Intertemporal Regulatory Tasks and Responsibilities for Greenhouse Gas Reductions

By Jeff Deason and Lee S. Friedman

Goldman School of Public Policy
University of California at Berkeley
lfried@berkeley.edu
jadeason@berkeley.edu

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Abstract

A number of jurisdictions are in the process of establishing regulatory systems to control greenhouse gas emissions that will include as a major component a cap-and-trade system. Both short-term and long-term emissions reduction goals are often established, as California does for the years 2020 and 2050, but little attention has yet been focused on establishing annual emissions targets for the intervening years. We develop recommendations for how these annual targets—which we collectively term a "compliance pathway"—can be set, as well as what flexibility sources should have to adjust to changing or unexpected circumstances in light of cost uncertainties. Existing cap-and-trade programs provide limited guidance on the choice of compliance pathways or on mechanisms for flexibility along them. We consider environmental effectiveness, efficiency, equity, and adaptability as appropriate criteria by which these intertemporal policy alternatives should be judged. We also consider how the strategic context of global emissions reduction may affect the design. Borrowing constraints that are likely to be present in any regulatory system affect our recommendations. We recommend that some allowances intended for future years be auctioned early, and that sources be allowed to use them early. We also find that a three-year compliance period can have substantial benefit over a one-year period. Furthermore, we find that many sources of cost uncertainty suggest a compliance pathway characterized by increasing emission decrements along it. This can be approximated by discrete linear segments, and the latter may fit better with ongoing global negotiations.

I. Introduction

In this paper, we consider a problem that confronts many jurisdictions that either have or are considering regulatory systems to reduce greenhouse gas (GHG) emissions. Many jurisdictions have passed or are considering passage of statutes that set targets for greenhouse gas reductions. These statutes typically specify reduction targets in specific future years (e.g., a target in 2020 and one in 2050) as a percentage of some past year's emissions. As we discuss here, such goal-setting stops well short of defining a limit on aggregate emissions over the full time period the statutes attempt to regulate. We here consider the intertemporal tasks and responsibilities that attend to an agency or other actor attempting to implement such statutes through a cap-and-trade program.

We use the state of California as an example in this paper. California has often played a leading role in the development and implementation of regulatory programs and standards to reduce air pollution. For example, when the U.S. Clean Air Act was passed in 1970, this role was recognized at the federal level: the Clean Air Act specifically grants to California the opportunity to develop more stringent standards for vehicle emissions than federal ones and to apply for a federal waiver allowing it to implement those standards. Through 2006 this opportunity has been sought and waivers granted approximately 50 times.[1] In each of these cases, other U.S. states may and often do adopt the more stringent California regulation if they prefer it to the federal standard.

California has continued its proactive environmental role by developing important regulatory programs to reduce GHGs. In the 2006 Global Warming Solutions Act (known by its legislative bill number AB32), California committed itself to reduce GHGs to the 1990 level by 2020. Its Governor has aggressively supported these efforts, and issued Executive Order S-3-05 that further commits the state to achieve by 2050 an emissions level equal to only 20% of the 1990 level. The California Air Resources Board (CARB) is the state agency with overall responsibility for developing the regulations that will achieve these goals. It has adopted the value of 427 million metric tons of carbon dioxide equivalents (mmts CO_2e) as the official 1990 level of emissions[2]. That amount is therefore the 2020 goal and 85 mmts (20% of that number) is the 2050 goal. California's new regulatory system is currently under design, and will be implemented beginning in 2012 when we estimate emissions are likely to be around 537 mmts.[3] How California chooses to implement its program will be carefully scrutinized by many other jurisdictions around the world, as almost all recognize the importance of the problem and seek constructive, effective solutions to it.

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[1] P. 2 of California Air Resources Board fact sheet on "Climate Change Emissions Standards for Vehicles," available on its web site at http://www.arb.ca.gov/cc/factsheets/ccfaq.pdf.

[2] Carbon dioxide is the greenhouse gas responsible for the lion's share of anthropogenic global warming; however, there are many other greenhouse gases. Carbon dioxide equivalents convert the global warming induced by greenhouse gases in aggregate to the amount of CO_2 that would produce an equivalent amount of warming, thus putting all emissions on a common scale.

[3] As of this writing, the most recent reliable emissions data is for 2004 when California had 480 mmts. If emissions grow at a slowed rate of 1.4% annually from 2004-2012, this leads to 537 mmts in 2012. Actual emissions growth from 1997-2004 was at 1.9% annually, but early actions under AB32 can be expected to slow this somewhat.

This article focuses on the intertemporal tasks and responsibilities of agencies like CARB, with the aim of recommending specific actions that they should take. These actions are by no means obvious for a number of important reasons. First, it is not clear by what criteria any proposed actions should be judged even if a jurisdiction like California is committed to achieving these goals no matter what the rest of the world is doing. Second, any single jurisdiction like California is a strategic player in a perilous game whose outcome affects all of the world's citizens and is determined by the worldwide and not local effort. Essentially, no one can win unless the whole world adopts mitigation goals for GHG emissions that collectively stabilize emissions at a level that prevents temperature increases of more than 3 degrees centigrade by the turn of the century. This means emissions reductions for the world that are somewhat like those adopted by California.[4] Third, we simply have no experience at managing this particular type of problem, and thus there are no pre-existing, satisficing bureaucratic routines under which this problem can comfortably fit.

Section II describes certain features of the global warming problem that make it unique as a problem for regulatory management. Section III explains the intertemporal constraints and latitude allowed to CARB by AB32 and by the Executive Order. We consider the likely cost differences implied by different possible "compliance paths" (the time progression of yearly required emission reductions), and conclude that these are likely to be quite large. We discuss criteria that can be applied to choose a particular compliance path.

CARB will be relying upon a cap-and-trade program as a significant component of its program.[5] In Section IV we consider saving and borrowing along the CARB-specified path. We find that allowing intertemporal flexibility in this market is an important tool for achieving a least-cost mitigation path, since cost and other market uncertainties prevent regulators from knowing this path in advance. We conclude that these market-based adjustments are likely to be highly desirable in terms of overall cost management if they do not threaten the environmental integrity of the overall program. We also find that under a fairly broad set of circumstances, the least-cost path to achieve a given aggregate emission reduction will be characterized by increasing incremental reductions over time. We find that there are reasons to limit borrowing in this context, but not to the degree that has characterized existing and planned cap-and-trade programs. We then consider several mechanisms that allow borrowing within periods of five years or less. We find that there

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[4] See, for example, Table 5.1 on p. 67 of Climate Change 2007: Synthesis Report, Fourth Assessment of the Intergovernmental Panel on Climate Change.

[5] The Scoping Plan adopted by CARB in December 2008 specifies that a variety of regulatory strategies will be used, including some command-and-control type of regulation that gives little discretion to emitters, programs restricted to specific sectors that require reductions with some flexibility to sources about how to achieve them, as well as a broad cap-and-trade program that by 2020 will include 85% of all California GHG emissions within it. CARB estimates that the regulations apart from cap-and-trade will achieve about 79% of the reductions required by 2020, with cap-and-trade achieving the other 21%. However, should CARB have overestimated (or underestimated) what the regulations apart from cap-and-trade will achieve in the covered sectors, the cap will automatically ensure that market-chosen reductions make up the difference. For an analysis of the scope issue, see Friedman (2009).

is substantial benefit to an advance auction each year of some future allowances with permission for sources to use them early if they wish—we use 20, 10, 5, and 5 % of the vintages for the next four years ahead as an example. We also find that there can be substantial benefit from having a three-year compliance period for truing up allowances rather than one-year compliance.

In Section V we consider whether California's plan is likely to be considered within its "fair share" of emissions, as defined by (or as likely to be defined by) global negotiations, and conclude that it is. In Section VI we consider the process of establishing a compliance pathway in the medium- and long-run. We find that there are reasons, notably the promotion of technological progress, for jurisdictions to make credible commitments to a long-term path with some adaptability to it. This adaptability can be very helpful both in terms of responding to new knowledge and in terms of ongoing global negotiations to ensure participation by all (discussed in Section VII).

In Section VIII, we conclude that all of these considerations can be achieved by a plan to achieve long-term goals in roughly ten-year increments, in which the goals for the next decade are set firmly and tentative goals for successive decades are announced but not finalized until approximately five years before the decade starts. We suggest a series of linear compliance path segments, each featuring a greater annual decline in the cap than the previous, as a simple mechanism that creates a pathway featuring increasing incremental reductions throughout the 2012-2050 time period.

II. Background for Intertemporal State Actions to Combat Global Warming

Global warming is not a problem that falls geographically near the source of the pollution. Increased emissions from anywhere raise the threat of ecological harm all over the globe. It does not matter if the extra emissions originate in the U.S. or in South Korea; either way they have the same harmful and global effects. The overriding criterion for all policies aimed at global warming is <u>effectiveness</u>: reducing warming to a level at which the world's ecosystem is sustainable for the indefinite future. No single nation or state can do this on its own: even if the U.S. were to stop permanently all GHG emissions next year, business as usual (BAU) in the rest of the world would still cause unsustainable global warming.

Since its founding in 1988, thousands of scientists worldwide have contributed to the United Nation's Intergovernmental Panel on Climate Change (IPCC). Its latest report indicates that achieving a stabilization rate of 445-490 ppm of CO_2e by the next century requires annual worldwide emissions to peak by 2015 and decline by 2050 to only 50-85% of the 2000 emission levels. This would still imply an average global temperature increase of 2-2.4 degrees centigrade.[6] Even achieving this will likely lead to some irreversible impacts; the report cautions that 20-30% of species will be at an increased risk of extinction if global warming exceeds 1.5-2.5 degrees centigrade. This increases to

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[6] See p. 21 of the "Climate Change 2007: Synthesis Report" of the IPCC Fourth Assessment Report, dated 17 November 2007.

40-70% of species if global warming exceeds 3.5 degrees centigrade. Many experts think that emissions cannot be reduced rapidly enough to achieve a stabilization level less than 500 ppm, and suggest that a goal of 550 ppm by the next century may be the best that we can do.

If the world were run by a benevolent dictator who was fully informed about this situation, we could turn to the economic question of how much it is worth spending in response to this threat. There is considerable scientific uncertainty about precisely how much global warming can be tolerated before its effects become irreversibly catastrophic. Given this, it becomes at least partially an economic question to consider the amount of spending that is globally rational to reduce this risk.

Despite the critical need to achieve a global goal of reducing annual GHG emissions by 2050 to something like 50-85% of the 2000 level (which was 40.8 gigatons of CO_2e), it is not at all clear that the world will do this. BAU paths have emissions increasing over time, not decreasing. While many countries of the world are working actively to reduce their emissions, important countries like the United States and China have so far refused to adopt specific reduction goals. For a country like China, which appears to be rapidly improving its relatively-low internal economic standard of living through economic development, appeals to halt its also rapidly growing GHG emissions seem unjust. It is hardly responsible for any of the CO_2e that is currently in the atmosphere; why shouldn't the developed countries that created the mess be the ones to clean it up? The failure of the United States to adopt specific reduction goals, knowing that it has been the major contributor to CO_2e, may seem somewhat less explicable. But these two extreme cases reveal an important part of the problem: determining just how much each country should reduce its future emissions in order to achieve the desired global result. There is neither a benevolent dictator nor even a world government that can impose a solution. Therefore we must find a solution that will be voluntarily adopted by virtually all. We refer to this as the "fair share" problem.

Another complicating factor is the relatively-long time period before atmospheric GHG emissions dissipate. Carbon dioxide, the GHG responsible for most anthropogenic warming, takes 50-100 years to dissipate in the atmosphere. Put differently, the carbon in the atmosphere now is roughly the sum of the carbon emissions over the past 75 years. Each year's emissions, even if substantially reduced, still adds to the existing GHG in the atmosphere and increases global warming. In 2005 our atmospheric level of CO_2e was 455 ppm, but only 30 years before it was 70% lower at approximately 268 ppm. Even if substantial worldwide absolute reductions were to begin now, our annual emissions will still be pushing the atmospheric concentrations to levels that would be better not to experience. In other words, it is critical that the world act decisively over the next 40 years and beyond to reverse global warming before its adverse effects become unmanageable and irreversible.

III. Alternative Time Paths for Allowances

A. The Jurisdiction's Intertemporal Problem

In at least one important way, California seems like most other jurisdictions that have seriously considered actions to reduce GHG emissions. Following the lead of the Intergovernmental Panel on Climate Change, many jurisdictions specify a short-term reduction goal and increasingly a long-term goal as well, and then proceed to develop regulatory programs intended to meet them. California's AB32 specifies that emissions in 2020 are to be reduced to the 1990 level of 427 mmts, and the Governor's Executive Order specifies that emissions by 2050 are to be no more than 85 mmts. Yet it is possible to achieve both of these targets by following an infinite number of alternative compliance pathways that are quite different from one another. How is a jurisdiction to choose from among them?

We believe two criteria are particularly important for determining this choice: equity and efficiency. Equity in this case refers to the "emissions budget" implied by the pathway, or the aggregate amount of allowed emissions over the years, and whether this amount represents a jurisdiction's "fair share" of global efforts to reduce GHG emissions. Efficiency in this case means minimizing the cost of achieving the emissions budget. However, additional criteria matter as well. Environmental integrity is a criterion to ensure that actual emissions are in fact limited to be within the emissions budget; this has been of some concern, for example, in considering the extent to which offsets may be used as a means of compliance and whether those offsets are indeed additional and verifiable. Adaptability is another important criterion, particularly with regard to how changing knowledge may affect the appropriateness of long-term goals, and procedures for revising the regulatory system in light of such new knowledge. Strategic considerations, in terms of engendering global cooperation, may also affect a jurisdiction's willingness to commit itself to a particular path.

In Section III below, we focus primarily on equity and efficiency objectives. We first illustrate why there are such a large number of different compliance pathways that can meet the adopted targets of a jurisdiction like California, and that these pathways differ substantially in terms of both their emissions budgets and the economic cost of following them as specified. We then show that unfettered borrowing and saving are quite important mechanisms for minimizing the cost of meeting any given emissions budget. However, due at least in part to the regulator's concern for adaptability, unfettered borrowing over a long time frame (such as 2012-2050 in California) is unlikely to be a realistic option. Therefore, in the balance of the paper we focus on ways that ensure short-term emissions budgets (e.g. 2012-2020) will be satisfied while still allowing savings and borrowing that can garner the lion's share of intertemporal efficiency gains.

