24-7 by the power grid, combustion turbines tend to be brought online only during the few hours of highest, or peak, demand, during the day. Thus, while steam turbines might see usage 50-70% of the time, capacity factors for combustion turbines are routinely in the single digits.

Another feature of combustion turbines should be mentioned, as it significantly limits the results of this sub-model. Most baseload units are owned by utility companies, and thus are included in the EIA 860 2000 dataset used for determining the retirement figures and the EIA 759 2000 database used for determining heat rates and capacity factors. However, peaking units, such as combustion turbines, are often owned by non-utilities, and neither of these datasets contains information on non-utility generators.[33] Thus, all of the figures calculated for the combustion turbine models are rough approximations based on the behavior of the utility-owned share of generators.

B.3.2.1 Combustion Turbine Retirement Models

The log-cubic model used for engineering scrappage for steam turbines did not fit the combustion turbine data well, as it did not drop off quite as steeply as the data suggests is the norm for combustion turbines. Thus, for these units, a logistic model was fit to the data, yielding a survival curve that moves through the period of rapid retirement much more quickly than the log-cubic model. Again, combustion turbines are treated separately depending on fuel type. The regression results for the engineering scrappage models are listed below:

Oil only:

$$Y = 1/(\exp(-4.903729 + .1330449{*}t) + 1)$$

(t-statistic) (-18.26) (8.22) Adj. $R^2 = .712$

Gas only:

$$Y = 1/(\exp(-6.17968 + .1098589{*}t) + 1)$$

(t-statistic) (-49.5) (26.3) Adj. $R^2 = .933$

Dual Gas-Oil:

$$Y = 1/(\exp(-5.800948 + .1239683{*}t) + 1)$$

(t-statistic) (-73.71) (42.51) Adj. $R^2 = .976$

where Y is the fraction of originally built generator capacity remaining after 10 + t years.

As with steam turbines, all attempts to link a cyclical retirement figure to the data proved fruitless. With natural gas turbines, for example, utility-owned generators have only been retired in six separate years, meaning that retirement was zero for the other 24 years. This limits the ability of the cyclical model to produce meaningful results. Thus, for the purposes of this model, the engineering scrappage figure for combustion turbines represents all of the projected scrappage. That is, for combustion turbines, no cyclical figure is included. The inclusion on non-utility power plant retirements might allow such a regression to be successfully reported, but the unavailability of such a dataset limits us to the engineering figure.

B.3.2.2 Combustion Turbine Capacity Factors

As mentioned above, the capacity factor for combustion turbines tends to be rather low. Investigation of the data found that, additionally, there is very little systematic variation

[33] When the vintage capital model is run, it uses the EIA 860 2001 dataset, which has both utility and non-utility generators in it, so all existing generators are included in the model. However, the 2000 dataset is the only one with comprehensive retirement figures, although it only contains information on utility-owned generators.

in the capacity factor along the lines of age or capacity. That is, the intensity of use of these generators does not appear to be based on either age or generator size. This may make sense given that, as peaking units, their usage will be determined more by demand than by supply-side characteristics such as age. To get around this fact, the mean capacity factor for each fuel type was used (the standard deviation of each mean appears in parentheses):

Oil Only:	.0165215	(.0680926)
Gas Only:	.0911429	(.2212842)
Dual Gas-Oil:	.0339475	(.0672977)

B.3.2.3 Combustion Turbine Heat Rates

The heat rates for the combustion turbines were determined using an age and summer capacity based regression model, yielding results similar to the coal steam turbines:

Oil Only:

$$\text{Heat rate} = 29476 * \text{age}^{(.1079179)} * \text{capacity}^{(-.009151)}$$

(t-statistic) (32.7) (1.93) (-3.83) Adj. $R^2 = .041$

Gas Only:

$$\text{Heat rate} = 15907 * \text{age}^{(.0927727)} * \text{capacity}^{(-.023813)}$$

(t-statistic) (22.1) (3.35) (-.63) Adj. $R^2 = .145$

Dual Gas-Oil:

$$\text{Heat rate} = 22606 * \text{age}^{(.0896531)} * \text{capacity}^{(-.0593075)}$$

(t-statistic) (43.16) (4.61) (-3.11) Adj. $R^2 = .097$

B.3.2.4 The Vintage Capital Models for Combustion Turbine

The vintage capital model equations are combined in a similar fashion as for coal plants to yield annual carbon emissions for non-coal steam generators. An additional calculation, however, is required for determining how much oil and gas are used at dual-fueled plants. The lack of historical information on this share limits us to a static model (rather than one built on relative oil and gas prices) that uses the fuel ratio in dual-fired generators from 2000: 22.2% oil and 67.8% gas.[34] This fuel ratio is then used to determine the amount of from oil and gas respectively, which are then transformed into carbon emissions using the appropriate carbon coefficient.