B. Three Illustrative Paths

Our Figure 1 and Table 1 illustrate three different pathways that achieve California's mandated goals. The blue line in Figure 1 is a linear pathway with two line segments, in which the incremental reduction from one year to the next is the same size along a segment (13.75 mmts per year from 2012-2020, and 11.4 mmts per year from 2020-2050). This pathway has the formula:

$$E_{t+1} = \begin{cases} E_t - 13.75 & t \leq 2020 \\ E_t - 11.4 & t > 2020 \end{cases}$$

However, nothing in the legislation or the executive order specifies that a linear pathway should be used. An alternative pathway is one that each year has a smaller incremental reduction than the year before like constant percentage depreciation of the allowed emissions (CDE). Given our starting point, a reduction of approximately 2.8% per year will achieve the 2020 goal, and thereafter a reduction of 5.2% per year will achieve the 2050 goal. Such a pathway is shown as the two red line segments in Figure 1, and it has the equation:

$$E_{t+1} = \begin{cases} 537 \times (1 - .02825)^{(t-2012)} & t \leq 2020 \\ 427 \times (1 - .05238)^{(t-2020)} & t > 2020 \end{cases}$$

Note that compared to the linear pathway, CDE has greater initial reductions and then smaller reductions as one approaches the goal. Such a pathway results in lower total emissions than the linear path, as shown in Table 1: from 2012-2050 the linear pathway averts 9096 mmts but the CDE pathway averts 10,435, almost 15% more.[7]

The compliance pathway might also be bowed in the opposite direction, shown as the green line in Figure 1. This pathway has increasing incremental reductions over time, like constant percentage appreciation of the reduction amounts (CAR) along its two segments. That is, the reductions grow by about 3% per year from 2012-2020, and they grow about 2% per year from 2020-2050. The formula for this pathway is[8]:

$$E_{t+1} = \begin{cases} 937 - 400 * (1 + 0.03083)^{(t-2012)} & t \leq 2020 \\ 827 - 400 * (1 + 0.02081)^{(t-2020)} & t > 2020 \end{cases}$$

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[7] We calculate the yearly reductions as equal to the 2012 level of 537mmts minus E_t. Thus throughout this article, a given total reduction implies the "emissions budget" for the period (for our 39 years, total emissions in mmts equal 537x39 – total reductions). For other purposes, it can be important to calculate a growing BAU base, and define reductions as the BAU base minus E_t. We return to this point in a later section.

[8] The formulae shown were chosen from a family of equations that allow for the arc of the curve to be more or less bowed. The general equation for the family that will fit the second segment is:

$E_{t+1} = 427 + s[1 - (1 + g)^{t-2020}]$

In this equation, g is the yearly appreciation rate and s is a number that determines how bowed the arc is. The higher s is, the less bowed is the arc and the lower will be the g necessary to fit the bow to its two end points. We chose s = 400 to give realistic changes in emission reduction levels from year to year along the bow. One could generalize similarly with the CDE form, with $E_{t+1} = 427 - s[1 - (1 - d)^{t-2020}]$ for its second segment, although we use s = 0 because of precedent in the Regional Greenhouse Gas Initiative to be discussed shortly.

This pathway allows the greatest total emissions: only 8554 mmts are averted. Still, it is as fully compliant with AB32 and the Executive Order as the other illustrative compliance pathways.

Figure 1

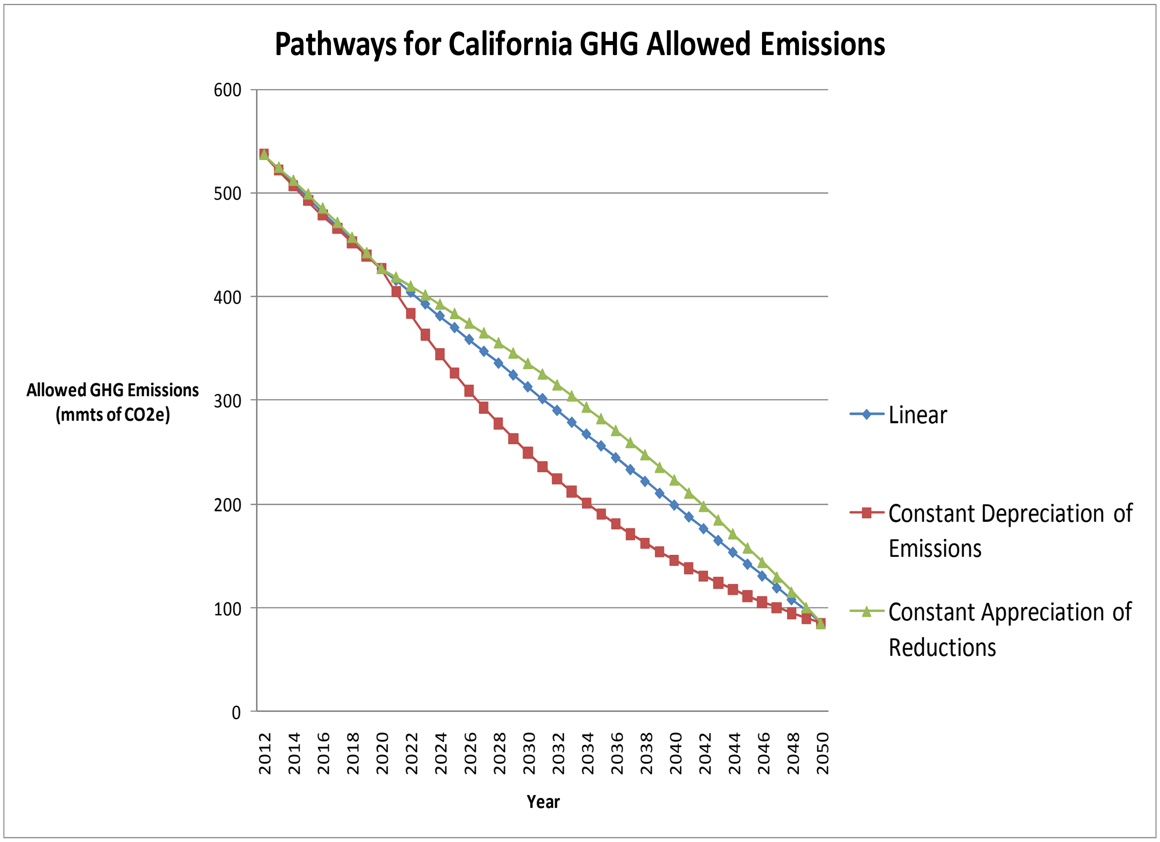
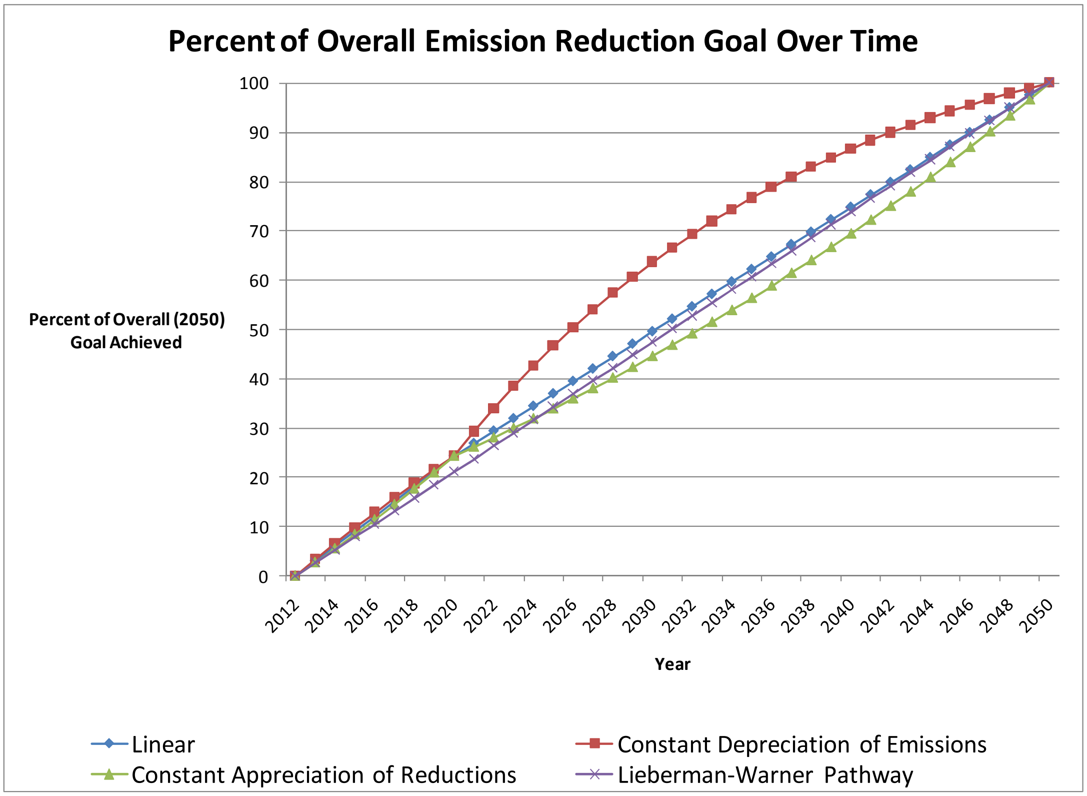


Figure 2 graphs the percentage of the 2050 reductions achieved over time for the same three compliance pathways. This allows us to add, as an interesting comparison, the compliance path specified in the proposed federal legislation by Senators Lieberman and Warner (S2191). Of course the absolute amount of emissions and reductions are much larger than those for California alone, but the relative speeds at which one approaches the 2050 targets from the 2012 starting point can be compared. As the figure shows, Lieberman-Warner is a linear pathway, very close to our two-segment linear pathway.[9] This comparison suggests that perhaps the existing cap-and-trade programs have lessons about compliance pathways, and we turn next to a brief review of them.

[9] The draft Waxman-Markey bill proposed in the House (American Clean Energy and Security Act of 2009) also features a compliance path with a 2050 emissions goal and a single linear segment.

Figure 2



C. The Compliance Pathways of Existing Regulatory Programs

Several cap-and-trade regimes are in place or under development.[10] Three U. S. markets for local and regional air pollutants have been operating for several years or more: the Acid Rain Trading Program, covering SO_2 emissions from fossil fuel-burning power plants in the 48 continental states; the RECLAIM program, covering NO_x and SO_2 emissions from power plants, refineries, and other industrial sources in the South Coast Air Quality Management District in California; and the NO_x Budget Program, covering NO_x emissions from electric utilities and large industrial boilers in thirteen Northeastern and Mid-Atlantic states and the District of Columbia. Two markets for greenhouse gases are currently in operation, the European Union Emissions Trading System (EUETS) covering large industrial emitters in the EU, and the Regional Greenhouse Gas Initiative (RGGI), launched on January 1, 2009 and covering ten Northeastern states. A third GHG market, the Australian Carbon Pollution Reduction Scheme (CPRS) is proposed to commence July 1, 2010. None of these market designs document a process by which their compliance pathways were specified. The Australian plan proposes a well-thought out process but without any long-term commitment to a specific path. Only RGGI can be said

[10] For good general reviews of cap-and-trade programs oriented toward their use for regulating GHG emissions, see Teitenberg (2003) and Ellerman, Joskow and Harrison (2003). Burtraw and Palmer (2008) have a very interesting analysis relevant to the issue of how allowances should be distributed in such systems.

to truly lay out a compliance pathway from program inception. We discuss each of these cap-and-trade regimes briefly.

The Acid Rain Trading Program was implemented in two phases, meaning that there was one step down in the cap that was planned from the start. In 2005 a federal statute tightened the cap for 2010 and beyond, creating a second step down. Unlimited saving (banking) was allowed, including across program phases; even the statutory reduction is written in such a way that existing permits retain their value. Borrowing of allowances (the use of future allowances to cover today's emissions) was not permitted.

The RECLAIM Program featured a reduction in cap levels over time for both NO_x and SOx, to a constant value beginning in 2003 (a target date for compliance with ozone requirements in the local Air Quality Management Plan). The compliance pathways were linear. The NO_x pathway had two linear segments: the cap decreased more quickly from 1994 to 2000 and then more slowly from 2000 to 2003. The SOx pathway had only one linear segment. We have not uncovered any discussion of why a linear path was chosen. Significantly, RECLAIM did not allow saving or borrowing of emissions from one year to the next. During the first several years of the program, emissions were well below the cap and credit prices were low—an environment in which saving might seem attractive. In 2000, as the cap was beginning to constrain emissions more significantly, the electricity crisis hit the market. As emitters had no banked allowances held in reserve, they found it impossible to comply with the cap, and credit prices in the NO_x market soared tenfold from 1999 to 2000.

The NO_x Budget Program was designed to impose a progressively more stringent cap over time. However, the actual cap levels have moved around substantially as additional states have joined the program, and we have not yet determined the initial logic of the compliance pathway. The NO_x Budget Program allows banking, but places special restrictions on it to keep some banked allowances from being used during the ozone season. No borrowing is allowed.

The EUETS features distinct five-year phases, the first of which has already drawn to a close. The first phase was a "learning phase" with mild noncompliance penalties. The EUETS is a relatively decentralized system: each member country produces a plan for its own cap level during each five-year phase. The initial caps for the learning phase were not very ambitious and allowance prices were low due to a lack of scarcity. Significantly, banking and borrowing of allowances within a phase was permitted, but not from one phase to the next. Allowances for the next year are only issued two months before allowances are due for the current year, essentially limiting borrowing to next year's allowances.

Given that caps have tightened significantly in the second phase that began in 2008, the prohibition on banking across the phases has resulted in prices of 2008 allowances that are much higher (around $40 per ton) than the price of 2007 allowances (which went under $1). Such price fluctuations are undesirable because they do not reflect any change in the social value of the emissions reduction they encourage. For example, European carbon emissions did not suddenly become more damaging in 2008 when the prices rose, yet the incentive to avoid them abruptly changed. If EU member countries had been allowed to save their Phase I allowances for use in Phase II, they could have achieved the same environmental goal at a lower cost, and the prices would not have been so different between the phases. Given the decentralized EU approach to cap-setting, it is difficult to discern any overall plan for a compliance pathway, though this bears further investigation.

The RGGI program possesses the clearest compliance pathway design. The cap will remain flat at current emissions levels from program inception in 2009 through 2014. Beginning in 2015, it will fall by constant depreciation of allowed emissions (CDE) of 2.5% per year. Unlimited saving will be allowed, and a three-year compliance period for turning in the appropriate number of annual allowances effectively permits some short-term borrowing. Despite the clear design, we have found no documentation of the rationale for the choice of this particular pathway shape. The first of its quarterly auctions for its CO_2 allowances was held in September 2008, at which time 12.5 million allowances were sold at the price of $3.07 per ton.

The proposed Australian CPRS cap-and-trade program would commence on July 1, 2010 and cover about 75% of Australian GHG emissions including those from the transportation sector. It is based on a long-term goal of achieving a 60% reduction from the 2000 level by 2050, and a 2020 goal of reductions that are 5-15% below the 2000 level, with 5% the minimum irrespective of the actions of other nations, and 15% if there is a global agreement in which all developed countries adopt comparable reductions. The government will specify annual caps 5 years ahead, and will also provide a further 10 years of guidance by specifying a "gateway" (a range) within which annual targets will be set. Each year the firm cap for the fifth year following will be announced, and the gateway updated every five years. Unlimited savings of allowances will be allowed, and sources will be allowed to borrow by the right to use the next year's allowances for up to 5% of their current year allowance liabilities.

This summary of existing cap-and-trade systems highlights three points. First, saving or banking plays a key role in averting large discrepancies in allowance prices from year to year, which otherwise can arise due either to program structure (EUETS) or unforeseen events (RECLAIM). Second, borrowing is either not permitted or is sharply limited in all of these systems, though unlimited saving is often allowed. Third, none of these systems has a clearly articulated explanation for why its compliance pathway should be the preferred one. In fact, we have yet to uncover any real evidence that the shape of the pathway was much more than an afterthought, although jurisdictions like Australia clearly have future global negotiations in mind.

D. The Present Value of the Cost of Compliance

If one criterion for choosing a pathway is environmental benefits, another one is cost. The three different pathways we have illustrated will differ substantially in the cost of following them. While no one yet knows how much it will cost to reduce emissions along these pathways, we can illustrate for an assumed marginal cost structure the order of magnitude of the differences.That is, suppose for illustrative purposes that the marginal cost per ton of CO_2e reduced increases according to this step-function schedule: $30 per metric ton for the first 100 mmts, and $10 more per metric ton for each additional 100 mmt. Given that California reductions (from our assumed baseline of 537) will in 2050 total 452 mmts, this means our assumption is that the (least) marginal cost will increase gradually from $30 to $70 over the period.[11]

Given this cost assumption, we can then calculate the net present value of the cost of following each of the three illustrative pathways. One measure of cost is the market value of the reductions. Within any year, the undiscounted market value will be the reduction for that year times a price that equals the marginal cost of abating the last ton.[12] Using a 3% real rate of discount, the least expensive pathway is CAR at $215 billion. The most expensive pathway is CDE at $285 billion, about 33% higher in total cost. The linear pathway costs $230 billion, about 7% greater than CAR. Using a 7% real rate of discount, the numbers are lower but the relative rankings are the same (CAR $89 billion, CDE $116 billion or 30% greater, and linear $92 billion).

An alternative measure of cost is the social cost necessary to achieve the compliance level each year. That is, rather than valuing each year's reductions at the market price, we simply add up the cost of each metric ton reduced (the number of tons at $30, the number at $40, etc. and then discounting). This gives a lower cost measure for each compliance pathway, although the comparative results are similar. At 3% discount, the social cost of reductions along the CAR path is $161 billion. Along the linear path this cost rises by 10% to $177 billion and it is $213 billion or 32% more expensive along the CDE path.

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[11] The true marginal cost schedule based on current technology is unknown, and the uncertainty about it will only gradually be reduced as we observe the costs of meeting scheduled reductions. Technological progress will also be at work to reduce at an unknown rate the marginal costs of abatement over time. We think our illustrative cost structure is plausible. It is roughly consistent, for example, with the estimates of McKinsey & Co. (2007) that the US as a whole can achieve reductions of 40-60% from 2005 levels in 2030 at marginal abatement costs of $50 with existing technology. For illustrative simplicity we also assume that our cost schedule is exogenous to California's choice of compliance pathway. However, as we discuss later, the compliance path itself can affect the degree and timing of technological progress that lowers the marginal cost schedule over time.

[12] Recall that in each year we define the reduction as the initial level of 537 mmts minus the compliance level. True reductions are greater, in that BAU would lead to growing emission levels each year (an increasing base to compare with allowed emissions). While this would tend to raise the marginal cost of compliance, this will be offset to an unknown degree by technological progress that lowers the cost to reduce emissions. An alternative way to think of our assumption of a constant marginal cost schedule is that it is equivalent to that of a growing base with technological progress that precisely offsets what would otherwise be the increase in marginal cost necessary to achieve the compliance level of emissions. Depending on the rate of actual technological progress, it could only partially offset the effects on marginal cost of an increasing base, or if strong could more than offset the increasing base effect (the latter has been the case for most exhaustible ores over long periods of time, see Nordhaus (1992)). Except in the case where each compliance pathway causes a different rate of technological progress, the marginal cost changes would be the same across all three compliance paths and thus would not affect the relative cost comparison. The market price in each period equals the marginal cost since it is the price that would result from a fixed level of emissions allowed each year (the compliance level) and competitive allocation of that number of allowances.

Again, using a 7% discount rate does not alter the relative rankings although the cost figures are lower (CAR $69 billion, CDE $92 billion or 33% greater, and linear $76 billion).

These figures are based upon a particular marginal cost structure and assume that the annual emission limits are enforced with no intertemporal flexibility. For many pollutants, the adverse health effects of high emission levels in any one year provide a strong rationale for little to no upward flexibility from the regulatory limit. However, there is no such rationale for a GHG like carbon, where there is essentially no difference in global warming effects if one ton of CO_2 is emitted this year or next year. We consider next how mechanisms that allow saving and borrowing (relative to the annual target) affect these costs.

IV. Market Adjustments to a Specified Compliance Pathway

A. Saving and Borrowing Equalize the Present Value of Allowance Prices Over Time

Most proposals for long-term cap-and-trade programs provide for saving and perhaps borrowing of allowances. In existing cap-and-trade programs, several studies have suggested that the benefits of allowing such flexibility can be substantial. For example, Ellerman et al (2000) estimate that intertemporal emissions trading reduced costs in the US Acid Rain Program by $1.3 billion or about 7% of the total cost savings in its first 13 years. Substantial benefits of intertemporal trading are expected to apply to GHG reduction programs, and furthermore, there is little environmental reason to be concerned about this.[13] As noted before, the environmental benefit is dependent primarily on the sum of allowed emissions and not the precise timing of them within the program period.

With both saving and borrowing permitted, the market will reallocate allowances over time in order to make the present value of an allowance in any one year equal to the present value of an allowance in any other year. Suppose, for example, the regulator committed to beginning with a very modest reduction in the first year (issuing a fairly generous number of allowances) followed by a substantial reduction in the following year (significantly fewer allowances). With no borrowing or lending, market participants would expect the (scarcer) second-year allowances to sell at a substantial price premium to those in the first year. Let’s say that these expected allowance prices were $30/ton for the first year and $40/ton for the second. That means participants in year 2 expect that they will be better off to undertake reductions that cost, say, $39 rather than have to buy a $40 allowance.

[13] See, for example, Leiby and Rubin (2001), Reilly (2007) and Stavins (2007). Reilly is evaluating a number of proposed U.S. cap-and-trade programs for GHG emissions, and writes (p. 3): “…a better measure of stringency [than the mid-century goal] is the sum of national emissions permitted between the start of the policy and mid-century. Stavins also writes (p. 16): “…the best measure of policy stringency may be the sum of national emissions permitted over some extended period.” We use the sum of allowed emissions from 2012-2050 as a measure of overall environmental effectiveness.

If participants are allowed to save some of the allowances that they buy in the first year, this opens up a much more cost-effective strategy: buy additional $30 allowances in the first-year and hold them to use in the second. This is much cheaper than paying $39 for an actual reduction. But as many participants recognize this, the overall demand for first-year allowances increases. With a fixed supply, the price of the first-year allowance must rise to clear the market. It is also important to recognize that the increased demand due to saving is offset by a corresponding reduction in demand for second-year allowances (the saved year 1 allowances used by participants in year 2 reduce the need to purchase year 2 allowances). Thus the expected price of the first-year allowances rises, and that of the second-year allowances fall. When will this stop? When the price of the first-year allowance relative to that of the second is such that it is no longer profitable for anyone to save additional first-year allowances. This will occur when both have the same present value:

$$P_1 = P_2/(1+r)$$

If, for example the first-year allowance price rose to and settled at $34 with $r = .03$, then the second-year allowance price must be $35.02.

In other words, despite regulators having decided to begin with only a modest reduction requirement, market participants will choose to reduce more in the first year in order to save allowances that can be used to supplement those available in the second-year. The total emissions over both years will still be the sum of the allowances issued by the regulators (maintaining environmental integrity), but the actual compliance path will be different from what the regulators envisioned. This difference is desirable, as the market has acted to minimize the cost of compliance through saving and borrowing. This potential conflict between the regulator-specified path and the least-cost path that is environmentally equivalent is the crux of the more detailed examples that we develop below, and is the only reason why borrowing or saving arises in our illustrative models.

There are other important reasons why aggregate borrowing and saving occur, although they are not our focus. At any time, unanticipated events may arise that alter allowance demand in either (or both) the current and future periods. Market participants recalculate the benefits to themselves of reducing emissions in the current period versus deferring reductions until the future, and in the aggregate additional saving or borrowing could arise in order to follow the (recalculated) least-cost path. For example, a substantial unexpected recession reduces economic activity and typically would thus also reduce allowance demand when it occurs.[14] The unexpectedly low allowance price for this time would set in motion the same forces that we have just described. Participants would realize that they could take advantage of the temporarily-low price to buy more allowances and save them for future use. This increased demand for saving would cause price to rise and partially offset the pure “recession effect.” While we do not include these effects in our estimates below, they may well be substantial in relation to the effects we do model.

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[14] This is what has occurred in the EU ETS, in which the allowance prices have dropped from about €27 in 2008 to €13 in April 2009. The drop may not only be due to the recession, but perhaps to additional uncertainty about future EU reduction commitments.

The examples so far are of saving allowances, but it is just as easy to illustrate examples where borrowing (if allowed) would save money. If the regulator requires very stringent reductions initially and then only modest additional reductions later on, market participants would borrow future (relatively inexpensive) allowances in order to use them instead of the high-priced current ones. The opposite of an unexpected recession is an unexpectedly strong, robust economy in which the demand is higher than expected for current goods and services and the emissions necessary to produce them. This causes current allowance prices to be unexpectedly high (relative to expected future allowances in a time of normal economic growth), and if allowed, participants will find it cheaper to emit more now by borrowing allowances in return for greater reductions later on when they are relatively inexpensive (their present value is less).

One might think, incorrectly, that the least-cost compliance pathway would be to defer all reductions as far as possible into the future. This would be true if all reductions were equally costly aside from timing. However because the marginal cost of reducing rises within any year with the quantity reduced, deferring too many reductions to the future would result in excessively high costs as the size of them necessitates a steep climb up the marginal cost curve (the marginal cost of reducing within that year would be very high). A simple example can illustrate. Suppose the goal were to reduce a total of 300 mmts over a 3-year period. Given the marginal cost schedule above, Table 2 shows 3 different compliance paths. Path 1 is linear, Path 2 defers all reductions to years 2 and 3, and path 3 defers all reductions until year 3.

Table 2: Choosing a Least-Cost Time Path

	Path 1		Path 2		Path 3	
	Reduction	Cost ($ billions)	Reduct ion	Cost ($ billions)	Reduct ion	Cost ($ billions)
Year 1	100	3.00	0	0.00	0	0.00
Year 2	100	3.00	150	5.00	0	0.00
Year 3	100	3.00	150	5.00	300	12.00
Present Value		7.85		9.57		11.31

As can be seen in this simple example, the linear Path 1 is much less costly than Path 2, and Path 2 is less costly than Path 3. This is because the linear Path 1 allows all reductions to be undertaken at $30 per ton, whereas Path 2 requires some $40 per ton reductions and Path 3 requires $50 per ton reductions. Nor, in this example, would it be cheaper to front-load the reductions. A Path 4 (not shown) that had 150 mmt reductions in each of the first two years would have cost in present value terms of $9.85 billion because it would require some $40 per ton reductions.

The real market task is of course far more complex. The time frame is much longer, and there are uncertain marginal abatement costs as well as uncertain value to allowing any given level of emissions in a particular year. Nevertheless, the market generally does the best that it can in trying to follow a compliance pathway that equalizes the net present value of expected marginal abatement cost along it.

B. The Unknown Marginal Cost of Abatement Curve Shapes the Least-Cost Compliance Path

The last section illustrated for a particular marginal cost structure (a step function) why market participants will in general have incentive to use mechanisms of borrowing and saving in order to minimize the cost of complying with an emissions budget. In this section, we wish to clarify more generally how the shape of the marginal cost of abatement curve influences the shape of the least-cost compliance path. The large uncertainty about the true shape of the marginal cost of abatement curve will imply that (a) it is not possible for the GHG regulator to specify in advance a compliance path that will be least cost; and (b) therefore it is especially important that the regulatory system allow sources to adjust emissions up or down in any one year as they learn more about the shape of the relevant section of the marginal cost of abatement curve. We assume here that an aggregate emissions budget has been set for a specified period.

It will be helpful to introduce some notation. Denote $E(t_i)$ as the emissions in year t_i, with r as the discount rate. Let $MC(E(t_i), t_i)$ be the marginal abatement cost, with $\partial MC/\partial E < 0$ (i.e. it is less expensive to abate an additional ton when emission levels are high). The second term t_i by itself represents technological progress with $\partial MC/\partial t < 0$, meaning that over time the marginal cost of abatement at a given emissions level decreases (i.e. improved, lower-cost methods of abatement become available). **For any aggregate emission reduction to be achieved at the lowest present discounted value over time, the present value of the cost of the marginal abatement in year *i* must be equal to that of year *j*.**

(1) $PDV = MC(E(t_i), t_i)e^{-rt_i} = MC\big(E(t_j), t_j\big)e^{-rt_j}$ for all t_i, t_j within the period

One simple implication of this is that, **for any given aggregate reduction, annual emissions will decline over time along the least-cost pathway**. That is, we will abate more in future years than we will in the near term in order to stay within a fixed emissions budget for the entire period. This is because the discount factor will be a smaller number for $j > i$, and thus the marginal cost in year j must be greater than in i in order to make the equality hold. If there were no technological progress, the only way to make the equality hold would be to have lower emissions (higher abatement) as we go further into the future. Since technological progress tends to lower the marginal cost of abatement over time, this means that to make the equality hold future emissions must be even lower (and future abatement greater).