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[34] This ratio is express in terms of percent of total BTUs burned, and is drawn from the EIA Form 759 2000 database.

B.3.3 Combined-Cycle Generators

Natural gas combined-cycle (NGCC) generators, insomuch as they are a hybrid between gas turbines and steam turbines propose a number of model methodological issues from the outset. Additionally, the limited data available on these units, combined with the recentness of their introduction (such that no units have had to be retired from service, as of yet) makes modeling their carbon shadows an uncertain task at best.

B.3.3.1 Combined Cycle Retirement Model

As with the models for the other power generators, the NGCC retirement model draws its historical data from the EIA Form 860A database for 2000 and its capital stock data from the same database from 2001. This dataset, however, provided a number of limitations. First, some units are listed with their gas turbine and steam turbine components separated into each individual generator unit, while other plants have these units aggregated into one combined-cycle generator. This makes pinning down the exact composition of the capital stock nearly impossible. Secondly, although combined-cycle technology has only been used in the last decade and a half, the historical database lists NGCC plants with startup years as far back as 1912. In fact, only 50% of the NGCC generating capacity listed have startup dates after 1990. Due to these discrepancies, we therefore decided not to use the age figures from the Form 860 dataset in our model.

Since no NGCC generators have been retired in the U.S., we were not able to derive a historically-based retirement model as we did with the other technologies. Furthermore, the dual-nature of NGCC units makes it hard to determine what the dominant retirement characteristic would be. On the one hand, the gas turbine components, which are used at approximately 10 times the intensity as normal GT generators, will wear out rather quickly (although not 10 times quicker than GTs, as the avoidance of destructive cold-start cycles reduces wear considerably). On the other hand, the much more expensive steam turbine components (steam turbines cost $1200-$1500 per kW, whereas combustion turbines costs as low as $400 per kW) last a very long time (there are still steam turbines in operation that were built more than 80 years ago).

In our model, we assume that the steam turbine component dominates the retirement decision (which is to say that the less expensive gas turbine components will be replaced throughout the service life of the steam turbine components), and we therefore use the same engineering scrappage model developed for natural gas steam turbines. Thus:

$$Y = \exp(.0124994 - .00000319*t^3)$$

where Y is the fraction of originally built generator capacity remaining after 10 + t years. No cyclical scrappage component was derived for NGCC generators.

B.3.3.2 Combined Cycle Capacity Factor

The inconsistent aggregation among the data discussed above limited our ability to develop a model of capacity factors based on age and size as with other generator types. Instead, an average capacity factor was computed as follows. The capacity factor was derived using the "total capacity" figures from the Form 860, 2001 database with estimations of generation derived from the other models. From the NG gas turbine, NG steam turbine, dual-fired steam and dual-fired gas turbine models, we were able to produce an estimate of the amount of natural-gas-fueled electricity (in GWh) that was produced by these generators in 2001, that is, 329,000 GWh. We subtracted this from the EIA figure for total electricity produced from natural gas in 2001 — 629,100 GWh — to get 310,000 GWh as an estimate for the amount of generation from NGCC units in 2001.[35] Dividing this figure by 8760 hours and the NGCC capacity in 2001 (which comes from the Form 860 database for that year) of 66.6 GW, we obtain a capacity factor of 53.1%.

B.3.3.3 Combined Cycle Heat Rates

Again, the data limitations kept us from deriving an age and size dependent model of generator efficiency. Instead, heat rate information for NGCC plants was drawn from David and Herzog (2000)'s paper on generation technologies, and a heat rate of 6201 Btu/kWh is used for all generators.[36,37]

B.3.3.4 The Vintage Capital Model for Combined Cycle

Since we decided to ignore the first-service data, the age structure of the existing capital stock had to be derived instead from the Form 860 2001 dataset. To do this, we used the "total capacity" figures from the EIA Annual Energy Outlooks (AEOs) of 1995 through 2003 to see how much NGCC capacity had been built in each year.[38] The number built in 2001 (and thus starting at age zero in the model) is equal to the capacity existing in the Form 860 dataset from 2001 minus the year 2000 capacity reported in the 2003 AEO. All capacity built before 1993 was assumed to have been built in 1992.[39]

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[35] http://www.eia.doe.gov/emeu/aer/txt/ptb0802a.html

[36] David, J. and H. Herzog. 2000. The cost of carbon capture. Fifth International Conference on GHGCT. Cairns, Australia

[37] This means that the decrease in efficiency normally observed as generators age is not included in the model. This is partially offset (at least in terms of project emissions) by the fact that, by not having capacity factor determined by age, generator use does not decrease later in the lifecycle.

[38] Ideally, we would have used the Annual Energy Review (AER), which has historical data, to get these numbers. However, the AER does not have breakdowns by generation technology, whereas the AEO does. However, each year's AEO only has 1-2 years worth of historical data, thus it was necessary to use multiple years (1995-2003) to get accurate figures for number built each year.

[39] It should be noted that this means that age cohorts in this model consist only of a total capacity, and not individual generators. Thus, while in other models we were able to drop generators based on their efficiency, in this model we are limited to just reducing the total capacity of each age cohort based as determined by the retirement model.

After that, the model is analogous to the others, previously described. Each year, emissions are calculated by first multiplying total capacity by 8760 and by the capacity factor to determine the total GWh of electricity produced. Then, the heat rate is used to convert this to a total Btu of natural gas consumed in NGCC generators. Finally, the carbon coefficient of 37.1 lbs CO_2/Btu converts energy to total amount of carbon emitted.

At the end of each year, the retirement model is applied to each age cohort to determine the percentage of capacity progressing to the next age cohort in the following year. Since we were not able to get age information for individual generators, the selective removal system used in the previous models is not employed here. Instead, each age cohort simply loses the amount of capacity dictated by the retirement model. The process is repeated for each year, 2001-2100.

Figure B9 shows how the model results compare to the original data for combustion turbines