Another way to see the same point is to take the partial derivative of the present discounted value with respect to time and recognize that it is zero along a least-cost path:

$$\frac{\partial PDV}{\partial t} = \frac{\partial MC}{\partial t}e^{-rt} - rMCe^{-rt} = 0$$

This simplifies to a version of the Hotelling rule—**the proportionate increase in marginal cost from one period to the next will equal the interest rate**:

$$\frac{\frac{\partial MC}{\partial t}}{MC} = r$$

Expanding this to show the MC function:

$$\frac{\left[\left(\frac{\partial MC}{\partial E}\right)\left(\frac{\partial E}{\partial t}\right) + \frac{\partial MC}{\partial t}\right]}{MC} = r$$

The numerator must be positive for this equality to hold, but we know that $\partial MC/\partial E < 0$ and $\partial MC/\partial t < 0$. The only way the numerator can be positive is if $\partial E/\partial t < 0$, i.e. decreasing emissions over time. Solving the above equation for $\partial E/\partial t$:

$$\frac{\partial E}{\partial t} = \frac{rMC - \partial MC/\partial t}{\partial MC/\partial E}$$

Less immediately clear is whether the amount by which emissions decline along this least-cost path is increasing, constant, or decreasing over time. This corresponds mathematically to whether the partial derivative of the above expression with respect to *t*, or $\partial^2 E/\partial t^2$ is respectively negative (i.e. bigger decrements), zero, or positive (i.e. smaller decrements). This expression need not have the same sign over the entire time frame and range of emissions changes of interest to us, although for the most part we will simplify to assume that it does. It is difficult to make generalizations about the least-cost rate of emissions decline based only upon theory because it depends heavily upon the shape of the marginal cost curve for GHG abatement. Unfortunately, very little is known about its shape (as well as what technological progress to expect over time), other than that it will be upward rising (increase with greater abatement) holding technology constant.

Nevertheless, we can at least clarify somewhat how the shape of the marginal cost of abatement curve influences the amount by which emissions should decline over time along a least-cost path. To increase the transparency of the next step, let us temporarily suppress the role of technological progress by holding it constant. That is, we consider the shape of the marginal cost curve using only existing technology. Then we calculate from above the second partial derivative (dropping out the technology term $\partial MC/\partial t$):

$$\frac{\partial^2 E}{\partial t^2} = \frac{[\partial MC/\partial E][r(\partial MC/\partial E)(\partial E/\partial t)] - [rMC][(\partial^2 MC/\partial E^2)(\partial E/\partial t)]}{(\partial MC/\partial E)^2}$$

Both long expressions in the numerator contain the same terms r and $\partial E/\partial t$ that can be factored out:

$$= \frac{r(\partial E/\partial t)\left[(\partial MC/\partial E)^2 - (MC)(\partial^2 MC/\partial E^2)\right]}{(\partial MC/\partial E)^2}$$

The signs of all of the terms in the above expression are known except for the last term in the numerator:

$$= \frac{(+)(-)[+\ - (+)(\partial^2 MC/\partial E^2)]}{+}$$

This expression is unambiguously negative if $(\partial^2 MC/\partial E^2) \leq 0$. It can only be positive if $(\partial^2 MC/\partial E^2) > 0$ (corresponding to a rapidly rising marginal cost of abatement), and then it must be big enough so that the last term outweighs the first + term in the brackets.

What does this mean? Keep in mind that in these expressions an emissions increase is an abatement decrease. Consider some common shapes of marginal cost curves as typically drawn and studied: (1) constant marginal cost; (2) marginal cost that increases linearly; and (3) marginal cost that increases at an increasing rate. The constant marginal cost case has second derivative equal to zero, and thus induces a least-cost path featuring bigger emission decrements over time. However, in this case the solution to the least-cost path is determined by the boundary conditions (the emissions budget and the total time period) rather than equalizing present values along the path, as they cannot be equalized: **with constant marginal cost, it is always less expensive to abate in the future compared to the present. The least-cost path is simply to push all abatement as far into the future as possible, subject to staying within the aggregate emissions budget.** Starting from the initial year, undertake no abatement at all until the emissions budget for the entire period is reached. Then allow no further emissions until the end of the period is reached. Technological progress that works to make future costs even lower simply reinforces this solution.[15]

Case (2), the linear marginal cost curve, also has second derivative equal to zero, and the least-cost solution is to have bigger emission decrements over time. There is more abatement in the early years compared to the constant marginal cost case, but the path might still be characterized as one that begins gradually with only small incremental abatement each year, and saves most of the heavy lifting for the future periods. **If the marginal cost of abatement increases linearly, then the least-cost path will be one of successively greater incremental reductions along it**. There are of course cases between (1) and (2), in which marginal cost is increasing but less than linearly, that have this path characteristic as well. Shapes of these types occur, for example, when there are substantial emission reductions that are possible at marginal costs not too much greater than the initial least-expensive ones.

Case (3) is the marginal cost of abatement curve that is increasing at an increasing rate: the cost of emissions reduction rises rapidly with greater and greater reductions. This

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[15] Note that we do not consider constant marginal cost to be a reasonable empirical possibility in this application.

happens when the only ways to reduce emissions further become sharply more expensive, perhaps approaching the limits of our technical ability to reduce GHG in the production of some goods or services and/or the willingness of consumers to forego any more of these goods and services (e.g. essential food). However, while this type of function is necessary for a reversal of the pattern of incremental reductions over time, it is not sufficient. Reversals are only caused by unusual shapes within this set (where the square of the first derivative is less than the marginal cost times the second derivative, as might be true at the elbow of a function that is fairly flat at lower abatement levels but then turns sharply upward). That is, **many steeply rising functions will still have the same pattern of increasing decrements of emissions over time. However, if the marginal cost of abatement is rising rapidly from a relatively high level but relatively low slope, it will cause the least-cost path in this range to be one of successively smaller incremental reductions along it.**[16] While emissions levels will continually decrease over the years, as the base level declines so will the absolute size of each successive year's increment.

There is nothing inherently implausible about marginal cost of abatement functions that may feature small regions that would satisfy the conditions for decreasing incremental reductions. However, such functions are likely a small subset of the plausible MC functions. Moreover, even functions that feature this behavior seem likely to feature it only at specific points or regions along the curve. As such, we are comfortable concluding that, in general, least-cost compliance paths are highly likely to be characterized by increasing incremental reductions almost everywhere along their paths.

C. Intertemporal Flexibility Generally Has High Value

We consider the value of intertemporal flexibility for several possible shapes of the marginal cost of abatement curve and with various discount rates. These cases are intended as illustrative, and generally indicate a substantial value to flexibility. While we do not treat technological progress explicitly in the calculations, we suggest that any given curve based upon current technology will become flatter (to an unknown degree) with time when technological progress is considered.[17]

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[16] At this point, we have not identified any marginal cost functions that cause this reversal, and thus they may be unusual shapes. We considered, for example, the family of marginal cost functions for which $MC(E(t)) = [B - E(t)]^{\alpha}$ with B a constant baseline level of emissions and $\alpha > 0$. When $\alpha > 1$, this equation has the rapidly rising marginal abatement costs necessary but not sufficient for the reversal in pattern. For this function, $\partial^2 E/\partial t^2 = -(r^2/\alpha^2)(B - E(t))$ which is always < 0 no matter how large α gets (and therefore the size of the emissions decrement along the least-cost path still gets larger over time). As another example, we considered the family of functions $MC\big(E(t)\big) = Ae^{bE(t)}$ with constants $A > 0$ and $b < 0$. This family has a linear compliance path, with constant emission decrements ($\partial E/\partial t = r/b$).

[17] This is the same phenomenon that explains why the price of many exhaustible resources over scores of years has declined in real terms. At least two factors push us to expect the opposite: the increased physical scarcity of the resource, and the fact that the remaining stock was often left unharvested precisely because it was relatively more expensive to extract than the supplies used earlier. But technological progress has in many cases over long periods of time more than offset what would otherwise be the increased scarcity and cost.

1. The Step Function Used for the Previous Illustration

Appendix Tables A1, A2, and A3 show, for the cost assumptions that we have made previously and a modest real discount rate of 3%, the least cost compliance path to reach the environmental goals of the three alternative compliance pathways from the earlier example (linear, CDE, CAR).[18] Appendix Table A4 shows the time pattern of saving and borrowing along these least-cost paths. There is substantial net borrowing along each of the three illustrative pathways. Along the linear pathway, for example, cumulative emissions always exceed the cumulative total along the regulator's path until the final year of the period. Total borrowing reaches its peak in 2033 at 562 mmts, after which it gradually declines to zero.

An important dimension of this analysis is the value of allowing intertemporal adjustments to the regulatory path through saving or borrowing. This can be seen easily by the difference in present values of the costs if (a) no borrowing or saving is allowed (the scheduled compliance path is precisely followed); and (b) the least-cost path (with borrowing and saving) is followed. Table 3 shows these results for the three compliance paths. With a 3% real discount rate, the gains from the intertemporal adjustments are on the order of 2% of total cost for the linear and CDE paths, and 1% for the CAR path (because in this example it is closer to the least-cost path).[19]

However, as Table 3 also shows, the gains from intertemporal flexibility are markedly higher when a 7% discount rate is used. It is important to note here that the real discount rate used is a behavioral phenomenon, not a normative one. That is, we are not deciding or recommending any particular social rate of discount for the government to use. We are illustrating alternative assumptions about the actual average real rate that sources will use

[18] We are not concerned here about possible borrowing or saving that involves the post-2050 period, although this could be a concern. In the European Union Emissions Trading System (EU ETS), allowances issued during the first compliance period (2005-2007) were not allowed to carry over and be used during the second compliance period (2008-2012). This caused a substantial problem, as allowance holders wanted to save the relatively inexpensive period 1 allowances to use in period 2 rather than purchasing period 2 allowances at the high prices expected for them. This regulatory ban on savings (across periods) caused the near complete collapse of allowance prices near the end of 2006 and throughout 2007, and retarded achieving actual emissions reductions. See King (2008), p. 70. Our example for simplicity does not include saving or borrowing from pre-2050 to beyond it, although we presume this would be allowed. A slightly more complex model could specify a terminal condition that assumes emissions remain at the level of 85 mmts beyond 2050 and computes any savings or borrowing that would carry over, but this would not change the point of our models which is that the least-cost path is highly likely to be different from a regulator-set path.

[19] Recall that these gains underestimate total expected intertemporal gains, as they are limited to gains from altering the regulator-specified path with no other uncertainties. For example, in percentage terms these savings are below the intertemporal savings mentioned earlier from the US Acid Rain program. The 7% cited earlier was not of total cost but of total savings from using cap-and-trade relative to command-and-control regulation. If cap-and-trade for GHG achieves reductions at 33% less cost than command-and-control, then the intertemporal gains here would be 4% of the savings for linear and CDE, and 2% for CAR. There would be additional intertemporal gains by borrowing or saving responses to all of the uncertainties that we exclude, like changes in marginal costs due to technological progress, macroeconomic fluctuations, or changes in environmental goals due to new knowledge. These additional gains may be large compared to those we have already estimated.

in deciding the timing of their emissions and weighing future versus current dollars (e.g. as when deciding the year in which to retrofit their plants). [20]

Table 3: The Value of Saving and Borrowing (Cumulative from 2012-2050)

		Reductions as Scheduled	Least Cost Reductions
Constant Appreciation (CAR)	Total Reductions (mmts)	8554	8554
	Cost (PV at 3%, $millions)	$161,410	$159,457 (99%)
	Cost (PV at 7%)	$69, 037	$54,056 (78%)
Linear	Total Reductions	9096	9096
	Cost (PV at 3%)	$177,033	$173,466 (98%)
	Cost (PV at 7%)	$76,025	$61,019 (80%)
Constant Depreciation (CDE)	Total Reductions	10435	10435
	Cost (PV at 3%)	$213,286	$209,914 (98%)
	Cost (PV at 7%)	$92,442	$77,859 (84%)

Of course the absolute value of scheduled (and least cost) reductions is substantially lower when the higher discount rate is used. What matters here is the proportionate reduction in cost achieved by the least-cost path relative to the scheduled one, and as well how the higher discount rate changes the shape of the least-cost emissions path. Table 3 shows that for all 3 schedule shapes, the least-cost path at 7% discount achieves very substantial cost reductions: CAR 22%, linear 20%, and CDE 16%. Furthermore, the patterns of saving and borrowing are altered substantially: no reductions at all are made before 2024, so there is heavy borrowing until the early 2030s that is then repaid in the remaining future years. For example, cumulative borrowing along the linear path reaches a peak of 1936 mmts in 2033 or 16% of the emissions budget, compared to a peak of only 562 mmts or 5% of the emissions budget when the discount rate is 3%.