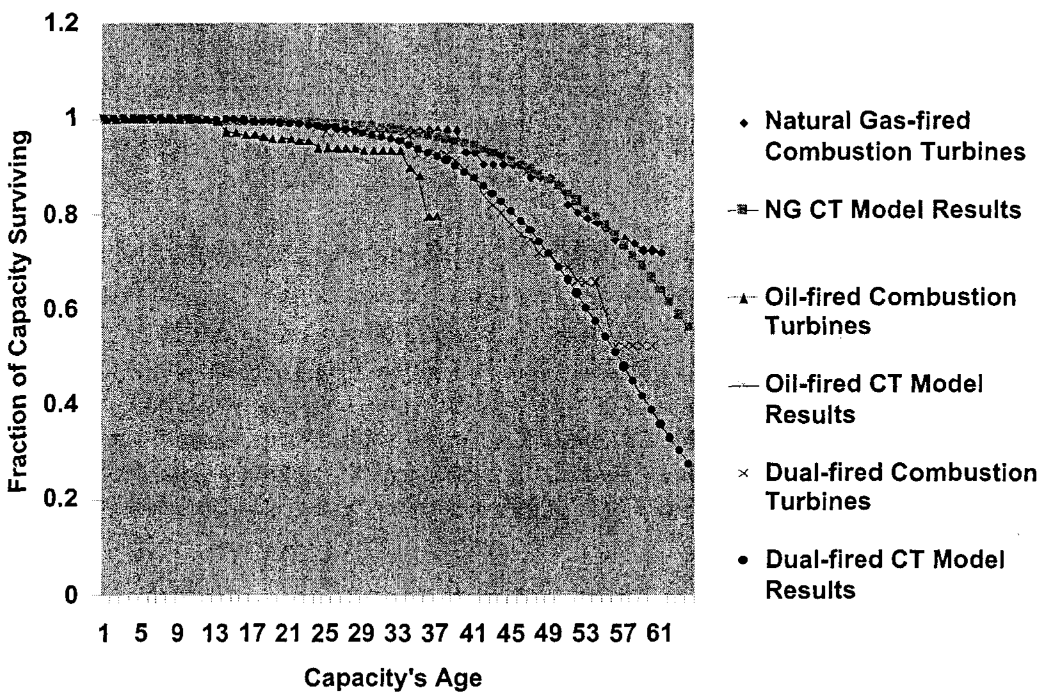

Figure B9. Combustion turbine capacity survival

Appendix C: Retirement Models for transportation

The model, like the generator models, works in three components. First, a retirement model calculates the total number of vehicles of each age group surviving into the next year. Second, a usage model determines how many vehicle miles are driven by each age group. The third component assigns the appropriate efficiency (measured in miles per gallon (mpg)) to each vehicle type and age group to obtain a total amount of fuel consumed. This is transformed into a total carbon emissions figure by means of a carbon coefficient. Each model component is discussed in turn below.

C.1 Transportation Sector Retirement Model

C.1.1 The Data

Polk Automotive Corporation produces the only existing dataset on retirements of cars and trucks in the United States. While we were not able to use this dataset directly, our retirement model was drawn from a report that did have access to it. An unpublished paper of Richard L. Schmoyer's is referenced in edition 23 of the Department of Energy's Transportation Energy Data Book as the source of three engineering scrappage models—for cars, light trucks, and heavy trucks.[40] Schmoyer used the Polk data set and the scrappage model developed by Greenspan and Cohen to produce nine engineering scrappage models: a separate one for model years 1970, 1980 and 1990 for each class of vehicle (cars, light trucks, heavy trucks).[41] These models assign a scrappage rate (percent of existing vehicles retired in a given year) for each vehicle age. That is, for each model year, it specifies the percent of vehicles that will be retired at age 1, the percent of those remaining that will be retired at age 2, and so on.

Data on the existing vehicle stock and its age structure is drawn from two smaller (and more affordable) Polk datasets. Data on cars and light trucks comes from Polk's 2001 National Vehicle Population Profile. The 2001 stock of trucks had to be estimated from Polk's 2003 Vehicles in Operation report (Polk apparently does not keep truck data that is more than a year old), using the Schmoyer retirement model to extrapolate back to the 2001 levels. Cars were treated as their own category in our modeling, as were light trucks (defined as trucks with gross vehicle weight (GVW) under 10,000 lbs). The other trucks were divided into three categories: medium (GVW 10,001-16,000), light-heavy (GVW 16,001-26,000) and heavy-heavy (GVW 26,001+). In 2001, the first period of the model, the vehicular capital stock was comprised of 128.7 million cars, 79 million light trucks, 1.7 million medium trucks, 640 thousand light-heavy trucks, and 3.7 million heavy-heavy trucks.

[40] The scrappage models can be found in the tables for chapter 3: http://www-cta.ornl.gov/data/chapter3.html

[41] http://www.federalreserve.gov/Pubs/FEDS/1996/199640/199640pap.pdf

C.1.2 Determining Retirements

Each of the five categories of vehicles is divided up into age cohorts, which are determined by model year. The Schmoyer model only has figures for scrappage of vehicles of model years 1970, 1980, and 1990, and thus we needed to derive figures for the other model years. For vehicles with model years between 1970 and 1990, scrappage rates are determined for each age level by assuming a linear change in scrappage rates between 1970 and 1980 and between 1980 and 1990. Vehicles with model years after 1990 are assumed to be retired at the same rate as those with model year 1990.

Also, scrappage numbers from the Schmoyer model are listed only for light and heavy trucks—medium and light-heavy trucks do not have their own figures. However, when estimating the 2001 numbers from the 2003 numbers for these two groups, it was observed that the estimates for the 2001 totals were considerably off if we used the heavy truck scrappage figures for medium trucks (in which case the 2001 estimates were much too low) or if we used the light truck scrappage rates for light-heavy trucks (in which case the 2001 estimates for the youngest 15 cohorts alone was larger than what the entire 2001 should have been). Thus, we decided to use the light-truck rates for medium trucks and the heavy truck rates for light-heavies.[42]

Each year, total retirements are determined by calculating the scrappage rate (percent of vehicles to be retired) for each model year and finding the rate associated with the appropriate age (i.e. the age that cars of that model year will be in the year under calculation in the model). These scrappage rates are applied to their appropriate age/vehicle cohorts, and the model outputs the vehicles surviving into the next year.

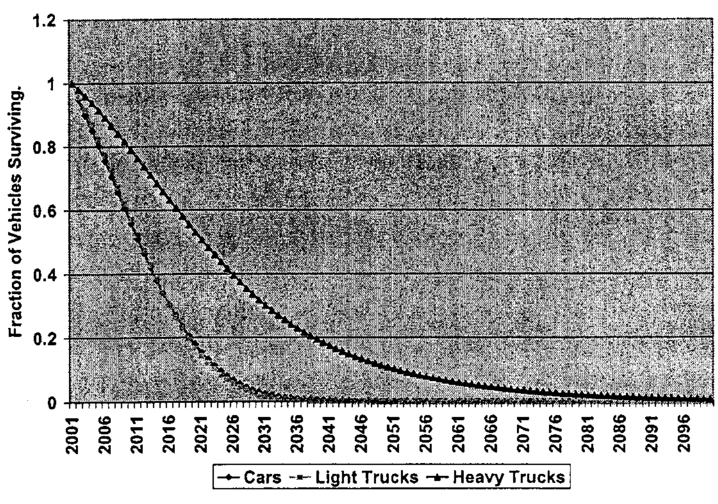

Figure C1. Fraction of vehicle capital stock Surviving

[42] Insomuch as the reference to Schmoyer's paper does not specify what exactly is meant by light and heavy trucks, it is possible that medium trucks were included in "light" and light-heavies were included in "heavy" in the first place.

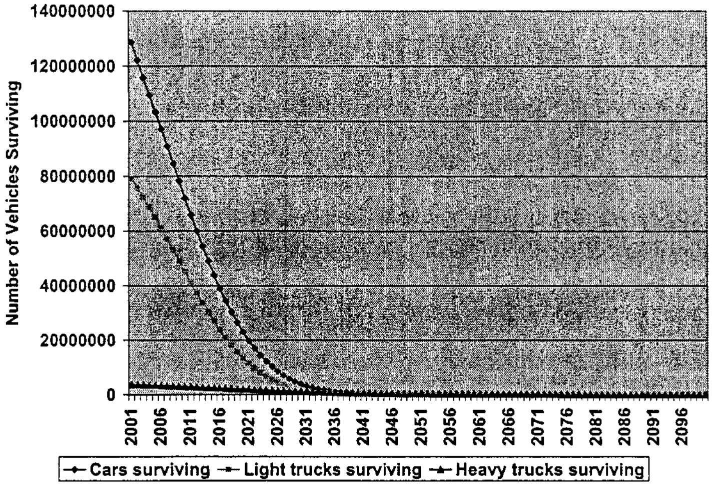

Figure C2. Number of vehicles surviving

C.2 The Transportation Usage Model

C.2.1 The Data

The usage models are derived from two surveys. Car and light truck usage information comes from the vehicle-level portion of the National Household Travel Survey of 2001, a survey of vehicle ownership and usage characteristics.[43] From this dataset, we extracted data on the type of vehicle (car or light truck/van), its age, and the total annual miles driven. The data on trucks comes from the vehicle-level version of the 1997 Vehicle Inventory and Use Survey, survey of truck ownership and travel characteristics conducted by the U.S. census bureau.[44] This dataset provided information on truck size, truck age (approximated by model year), and annual miles driven.

C.2.2 The Regression Models

A brief glimpse at the data shows that there is a negative relationship between age and the number of miles driven in a year—older vehicles are driven less distance than newer vehicles, on average. This relationship tends to level off in later years, however, with the difference in driving distance between a 30-year old and 31-yar old vehicle being considerably smaller than the difference between younger vehicles one year apart. For each of the five vehicle types, we used data from the appropriate data set to regress the number of miles driven against the age of the vehicle for all vehicles under 30 years old.

[43] http://nhts.ornl.gov/2001/index.shtml
[44] http://www.census.gov/svsd/www/97vehinv.html

The data was weighted using the weight figure included in the two datasets. The regression results are listed below.