It is interesting that these results arise even with significant increases in the marginal cost of abatement assumed as emission limits tighten. The increase in assumed discount rate

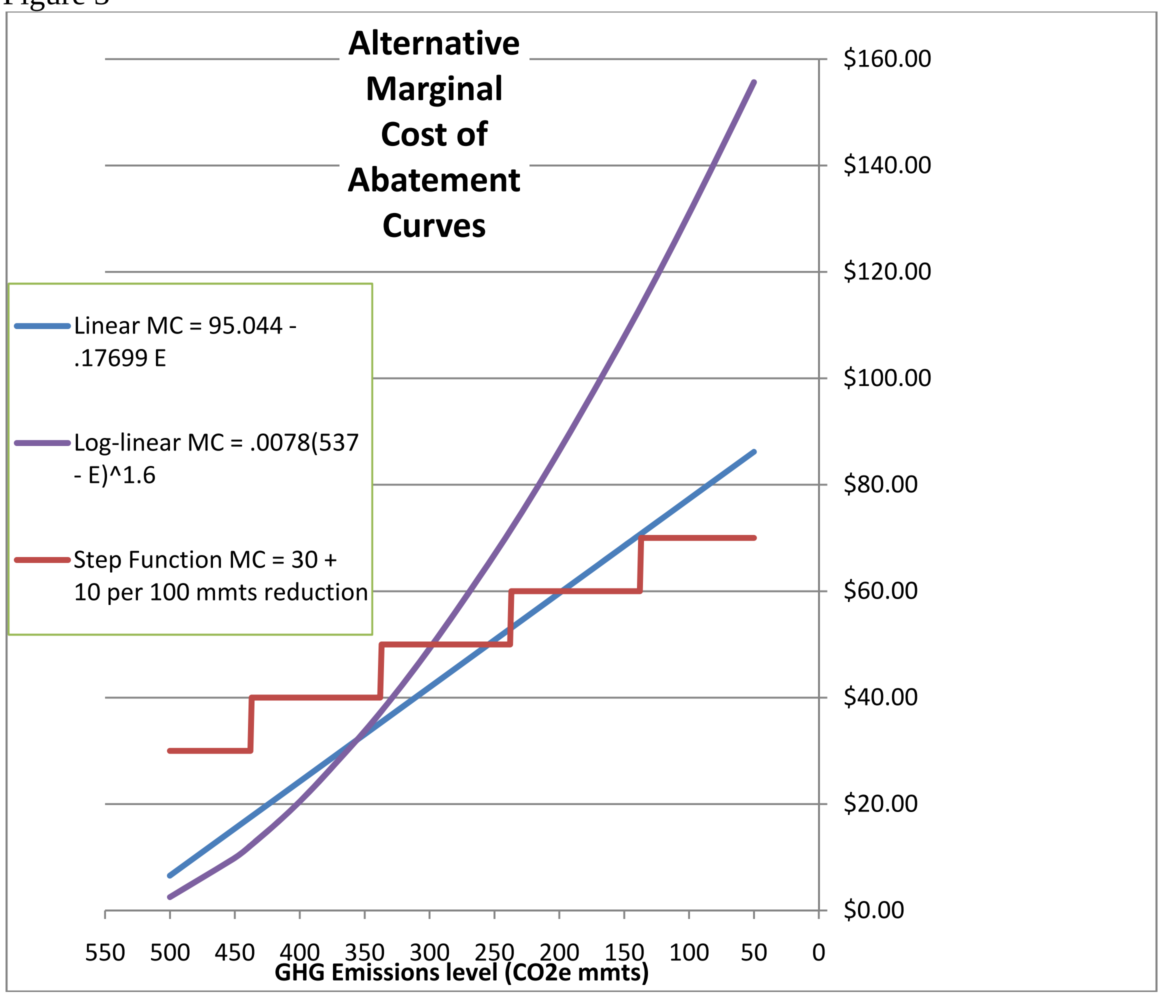
[20] There is no GHG market yet operating in which the regulatory compliance path (or the emissions budget) has been set for a reasonably long time frame. The most established market is the EU ETS, and one can observe the expected price path by the prices of the allowance and its EUA futures on any given day. On April 6, 2009, the prices (in Euros) for December allowances from 2009 to 2014 were 12.71, 13.38, 13.99, 14.98, 16.01, and 17.28. This fits a 6% nominal interest rate path very closely, and with EU inflation in the 2.6 -3.5% range in the past year, this suggests a real rate of about 3%. Back approximately a year earlier before the financial crisis struck that marked the beginning of a worldwide recession, the same futures were trading at much higher absolute rates: 28.19, 28.86, 29.59, 30.65, 32.75, and 34.10. The annual increases then fit closely the nominal path of 4% or 1% real. However, we caution that substantial uncertainty about any future years beyond the immediate few for which policies are firm make such calculations an unreliable guide to the price path that would be observed with a credible commitment to a long-term emissions budget.

from 3% to 7% radically alters the pattern of borrowing and saving, as well as the value of cost reductions derived from it.

2. Other Marginal Cost of Abatement Functions

We have similarly examined a number of other marginal cost of abatement functions in order to get a sense of the plausibility of the patterns that we have observed. Figure 3 and Table 4 provide a representative summary, with the comparable results from the earlier step function included for reference. For the linear regulatory path with emissions budget of 11, 847 mmts, the table shows the results for a linear marginal cost function that rises from $0 to $95 over the range of emissions. It also shows for the same emissions budget a log-linear function chosen to be more steeply rising (at an increasing rate) with marginal costs over the range from $0 to $181.[21] For each function, we calculated the least-cost path at both 3% and 7% discount rates, and compared it with the regulatory path to calculate savings and borrowing.

Figure 3



[21] We did not examine further very flat marginal cost functions, as it is transparent with these that the least-cost path is tilted heavily toward future-intensive reductions (and thus very substantial borrowing).

Consistent with our earlier theoretical analysis, the least-cost path for the linear marginal cost function at both 3% and 7% discount rates, consistent with our earlier theoretical analysis, is characterized by saving in the early years and increasing incremental reductions as time progresses. These paths are shown in Figures 4a (3%) and 4b (7%). At the 3% rate, the initial reductions are quite substantial so that there are cumulative savings that peak at 938 mmts in 2027 (8% of the total emissions budget), and then dissaving without ever needing to enter a situation of net borrowing. The least-cost path is achieved at a savings of 7% over the regulatory schedule. At the higher 7% discount

Table 4

The Least-Cost Path for Alternative Marginal Cost of Abatement Functions

(California Model: 2012-2050, 11,847 cumulative mmts of CO_2e allowed)

	Step Function	**Linear**	**Log-Linear**
Parametric Form	MC = 30 (+10 after each 100 mmts)	MC = 95.044 - .17699E	MC = .0078(537 – E)$^{1.6}$
MC when E = 537	$30.00	$0.00	$0.00
MC when E = 0	$80.00	$95.04	$181.99
Least-Cost Path Features, 3% Discount			
Emissions in 2012	537	412	377
Emissions in 2050	0	147	211
Max. Cumulative Savings	0	938 (2028, 8%)	1383 (2028, 12%)
Max. Cumulative Borrowing	562 (2033, 5%)	0	0
Annual Reduction Increments	Increasing	Increasing	Increasing
Percent Cost Reduction	2%	7%	21%
Least-Cost Path Features, 7% Discount			
Emissions in 2012	537	489	447
Emissions in 2050	0	0	61
Max. Cumulative Savings	0	138 (2016, 1%)	499 (2023, 4%)
Max. Cumulative Borrowing	1936 (2033, 16%)	748 (2040, 6%)	46 (2047, .3%)
Annual Reduction Increments	Increasing	Increasing	Increasing
Percent Cost Reduction	20%	6%	7%

rate, there is also saving in the initial years but at a much-reduced level. The savings peak in 2016 at 138 mmts (1% of the emissions budget), then dissaving occurs with entry into net borrowing in 2023 that reached a peak of 748 mmts (6% of the emissions budget) in 2040 and is then repaid by 2050. The least-cost path at a 7% discount rate is achieved at a savings of 6% over the cost of the regulatory schedule. It is interesting that in this case the higher discount rate does not particularly increase the value of intertemporal flexibility, although it clearly shifts the pattern to one of fairly substantial borrowing as with the step function.

For the log-linear function chosen to illustrate a rapidly rising marginal cost of abatement, the least-cost path for both the 3% and 7% discount rates is also one of increasing incremental reductions over time. As with the linear case, the initial reductions are substantially greater than those along the regulatory schedule, so that there are substantial periods of savings. At the 3% discount rate, savings continue in each year until 2029 where cumulative savings peak at 1391 mmts (12% of the emissions budget). Thereafter there is dissaving until the emissions budget balances in 2050, so there are no periods of net borrowing. The savings of the least-cost path over the regulatory schedule are substantial: costs are reduced by 21%. At the 7% discount rate, there is still saving in the initial years but substantially less than with a 3% discount rate. Cumulative savings peak earlier in 2023 at 499 mmts (4% of the emissions budget), and then dissaving begins. In 2043, the cumulative savings are exhausted and a relatively brief period of net borrowing begins until 2048 when small savings come in to balance the emissions budget. Peak cumulative borrowing occurs in 2047 but only at 46 mmts (.3% of the emissions budget).

Figure 4a

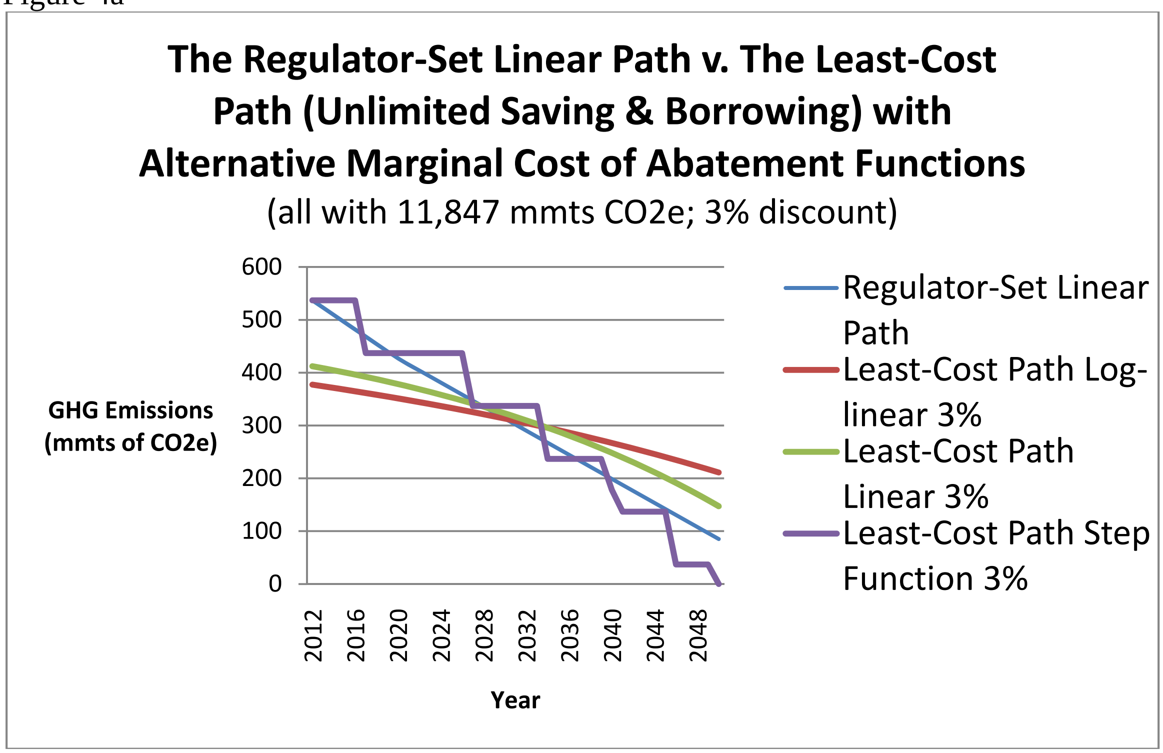
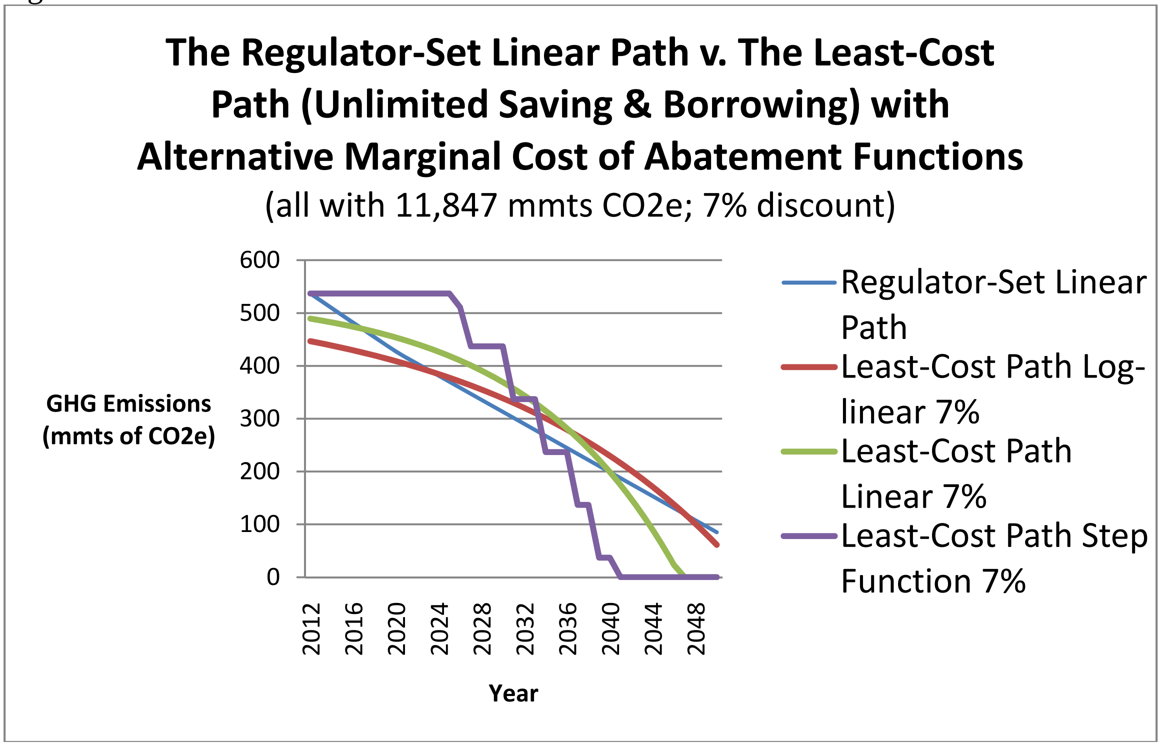


Figure 4b



In sum, this section has shown that there is a high value to intertemporal flexibility with particular patterns of borrowing and saving caused by the (unknown) shape of the marginal cost of abatement curve and the discount rate used by emissions market participants. It is important to remember that the illustrative values shown here completely abstract away from an additional well-known source of value to intertemporal flexibility: macroeconomic fluctuations in the overall economy. All of the least-cost paths that we have illustrated, from modestly to steeply rising marginal cost curves, are characterized by increasing incremental reductions over time. The flatter the curve, other things equal, the more valuable will borrowing be (and conversely for savings). This pattern is apparent across the borrowing (and saving) rows of Table 8, where the flattest curve is the step function, then the linear function, and finally the log-linear function. We did not illustrate a truly flat marginal cost curve, as the theoretical section made clear that the least-cost path for it would entail very substantial borrowing even at a low discount rate. Finally, while we did not explicitly model technological progress in our illustrations, it has the effect of increasingly "pulling down" the marginal cost curve over time, generally causing the least-cost price path to be less upward-sloping than it would be based purely upon current technology. In other words, technological progress is another force that generally increases the value of borrowing.