Cars:

	Miles = 13878.8	- 422.2 * age	
(t-stat)	(100.23)	(-28.4)	Adj. R^2 = .0334

Light Trucks:

	Miles = 15974.9	- 508.9 * age	
(t-stat)	(110.53)	(-33.17)	Adj. R^2 = .0595

Medium Trucks

	Miles = 26874.5	- 1123.8 * age	
(t-stat)	(50.0)	(-12.9)	Adj. R^2 = .0329

Light-Heavy Trucks:

	Miles = 34204.9	- 1386.8 * age	
(t-stat)	(32.0)	(-8.12)	Adj. R^2 = .0272

Heavy-Heavy Trucks:

	Miles = 91714.3	- 5167.7 * age	
(t-stat)	(168.9)	(-55.4)	Adj. R^2 = .1061

As vehicle size increases, the number of miles driven by age 0 vehicles also increases. However, the steepness of the age-related drop-off in driving also increases, so that while new heavy trucks are driven over 6 times the distance of new cars, the driving drops off 13 times faster with age. It should also be mentioned that, although these regressions have low R-squares, they are still useful average indicators. Since we're dealing with vehicle stocks in the aggregate, the individual variation among vehicles is not as important as the general relationships—such as the generally observed relationship between age and usage.

In the model, these five usage models are applied to each age/size cohort to yield the average number of miles driven by each cohort. This, in turn, is multiplied by the total vehicles in each cohort to give the total vehicle-miles per cohort. Totaling these cohort totals yields the total vehicle miles driven in each year.

C.2.3 Fuel Use and Carbon Emissions

For cars and light trucks, vehicle efficiency is determined using model-year fleet averages published by the EPA.[45] Each cohort (model year) is assigned the appropriate mpg figure provided by the EPA, and is assumed to maintain this efficiency throughout its useful life.[46] For trucks, limited EPA data led us to turn back to the 1997 VIUS, which

[45] http://www.epa.gov/otaq/cert/mpg/fetrends/r03006-a.pdf

[46] While this may or may not be a realistic assumption, we are limited to it by the data available. There is, to our knowledge, however, no published research that shows that efficiency declines with age for vehicles.

also contains user-reported mpg figures for most trucks in the survey. We took the average of each model year for each truck weight class. Unfortunately, the dataset only demarcates model years 1988 through 1997, so we were forced to assume that all trucks built before 1988 have the 1988 model year efficiency for their weight class and that all trucks built after 1997 have the 1997 level of efficiency appropriated to their weight class.

Each year, the total vehicle-miles driven by each age/size cohort is divided by these mpg figures to yield the gallons of fuel consumed. For cars, all fuel is assumed to be gasoline and for heavy-heavy trucks, all fuel is assumed to be diesel. For the other three classes, the VIUS was again used to determine the average fuel share between diesel and gasoline for these weight classes. It was found that for light trucks, 3.2% of miles driven were diesel-fueled, 35% for medium trucks, and 12% for light-heavy trucks. Using these figures, the total number of gallons of gasoline and diesel consumed by each weight class could be determined for each year of the model.

These fuel totals were then converted into carbon emission totals. Each gallon of fuel contains .125 MBtu and each MBtu of fuel burned emits 42.8 pounds of carbon for gasoline and 44 pounds of carbon for diesel fuel. A cumulative total of these carbon emission numbers provides the carbon shadow estimate of the model.

Appendix D: Uncertainty and Sensitivity

All analyses like the ones described in the preceding sections are subject to uncertainties and are sensitive to underlying assumptions. The current analysis faces one major uncertainty associated with the carbon cycle and two major sensitivities to the underlying assumptions. There are of course other uncertainties and sensitivities, but these three have been set aside in the baseline analysis to clarify the basic story. While other sensitivities and uncertainties need to be addressed, these three deserve special mention because they have important policy implications. The three are:

1. Uncertainty in our understanding of the carbon cycle. The calculation of a carbon budget helps put the carbon shadows in context. However our knowledge is of the global carbon cycle is not perfect and one uncertainty in particular has a major impact on the stabilization budgets. This is the value for the long-term uptake of carbon dioxide by the oceans.

2. Sensitivity to the carbon stabilization goal. The reference analysis was done using a concentration of 550 ppmv for a CO_2 stabilization goal. This is a frequently used target value, simply because it represents a doubling of the pre-industrial concentration of carbon dioxide. Performing the analysis for other concentration targets shows the sensitivity of the results to the stabilization policy.

3. Sensitivity of coal analyses to the type of coal used to compute carbon emissions. Coal is a very non-uniform fuel and assumptions were made about the quality of coal that might be burned as part of projecting future emissions. While this is a relatively smaller effect than the previous two, it does affect the largest single source of the U.S. capital stock carbon shadow.

D.1 Carbon cycle uncertainties and sensitivity to stabilization level

Recall that allowable carbon dioxide emissions were calculated based atmospheric stabilization targets and assumptions with regard to the behavior of the Earth's carbon cycle. Least cost pathways to reach stabilization targets were obtained through an optimization algorithm with cost curve inputs and the widely used "simple climate model" MAGICC which translates carbon dioxide emission inputs into atmospheric concentrations over time.

There are a number of uncertainties associated with our understanding of the natural carbon cycle. One of the most important, for long-term stabilization trajectories, is the one associated with the projected rate of uptake of carbon dioxide by the Earth's oceans. In order to illustrate the impact of these uncertainties on our projected carbon budgets we have repeated our calculations using 10%-90% percentile bounds on carbon-cycle uptake (Dr. Tom Wigley personal communication; see also Wigley and Raper 2001).

We have also calculated the carbon budgets not only for the 550 ppmv concentration target used in the earlier analysis, but also for a much more constrained atmospheric concentration target of 450 ppmv and for a more relaxed target of 650 ppmv.

Cumulative carbon emissions in the WRE reference case amount to 500 GtC by 2050 and 1345 GtC by 2100. These represent the cumulative carbon emissions to the given year if no climate policies are in place. In reality, future emissions are not known and could be higher or lower than the value given here (IPCC Special Report on Emissions Scenarios, Nakicenovic and Swart 2000).

The impact of uncertainty associated with the carbon cycle and the sensitivity to stabilization goals on carbon budgets to 2050 and 2100 are summarized in Table D1 and figures D1 and D2. Examination of this material suggests two important conclusions.

1. The uncertainty in the carbon cycle budgets has a larger impact on the carbon budgets associated with the lower target concentration (450 ppmv) than the corresponding values for 550 and 650 ppmv.

2. From the perspective of science impacting policy, eliminating the possibility that the ocean uptake is lower than the current best estimate in carbon cycle models has a great impact on the flexibility policy makes may have in meeting any particular stabilization target.

	Stabilization at 650 ppmv	**Stabilization at 550 ppmv**	**Stabilization at 450 ppmv**	**Reference case**
Global carbon budget to **2050** (GtC)	505	460	373	500
Uncertainty range (GtC)	451 – 515	423 – 463	311 – 397	
Global carbon budget to **2100** (GtC)	1089	870	579	1345
Uncertainty range (GtC)	815 -1 176	663 – 973	331 - 655	