D. Three-Year Compliance Periods and Advance Use of Near-Term Future Allowances Provide Valuable Borrowing Flexibility

We have emphasized the value of borrowing in our above description because of an asymmetry in the existing and planned GHG cap-and-trade programs. Most such programs allow essentially unfettered allowance saving, but provide no or few opportunities for allowance borrowing. That is, savings has high value in many circumstances but the existing and planned mechanisms are already designed to capture that value. The EU ETS system, for example, has been modified to allow savings across its phases but still effectively limits borrowing to one-year ahead.

The only way that aggregate allowance borrowing can occur is if there is some mechanism in place that can authorize a situation in which emissions in one year are greater than the number of allowances issued for that year plus older allowances still in savings. California's Market Advisory Committee (2007, pp. 66-67) recommended against borrowing as possibly retarding environmental progress and technological advance, and to avoid the possibility that borrowed tons will not be repaid. But the Committee also recommended that the compliance period for comparing an individual source's emissions with its submitted allowances be approximately three years.[22] That is, a source would be required every three years to submit allowances to cover its emissions for the past three years. It recommended this to enable market participants to manage emissions levels in the face of unexpected short-term events (e.g. a year with unusually heavy electricity demand requiring more GHG allowances than expected). This is equivalent to allowing short-term borrowing (interest-free) within each three-year compliance period.

The presence of limits on borrowing implies that the market will be unable to make full use of this mechanism to reduce the cost of achieving a given environmental goal (sum of reductions). The more front-loaded are the reductions on the compliance path chosen by regulators, the more likely that borrowing would be the market's method of adjusting to minimize costs, and the greater the likely divergence of actual compliance costs from the least cost way of achieving the same environmental goal. If regulators are uncertain about the optimal compliance path to set, they should avoid the front-loaded ones. Put another way, specifying a pathway has two separate effects. The pathway defines total emissions, but also places a constraint on intertemporal substitution if we assume that borrowing will be significantly limited. Some concession on the total emissions might be justified as a way to reduce harm from this constraint (e.g. specifying a CAR-like path rather than linear).

Let us think further about borrowing. We have been referring to it in the aggregate, defined as the difference between allowances issued for a year and actual aggregate emissions for that year not covered by prior savings. At the level of an individual participant, the analogous definition does not apply. In systems that distribute initial allocations for free to participants like the US Acid Rain Program, it is perhaps natural to think of borrowing from a future distribution to that participant. But in a system in which all allowances are owned by the government until they are auctioned and thus there are no free initial entitlements, this meaning would not apply. We think the latter is likely to characterize the California system and most other regional or national trading systems, even if there is some free distribution in the initial years. Expressing the difference

[22] This has no bearing on the period for reporting emissions, which is expected to be no longer than annually for small sources and more frequently for large sources.

somewhat differently, free distribution implies that many participants have future entitlements, and it is easy to imagine a robust market in which these future entitlements are bought, sold, borrowed or lent. But with no free entitlements, there is only one potential lender: the government issuing the allowances.

To the extent that borrowing arguments focus on individual participants rather than just the aggregate, there may be no reason to set up a special allowance borrowing mechanism. Current allowance costs can be treated like the cost of any other inputs used by the source; they are simply one of the many costs of doing business. All the standard market borrowing mechanisms to assist a business in financing its operations exist; these should be sufficient to handle individual borrowing needs that arise due to allowance costs.[23]

Therefore, we think the main reason for a system that enables allowance borrowing is for the concern that we are addressing: aside from transaction costs, aggregate borrowing can facilitate a less costly way to meet a given environmental goal than by strictly following the regulator-specified compliance path. No matter how wisely and carefully the regulatory compliance path is set, there is substantial uncertainty about the true shape of the marginal cost of abatement curve, the discount rate that sources will apply, and other circumstances that will inevitably change and cause some adjustment to the least-cost path. Knowledge about marginal costs is learned first through market experiences, and changing circumstances do not occur uniformly but affect different industries and different technologies at different times. It is the market rather than the regulator that is best suited to adapt to them.

Our illustrative calculations suggest that there are many plausible scenarios in which fairly substantial borrowing may characterize some portion of the least-cost path. Perhaps a good example is the step function with marginal abatement costs from $30-$80 at 3% discount, given a total emissions budget of 11,847 mmts (from the regulator's linear path). Cumulative borrowing along the least-cost path reaches a peak of 562 mmts in 2033. While this represents only 5% of the total emissions budget, it is 201% of that year's cap of 279 mmts. Peak borrowing for any single year along this least-cost path is 78 mmts, which occurs in 2026 when it is 22% of that year's cap of 359 mmts. Are there borrowing mechanisms that can help to achieve this type of intertemporal flexibility, without threatening other aspects of the program important to its success?

We are respectful of a number of factors that make policy-makers reluctant to allow long-term borrowing. One is that we are in a world in which securing global cooperation to achieve worldwide reductions is paramount. To this end, it is of substantial symbolic importance that jurisdictions attempting to support global cooperation make real,

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[23] One exception to this argument is if the transaction cost of obtaining current allowances becomes significant relative to obtaining a future allowance. There could be simultaneous saving by some sources and borrowing by others, and this may be less costly than if extensive search costs would be necessary for the borrowers to find and make matches with the savers. This is most likely to occur as the market for current allowances approaches the time for compliance (when most trades have already occurred), and thus would presumably be limited to some small percentage of that year's cap. It is perhaps a need like this that is addressed by the limited borrowing of the EU ETS system described by Trotignon and Ellerman (2008).

verifiable reductions over time frames much shorter than the 39-year period we are discussing. Of the jurisdictions either already active in capping emissions or like California about to start, all either have adopted or are adopting short-term reduction goals, typically for 2020. That is, even if circumstances were like those in the high-discount rate version of our step-function, in which the least-cost path entails no actual reductions until 2026, we think this would not be tolerated. There would be too much skepticism that governmental commitment to real reductions is not credible.

A second factor is the concern raised in the MAC report that unfettered long-run borrowing may reduce somewhat the incentive for the research and development necessary to support technological progress. While this is true of long-term borrowing for any economic activity, it is also true that ordinary market incentives for technological progress are generally too low because often the benefits of discoveries cannot be fully appropriated. If reasonable limits on long-term borrowing strengthen climate change R&D focused upon long-term solutions, that is perhaps a good tradeoff. A third possible concern, also raised by the MAC report, is that if borrowing in the aggregate is allowed from future entitlements, then there must be reasonable limits set on individual source borrowing in order to protect against market exit with unrepaid allowance debts.

The above considerations cause us to focus initially on mechanisms that generally limit borrowing to be within 5-year periods. It also reinforces our belief that distribution by sale at auction is much preferable to any system of free distribution. Then we can at least consider the method of borrowing achieved by advance sale of future allowances combined with permission to use vintages up to 4 years ahead to cover current emissions. One advantage of this is that it eliminates the concern about individual source borrowing and repayment: the individual sources cannot use this mechanism to “owe” allowances, even if the market as a whole can.

In our models, the three-year compliance period provides some quite valuable “borrowing” flexibility so that costs are significantly reduced from the one-year compliance period that we assumed in our earlier examples. However, the savings are not uniform across the models. Consider the step function at 3% discount with respect to each of the three regulatory paths we have considered (linear, CAR and CDE). Along the linear path, for example, allowing saving and a 3-year compliance period results in total costs that save $2.131 billion of the $3.567 billion excess cost of the scheduled path compared to the least-cost path, about 60% of the excess cost. Along the CAR path, allowing saving and the 3-year compliance period saves $.576 billion of the $1.953 billion in excess costs, 29%. However, the CAR path still has lower excess costs than does the linear (CAR has $1.377 billion excess cost, linear has $1.436 billion). Along the CDE path, saving with 3-year compliance saves only $.661 billion of the $3.372 billion excess cost, or 20%. The CDE model with $2.711 billion in excess cost clearly does worse than the other two, either with one-year or three-year compliance.

Let us consider how the additional mechanism of allowing some early use of future vintage allowances might further reduce these excess costs. Specifically, suppose that each year we auction allowances as follows: the balance of those for the current year, 20% of those one-year ahead, 10% of the two-year ahead, and 5% each of the three-year and four-year ahead (and perhaps some for further-ahead allowances as well). Something like this needs to be done anyway, as sources need guidance in the form of expected future allowance prices in order to make good investment decisions, and many may wish to buy in advance as insurance against unexpected future price increases (e.g. if the economy heats up two-years ahead). However, our idea is not just that they be auctioned, but that sources be allowed to use vintages up to four-years ahead to cover current-year emissions. Sources will of course know that any use of them for the current period means that there will be fewer of them to cover emissions a few years later.

This system also has great advantages as a "safety valve" that does not threaten the environmental integrity of the program. That is, suppose there are circumstances that absent this mechanism would lead to a "price spike." For example, perhaps an unusually adverse weather pattern arises that significantly reduces the supplies of a relatively clean biofuel that had been expected to be a major way of reducing GHG emissions this year. In the short-run, there may be only expensive alternatives for reducing current year emissions. However, our mechanism could prevent most of the price spike by borrowing to increase the supply of allowances available to cover the current emissions. This allows time and flexibility to make the reductions in the next few years instead, when the biofuel supply may be restored or expanded and other less-expensive methods not available in the short-run utilized. Our mechanism leads to a more gradual increase in the level of the price path, effectively spreading the risk from such events over the years. Furthermore, because the early use of the allowances necessarily raises somewhat the future prices, incentives for continued technological progress through research and development are if anything strengthened.

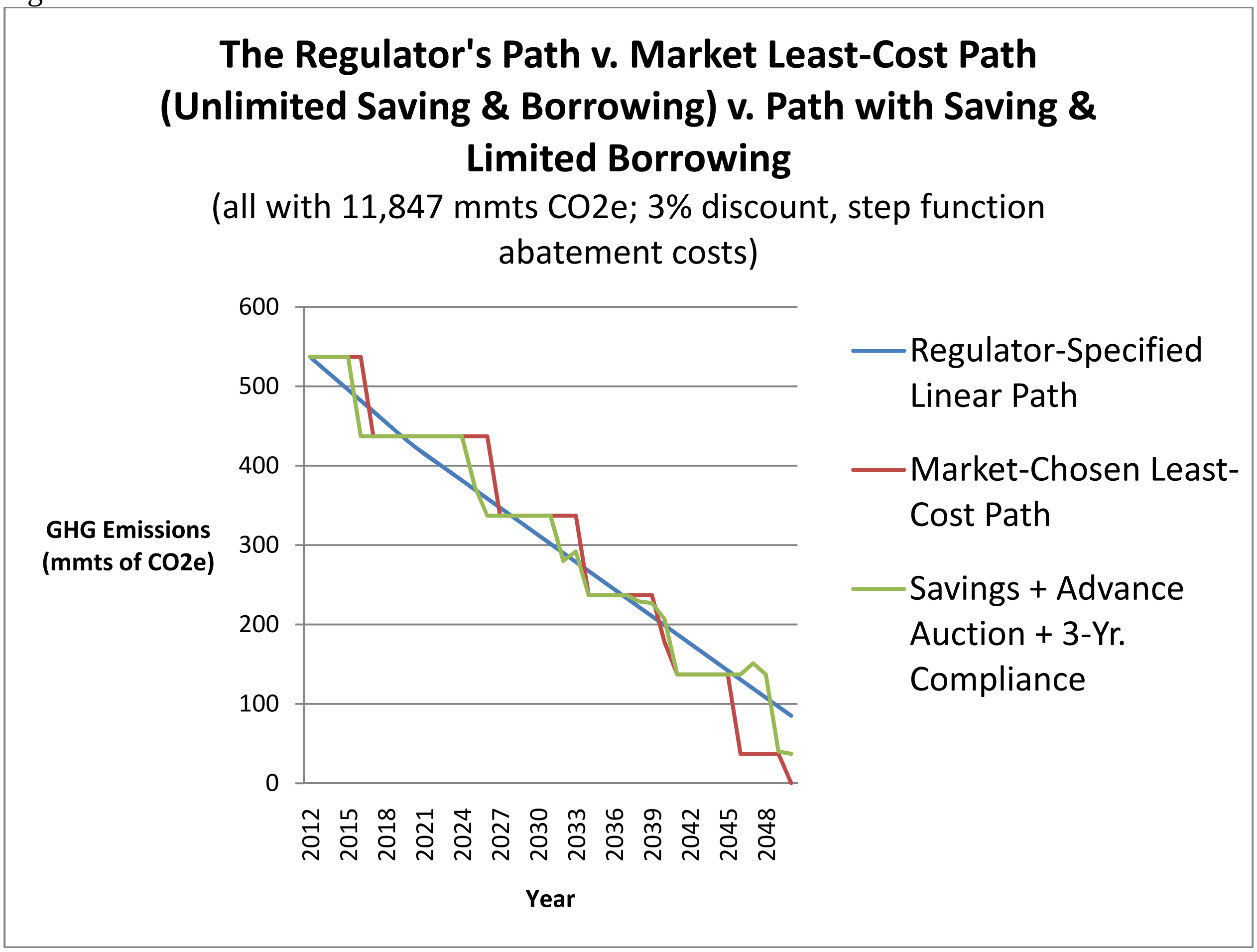
We calculate the effect of allowing this option and savings along the linear path assuming the step cost function, 3% discount, and one-year compliance.[24] This leads to a present value of the cost of compliance equal to $174.049 billion, or a cost savings of $2.984 billion or 84% of the excess cost of $3.567 billion. This compares to the 60% saving of the 3-year compliance period. The advance auction with 4-year borrowing allows the least-cost path to be followed almost exactly up to 2024 (actual emissions reductions start one year earlier in 2016), at which time the limit on borrowing that gets reached in 2038 begins to cause somewhat larger reductions than the least-cost ones in six of the remaining years.

If we now allow both the limited 4-year ahead borrowing from advance auctions, and a 3-year compliance period, there are some additional cost-reductions that are possible. The present value of the reduction cost with both options is $173.944 billion, or a cost savings of $3.089 billion or 87% of the excess cost. These small additional savings arise because in a few instances along the path it becomes possible to substitute slightly less-expensive reductions for others within the same 3-year compliance period. However, it is clear that

[24] To make this comparable with our other linear-path calculations that satisfy the 2012-2050 emissions budget of 11,847 mmts, we do not allow the 63.75 mmts of advance allowances for 2051-2054 to be used during the 2012-2050 period. Allowing their use would slightly increase the cost savings, and of course if this borrowing mechanism were actual they would be available for use.

the advance auction mechanism with limited 4-year ahead borrowing is doing most of the cost-reducing work. Figure 5 provides a graphic summary of this analysis, in which the contrast between the regulatory linear path and the unfettered least-cost market path is apparent, as well as the ability of our limited borrowing mechanisms to provide the flexibility to come close to the least-cost path.

Figure 5



Of course there is nothing magical about the precise time frames for these borrowing mechanisms that we have illustrated.. A four-year compliance period for "truing up" allowances with emissions would allow greater cost savings, to be weighed against a somewhat greater likelihood of difficulties enforcing compliance. It also might be possible to assign sources compliance periods that vary in length, in which the most dependable sources are allowed longer compliance periods. [25] Similarly, one could have

[25] Our calculation of the three-year compliance period assumed that the periods are 2012-2014, 2015-2017, etc. up to 2048-2050. We then computed the least-cost way of meeting the scheduled reductions within the three-year period. This leads to cost estimates for linear, CAR and CDE models of $174.902 billion, $212.625 billion, and $160.834 billion respectively. However, all sources do not necessarily have to have the same compliance periods. For example, sources could be randomly assigned to one of the first three years to be the start of their future individual three-year compliance periods, so that the burden of compliance-checking procedures falls evenly over the years.

higher or lower percentages of allowances auctioned in the advance sales, and could limit the borrowing to a greater or lesser number of years ahead. It is also good to keep in mind that our models, because they do not incorporate any uncertainty from macroeconomic fluctuations, are underestimating the true value of intertemporal flexibility and thus mechanisms that improve it.

Let us sum up the analysis of this section. We have illustrated that, regardless of the time path for allowances specified by regulators, it is a near certainty that the least-cost path for emissions that achieves the same aggregate reduction will be substantially different. This is because of all of the uncertainties involved: the shape of the marginal cost of abatement curve, the pace of technological progress, and other changes in the economy that affect either or both benefits and costs of emissions reductions at any particular time. If the market is allowed to adjust as necessary by borrowing or saving allowances in the aggregate, it will substantially lower the present value of the cost of achieving the emission reductions. All of the GHG cap-and-trade programs that are operating or are nearing operating allow savings with few if any restrictions. Borrowing, on the other hand, is generally not allowed or severely limited. We agree that unfettered borrowing would be problematic for a variety of reasons. However, we have shown that there is substantial cost-saving value to two mechanisms of borrowing that still limit it to be within a quite short time frame—roughly five years or less—for the climate change problem. One is each year to auction and allow the advance use of small portions of future allowances—we suggest something like 20, 10, 5, and 5 percent of the next four year's vintages. The other is to have a multiple-year compliance period for truing up allowances—perhaps three-year compliance.

These mechanisms are important to include no matter what the shape of the allowance path specified by regulators. However, we also showed that least-cost paths are most likely to resemble the CAR-shaped path rather than linear or CDE. That is, for quite a broad range of shapes for the marginal cost of abatement function, the least-cost path is characterized by one of increasing incremental emissions reductions, and technological progress over time generally reinforces this. Given a long-range emissions reduction target (e.g. 80% reduction by 2050), the CAR path to meet it will have a lower cost than linear, and the linear path lower than CDE.   However, recall that the environmental reductions have the opposite order: CDE the most, linear next, and CAR the least. Rather than specifying an aggregate emissions budget for the period, regulators seem to be choosing it implicitly by specifying a long-range goal and a path of allowances to meet it. Thus we wish to consider next not just the cost of following a particular path, but the environmental benefit that it offers. That is, we turn now to another consideration—for the case of California that we have been considering, how much of an environmental reduction is its "fair share"?

V. What is California's "Fair Share"?

The literature on GHG reductions contains a large number of proposals and studies that offer various definitions of a country's or region's fair share of the reduction necessary to achieve a well-defined environmental goal, such as stabilization at 550 ppm by 2100. In this section, we consider how California's reduction goals, if pursued along any of our three illustrative compliance paths, measure up to these "fair share" measures. We shall keep in mind the following cumulative emissions from 2012-2050 allowed by each of our three representative compliance paths: 12.4 Gt under CAR , 11.8 Gt under Linear, and 10.5 Gt under CDE. It should quickly become apparent that California's reduction goals substantially exceed all but the most extreme concepts of fair share.

A. Contraction and Convergence

Let us begin with a fair share concept that is one of the most appealing as a matter of practicality, simplicity and transparency: the "contraction and convergence" (C&C) standard described in GCI (2005). "Contraction" is the process of reducing collective emissions to meet a concentration goal, e.g., 550ppm. "Convergence" is the process of redistributing those emissions among countries to eventually attain equal per-capita emissions. Many of the fair share methods rely to some extent on the norm of equal per-capita shares, particularly in the long-run when unequal economic circumstances across jurisdictions might be reduced and all countries developed.

Under the basic approach, one must pick a year by which all countries will agree to converge on an equal per-capita allocation. One must also choose a base (starting) year, and a global emissions target in the year of convergence. All countries' emissions allowances then change linearly over time from their current levels to an equal per-capita share of the chosen target in the year of convergence. While for most countries this will be a gradual decline in emissions, a number of less developed countries with current per capita emissions below the target for convergence would be allowed an emissions budget that gradually rises. Some authors, including GCI, recommend using the population shares as of the base year to avoid encouraging population growth; others recommend against that, reasoning that this incentive is small compared with all the other incentives involved and that such action effectively punishes future inhabitants of countries whose current growth rates are high.

For purposes of our exercise, we set the base year at 2012 (when California's new regulatory system goes into effect) and the year of convergence at 2050 (the target year for attaining California's long-run goal of emissions at 20% of the 1990 level). We specify the global emissions target in 2050 at 53.11 $GtCO_2e$, a level calculated from IPCC data on Scenario B1, which involves stabilization near 550 ppm.[26] We used 2000 population levels: 6.122 billion for the world (from the same IPCC Scenario B1 Image) and 33.87 million for California from the U.S. Census, yielding a population share just under 0.6% for California.

[26] We used the IPCC Scenario B1 Image figures for the GHGs included in the calculation of California's emission goals (CO2, CH4, N20, CFCs, PFCs, and SF6), converting by using the global warming potentials from the IPCC Second Assessment Report (as specified in the Kyoto Protocol) into CO2e. These figures are commonly expressed in metric gigatons (Gt) and megatons (Mt), where 1 gigaton equals 1000 megatons and 1 megaton is one million metric tons (1Mt = 1mmt).

Under these assumptions, California's emissions allowance in 2050 would be 293.8 $MtCO_2e$. However, the Governor's 2050 target is 20% of 1990's 426.6 $MtCO_2e$, for a considerably lower value of 85.3 $MtCO_2e$. In other words, California's actual 2050 target is a very ambitious target compared to this standard. The C&C standard would only require California to cut back to 69% of its 1990 level, whereas the adopted goal is only 20% of the 1990 level. The C&C goal may seem modest only because California starts from a relatively "clean" position for a developed jurisdiction. In 2020, allowable emissions under C&C with the above assumptions lie along a line segment between 2012's emissions (estimated at 537 $MtCO_2e$) and the 2050 value, for a 2020 target of 441.9 $MtCO_2e$. The AB32 target of 426.6 $MtCO_2e$ is again lower, albeit only slightly.

Under the assumptions above, C&C yields a total CA emissions allowance of 15.8 $GtCO_2e$ from 2012-2050. This is substantially above the 10.5-12.4 $GtCO_2e$ range from our three illustrative compliance paths. Put differently, any of the three shapes would more than satisfy environmental equity if California's responsibility from a global perspective were judged by the C&C standard with 2050 as the date of convergence.

Of course there is nothing magical about 2050; one can imagine the date of convergence being either earlier or later and that would change the fair share calculations. We are reluctant to consider later dates because we think it critical globally that emissions are under control by this time. We do consider earlier dates, recognizing that they may be impractical (in terms of actual global accomplishment) unless new evidence propels the world to act more quickly than suggested by the most recent IPCC assessment. Moving the date of convergence forward to 2030 tightens California's emissions allowance to 13.4 $GtCO_2e$, still higher than any of our three illustrative paths. In the extreme case of convergence in 2012 or earlier (effectively meaning a uniform per capita standard around the globe from the outset of the program), California's cumulative emissions allowed from 2012-2050 would be 11.0 Gts, slightly lower than the allowance produced by a linear pathway.[27] We think this last calculation simply shows the aggressiveness of the California standards, as we think the likelihood of global political consensus and action around this norm is quite low.[28]

B. Grandfathering

A strict grandfathering approach would require all countries to reduce current emissions by an equal percentage to attain some specified emissions schedule. All countries therefore retain their share of current emissions. Here we must choose the emissions schedule and the date at which "current emissions" are evaluated.

[27] We also varied the population assumption, and rather than using the fixed base we used projected population over time. This increased California's allowed emissions, as its population is expected to grow faster than that of the rest of the world.

[28] Another way to see the stringency of this particular concept is to calculate the fair share amount for the U. S. as a whole and compare it to pending U.S. legislative proposals. The U.S. fair share amount by this definition is 91.39 GtCO2e from 2012-2050. The most stringent U.S. proposal to date is Lieberman-Warner (S2191) that permits 131.67 GtCO2e during the same period. Reilly et al (2007) calculate the sum of allowances in the same period for 7 other U.S. legislative proposals. The range of these is from 148-306 GtCO2e; see Table 3, p. 13.

To be consistent with the approach chosen at Kyoto, suppose that the base year is 1990. In the year 1990, global emissions were 36.4 $GtCO_2e$. CA emissions were 426.6 $MtCO_2e$. CA's share of global emissions is thus 1.17%.

Using IPCC Scenario B1, we estimate that total global emissions from 2012-2050 will be 2426 $GtCO_2e$. Applying CA's 1.17% share yields a CA allowance of 28.4 $GtCO_2e$, more than double the allowance along any of our three illustrative paths. Indeed, since 2050 emissions are higher than 2012 emissions in Scenario B1, a simple freeze of emissions at the 2012 level would be allowable, so any pathway that reduces emissions would more than meet this criterion.

We have included this calculation because it is most like the methods that have been used to decide upon allowance distributions in the existing cap-and-trade programs. Despite these precedents, we note that no serious support seems to exist for a pure grandfathering approach at the global level (in which shares must be assigned to jurisdictions in very different circumstances from one another, unlike the units in the existing programs).

C. Global Preference Scores

The global preference scores method (GPS) is a weighted sum of two methods: per-capita and grandfathering. To derive the weightings, each country chooses which method it prefers. Then these preferences are aggregated based on the population of each country. The weightings thus correspond to what fraction of the world would (indirectly) choose that method. GPS results in approximately an 8.4% U.S. share. 8.4% of the emissions in Scenario B1 from 2012-2050 is 203.8 $GtCO_2e$.

We can use 2000 populations to assign California a per-capita share. Using census data, the U.S. population in 2000 was 281.4 million. As noted above, the California population in 2000 was 33.87 million. CA would thus have a share of 12.0% of the U.S. allowance, or 1.01% of the world allowance. This is comparable to but slightly smaller than the 1.17% share derived using the grandfathering approach. The resultant CA share from 2012-2050 is 24.5 $GtCO_2e$, again achievable by any conceivable non-increasing emissions pathway.

Of course, perhaps we should not assign U.S. shares on a per-capita basis. A grandfathering basis within the U.S. itself would be less favorable to California, as California emissions per capita are currently low relative to the U.S. as a whole. While we doubt that California's earlier efforts to stay clean would not be factored in to its U.S. share calculation, let us ignore this and consider a strict grandfathering approach using the usual 1990 as the base year. In 1990 CA's emissions were 426.6 $MtCO_2e$. U.S. emissions were 6.148 $GtCO_2e$. On this basis, CA would have 6.94% of U.S. emissions, or 0.58% of world emissions, for a share of 14.1 $GtCO_2e$. This is slightly under the amount that would be allowed by the C&C method, but still substantially more than enough to follow any of our three illustrative paths.

There are of course many other possible ways to assign fair shares, including those that would make use of data on economic circumstances like GDP, and those that assess historical responsibility.[29] Moreover, there are different concepts of the total reductions that should be apportioned on some "fair share" basis. Were we to take the recommended reductions of the Stern Review, for example, the suggested reductions would be much greater and California's reduction goals would not look as ambitious. On the other hand, if we used a different IPCC scenario, the suggested reductions would be less. Our purpose is not to try and resolve these complex issues, but merely to try and give some perspective to the goals that California has adopted. We think it is clear that California's adopted goals must be viewed as an extraordinary effort, regardless of which of the three path shapes it chooses for its compliance path. This is especially true given the very low target set for 2050, which is significantly lower than any of the fair share paths require. A California economy that has been reconfigured to achieve this emissions target in 2050 will be very well positioned to continue to serve as an exemplar in the years ahead by emitting less than its fair share.

VI. The Compliance Pathway and Technological Progress

There is much uncertainty about the relationships between climate change policy and rates of technological progress in addressing climate change. However, virtually all analysts believe that there is a relationship: the type of policies instituted affect the rate of technological progress, and generally increase it compared to no policies at all. Compared to unpriced and unregulated GHG emissions, charging a price for these emissions in the form of a cap-and-trade program is expected to induce technological progress. It does so for at least two reasons. One is that it provides incentives for private research and development activity intended to come up with cost-lowering methods of reducing emissions. Very few analysts think this incentive provides a sufficient amount of R&D because inventors cannot always capture the full benefits of their efforts; additional government policies to increase R&D efforts, particularly those aimed at promising ideas not yet close to the commercialization stage, are often promoted by sponsoring basic research at universities and laboratories and through tax subsidies. The second reason is that the activity of reducing emissions itself causes "learning by doing," so that some incremental improvements are routinely found and adopted over time.[30]

In order to understand the power of market incentives for technological progress, we shall turn away for a moment from the exhaustible atmosphere and consider the long-run record of exhaustible minerals provided through markets. Recall our earlier discussion of intertemporal allowance pricing: absent technological progress, an unfettered well-working market is expected to cause the price of GHG allowances to rise over time with the interest rate. The same force applies to exhaustible minerals like aluminum or copper, after accounting for any extraction cost: the rent or royalty portion of the mineral's price

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[29] A good summary of many of these is contained in the IPCC Fourth Assessment Report, Chapter 13, Table 13-2.