Table D1. The carbon budget, assumptions and uncertainties

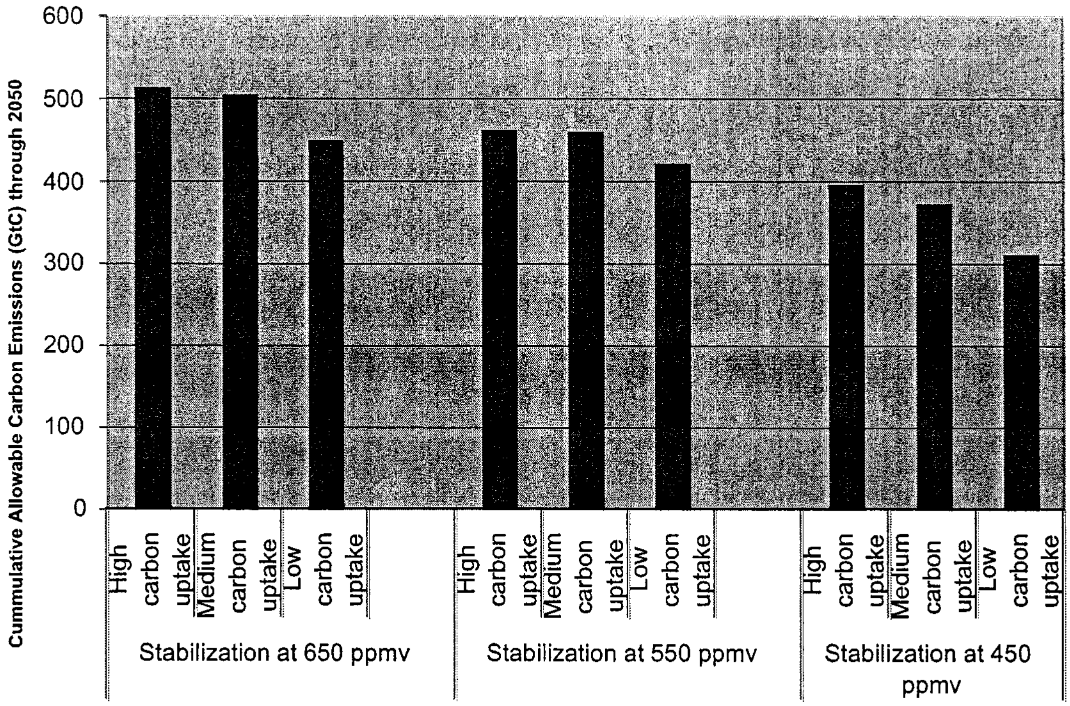

Figure D1. The global carbon budgets of cumulatively allowable carbon emissions (GtC) through 2050 and their uncertainties due to various assumptions on carbon uptake by carbon cycling calculated based on least cost emission trajectories.

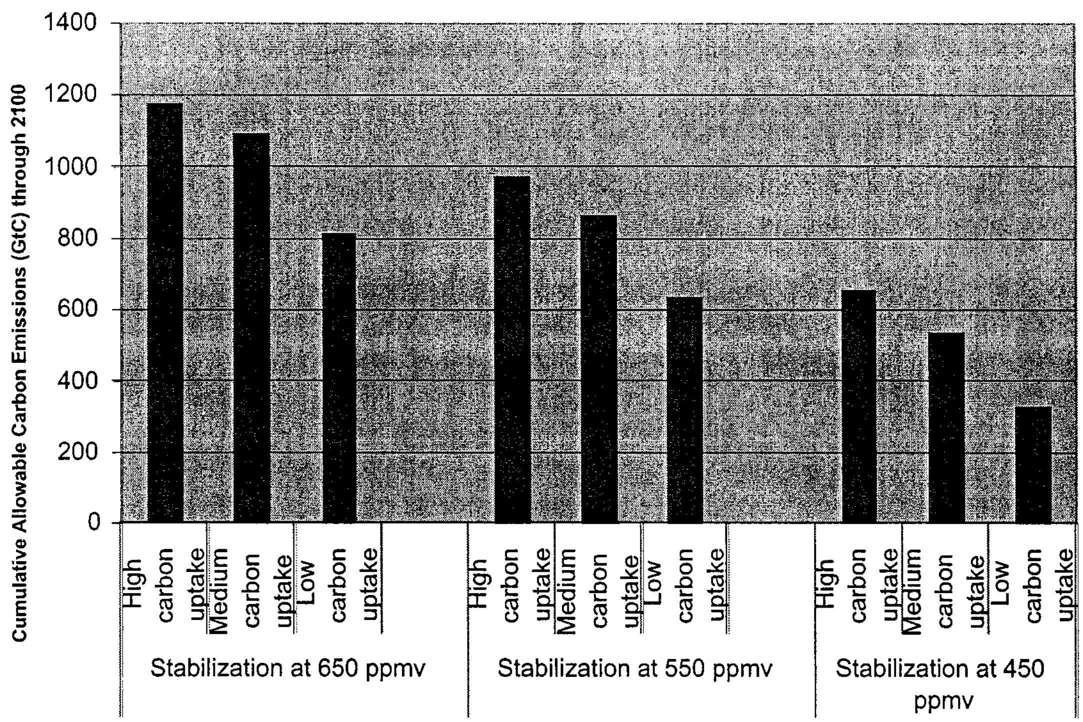

Figure D2. The global carbon budgets of cumulatively allowable carbon emissions (GtC) through 2100 and their uncertainties due to various assumptions on carbon uptake by carbon cycling calculated based on least cost emission trajectories.