[30] An excellent analysis of this issue is provided in Goulder (2004).

should rise with the interest rate.[31] If demand for these minerals is also increasing over time, that puts further upward pressure on price as the exhaustible supply becomes scarcer and scarcer. Yet economists have found just the opposite for most exhaustible resources characterized by increasing demand: over periods of 100 years or more, the real price of these commodities has fallen dramatically, often by 50% or more.[32] Why? Because the power of the market to find technical advances that economize on the use of the scarce resource has more than offset the upward price pressure.

Even if very well-working markets are created for GHG allowances, that does not mean that allowance prices will fall over the long-run: we do not know, in this case, if technological progress will be strong enough to offset increasingly stringent limits on emissions. However, our interest is in the regulator's responsibility to create as well-working a market as possible, so that there are appropriate incentives for technological progress generated by it. It is not at all clear that existing cap-and-trade markets do this. We have already mentioned that the RECLAIM program does not allow saving or borrowing of allowances from one year to the next. This discourages investment efforts today that could have a greater return through saved allowances in the near term for use in the future (when allowances are expected to be more costly). As California's GHG program will allow saving, we do not expect this to be a problem.

A problem that characterizes the EU ETS and discourages technological progress is that there is very little knowledge of the compliance path beyond the current 5-year phase. This is undoubtedly a function of the complex political negotiations necessary to reach agreement on a future path, but it adds to the uncertainty about future allowance prices and this discourages R&D efforts that have a substantial part of their expected payoffs in these future periods. We think it is very important that California provide a clear, long-run picture of its intended compliance path, although of course it needs to be adaptable to changing circumstances (e.g. new knowledge about the effects of global warming and the global efforts to prevent it). In other markets like those for exhaustible minerals, the relatively steady growth in market demand over the years gives a very important predictability to the market, even if any one year's demand is uncertain and subject to buffeting by the state of the economy or unexpected technological breakthroughs. But in the emissions markets, the quantity demanded is determined by the number of allowances issued by the government, and the question becomes what predictability is there to this?

CARB knows with a high degree of certainty that it must plan to meet the legislated AB32 target for 2020, and at a minimum should announce the allowed emissions for each year of its programs that will bring us from 2012-2020. There should always be the ability to make adjustments due to unexpected emergencies, but there should be a very high degree of certainty that this path will be followed barring major emergencies. We think it must go further than this, and recommend a procedure along these lines: Announce a tentative interim compliance path for each successive decade that will bring

[31] A mineral's price P(t) at time t may be thought of as the sum of two components that can vary with time: the marginal cost of extraction z(t) and the royalty y(t): P(t) = z(t) + y(t). See Chapter 19 of Friedman (2002) for an exposition.

[32] See, for example, Figure 5 of Krautkraemer (2005) or Figure 3 of Nordhaus (1992).

us from 2020-2050. Adopt by 2015 a final compliance path for the 2020-2030 period, and confirm or adjust the tentative paths for the successive decades. Similarly, adopt by 2025 a final compliance path for the 2030-2040 period, and so on.[33]

While this kind of predictable long-run stability in the regulatory environment is extremely important, it would apply to any of our three basic shapes for compliance paths (CAR, linear and CDE). The main fact that we know about technological progress is that it lowers the cost of future emissions reductions relative to the present. This fact alone, all else equal, means that the least-cost path (for a given cumulative reduction over the 2012-2050 period) tilts somewhat away from the present and toward the future--in other words, toward the CAR shape. However, an educated guess might be that this would tilt the path (increase allowance percentages) by only about 1% per year in the first half of the period (and reduce percentages commensurately in the second half), based on the fact that each year in the national economy technological progress results in about 1% growth of the GDP.

VII. Strategic Consideration

It is critical that we do not overlook the most fundamental aspects of the climate change problem while we diligently try our best to set the regulatory rules for particular jurisdictions like California. In particular, California's efforts (and that of the EU and other jurisdictions that are already taking strong actions) will be worth nil unless the world joins in and works for the global public good of mitigating climate change. Each jurisdictional GHG regulatory system must be encouraging of, and welcoming to, other jurisdictions that adopt the necessary goals. We think this is a factor that makes it difficult for individual jurisdictions to make credible commitments to long-term goals, as the jurisdiction's willingness to meet them depends on what other jurisdictions are doing.

We think that our work on the shape of the least-cost path, and a strategic element to the regulation suggested explicitly by the Australian model discussed earlier, combine nicely. The Australian model proposes a modest 2020 reduction goal of 5% for itself regardless of what other countries do, but a more stringent 15% if all other developed nations join in. We think this is the right idea, although perhaps too blunt. A related but more subtle idea is to approximate a long-run path that is intended to be CAR-shaped by a series of shorter-term linear approximations, each well within the "fair share" ranges. As more nations join in, the size of the incremental reductions along the next linear segment increases. This also fits nicely with worldwide adaptability to new knowledge as it becomes available, and is consistent with the roughly-decade intervals we suggested in the previous section. It is both economic and strategic.

[33] The Warner-Lieberman bill S.2191 in the U.S. Senate specifies the exact allowance quantity for each year from 2012-2050, and proposes a Carbon Market Efficiency Board with the authority as a cost-relief measure to increase the number of allowances in any year through extended borrowing from future allowance allocations.

VIII. Summary and Conclusions

This paper addresses the intertemporal responsibilities that GHG regulators like those in California face. We characterize the situation as one that begins with a short-term and a long-term goal and directs the regulators to set up a regulatory system that will meet them. In the California case, the regulatory system is to start in 2012, reduce emission to 427 mmts by 2020, and to 85 mmts by 2050 (equal to 1990 emissions and 20% of 1990 emissions respectively). We point out that there are an infinite number of compliance paths that can be taken to reach these goals, and important regulatory choices to be made about the intertemporal flexibility that sources will have in order to comply. We apply multiple criteria in order to narrow the regulatory choices to a recommended subset.

The criteria we use include environmental effectiveness, intertemporal efficiency, equity in terms of considering California's fair share of global reduction responsibilities, strategic considerations relevant to inducing global cooperation, and adaptability to changing circumstances. Intertemporal efficiency raises a number of important considerations, including the effect of the regulatory choices on technological progress, the value to sources of saving and borrowing, and the cost differences implied by alternative compliance paths.

One key responsibility of the regulators is to choose and announce a specific regulatory compliance path (number of allowances to be issued annually from 2012-2050). We recommend that this be set with a high degree of certainty for the coming decade (subject only to unexpected emergencies), with preliminary paths announced for successive decades that are finalized approximately 5 years before each decade starts. The long-term path announcements take the place of trends in long-term aggregate demand in ordinary markets that are crucial to investment expectations and research and development efforts. We believe that other emissions markets, like the EU ETS, work less well than they should because of the absence of anything other than short-term emissions reduction goals. On the other hand, we recognize that important new knowledge about global warming and technologies available to reduce it will become available in the future, and the regulatory system needs to be adaptable to this.

A key characteristic of a chosen compliance path is that its environmental effectiveness is determined essentially by the sum of allowed annual emissions (due to the very long time that emitted carbon stays in the atmosphere). Among the possible compliance paths that meet the targets, we characterize three distinct types (although combinations of these are possible) that differ by how the required annual reduction amounts change in size over time, specifically whether they have increasing, constant, or decreasing incremental reductions. For simplicity we characterize a representative member of each set as constant percentage appreciation of reduction amounts (CAR has growing increments), linear (constant increments), and constant percentage depreciation of allowed emissions (CDE has decreasing reduction increments). CAR paths take the fewest total emissions out of the atmosphere, then linear, and CDE the most. But all paths meet the required targets.

With no borrowing or saving, the CAR path is least expensive: using a 3% discount rate, the linear path increases costs by 10% and the CDE path by 32%. However, for any path set by regulators, the market will reset it by saving and borrowing of allowances across years if allowed. The saving and borrowing are cost-reduction measures that have no bearing on environmental effectiveness if within reasonable time periods. We consider a wide range of possible shapes for the marginal cost of abatement to make plausible estimates of the gains from intertemporal flexibility: the difference in present value of total reduction costs between a plan that allows no saving or borrowing compared to one with unrestricted saving or borrowing within the 2012-2050 period. These calculations attempt to capture the degree of inefficiency that is likely to arise between a regulator-specified path and the least cost intertemporal path due to uncertainty about the true shape of the marginal cost of abatement curve. All paths save costs by allowing borrowing and saving. We find that this value ranges from 1-2% of total costs to over 20% of total costs, calculated over a fairly broad range of shapes for the marginal abatement cost curve from modestly to steeply rising and with discount rates used by sources assumed to be 3% or 7%. For the flatter curves at either discount rate, and for any of the curves at the high discount rate, borrowing accounts for most or all of the cost savings. These figures underestimate the true value of intertemporal adjustments because they abstract away from any changes in macroeconomic conditions that are important drivers of such adjustments and lead to additional important gains from allowing them.

The California plan is expected to allow savings, but not allow borrowing. We note that this is only a restriction on aggregate annual borrowing—within any year, all emissions must be covered by current or saved allowances. Any individual source is of course free to borrow funds in the market place to meet its current expenses. Other cap-and trade programs are similar, in that they allow savings but have either no borrowing (RGGI) or very limited borrowing (like one-year ahead within a phase in the EU ETS). The no borrowing restriction makes great sense for those pollutants that have short-term adverse health effects like SO_2 or NO_x, but this is not the case for carbon emissions. There are reasons why borrowing should be limited, not the least of which is the demonstration of substantial real net reductions within a reasonably short time frame (e.g. 10 years) to motivate other jurisdictions to act similarly. But none of these reasons imply that borrowing needs to be as severely limited as in current programs and plans. This leads us to consider mechanisms that might provide very valuable borrowing ability within five-year time frames. We find that an advance auction and allowed early use of limited portions of future vintage allowances up to four-years ahead can capture very substantial shares of the total cost-saving potential of unfettered borrowing (84% with our modestly-rising step function at 3% discount). An additional way of effectively allowing some borrowing is to have a multi-year compliance or “true-up” period. The State’s Market Advisory Committee recommended that California have a three-year compliance period (i.e. a source would have to turn in the necessary allowances every three years). Our calculations also suggest that there can be considerable value to the three-year compliance period. We find, for example, that the combination of unlimited savings and the three-year compliance period saves 20-60% of the potential intertemporal cost savings along the original three paths we discussed (CAR, linear and CDE).

Our three illustrative paths allow cumulative California emissions of 10.5-12.4 Gts of CO_2e from 2012-2050. Another important consideration, from the perspective of inducing global cooperation, is the amount of cumulative emissions that might be considered California's fair share. To the extent that these amounts are considered excessive by other jurisdictions, California's effort will be unlikely to contribute much in the way of inducing satisfactory global action. To the extent that these amounts are considered fair, then California's efforts and specific mechanisms may be emulated to good effect. And to the extent that California's efforts are considered beyond what is necessary, then it may serve as an exemplary model and a significant spur to action by others.

We consider several different concepts of fair share that have received significant attention: Contraction and Convergence, Grandfathering, and Global Preference Scores. While there are a great number of other fair share concepts, we used these because we think the first is the most centrist, the second has the most precedence due to its use by most existing cap-and-trade programs, and the third is an interesting hybrid between grandfathering and an equal per capita approach. The "fair share" California emissions budgets for 2012-2050 that we derive under these approaches range from 11.0-28.4 $GtCO_2$e. All paths that we analyze with the adopted California targets are well below the "fair share" amounts, with the one exception being the extreme case of equal per capita shares from the outset (and in this case California is surprisingly close to meeting it). Thus we think California is likely to be regarded as exemplary regardless of which of the three path shapes it chooses. In particular, the 2050 target is very aggressive, and California will have reduced its emissions considerably below the likely per-capita 2050 emissions worldwide by that time, in the process creating a non-carbon-intensive economy that will continue to benefit the climate into the future.

All of the above calculations assume a fixed technology for reducing emissions, but we know that over long periods technological progress is one of the great drivers of all developed economies. An important desired characteristic of any GHG regulatory system is that it generates R&D that will lower the cost of reducing emissions over time. While some of this can and should be publicly funded, it is also important that there be appropriate incentives for private R&D. We have already emphasized the importance of the regulator specifying a long-run compliance path that is adaptable to new knowledge for creating a healthy private R&D and investment environment. We also point out that the expectation of some technological progress encourages a slight tilt for any given emissions budget to increase future reductions relative to current ones. This is equivalent to a tilt toward a CAR-like path, and away from a CDE-type of path.

While there remains much uncertainty about how to best specify a compliance path, we find that Califonia's very strong reduction goals give it much flexibility—all of our paths that meet the targets involve emissions below the fair share amounts. On grounds of cost, avoiding intertemporal inefficiency due to borrowing constraints, and generating and taking advantage of technological progress, we find that CAR-type paths are most favorable and linear the next-most favorable. An approximation to a planned CAR-path in decade-long linear segments may be the best choice overall, in that it preserves adaptability both to new knowledge and to what will hopefully be an increasing group of jurisdictions from around the globe that have agreed to fair share limits on their emissions. Thus we recommend that California regulators not only specify the compliance path from 2012-2020, but lay out a tentative long-run plan to 2050 with intent on specifying firmly by 2015 the path from 2021-2030. We also recommend that they plan to include some future vintages in annual auctions of allowances, and allow the early use of auctioned future vintages as much as four-years ahead. Finally, we recommend the three-year compliance period for truing up allowances.

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Appendix: Least-Cost Paths with Marginal Cost of Abatement as a Step Function

This appendix explains the least-cost pathways that restrict aggregate emissions to the same amounts as allowed respectively by our CAR, linear and CDE regulator-specified paths. Tables A1, A2 and A3 illustrate the least-cost pathways when the discount rate is 3%; similar calculations are undertaken but not shown for a 7% discount rate. The columns labeled $30-$80 show the present value of the cost of undertaking an emission reduction of the specified marginal cost in a particular year. For example, the present value of undertaking a $50 per ton reduction in 2035 is $25.33. Each cell applies to up to 100 mmts of reductions that could be undertaken in its year (after that the marginal cost increases to the next level until $80 undiscounted, within which the maximum reduction of 537mmts in one year is reached).

The CAR path in Table A1 requires a reduction of 8554 mmts, achieved at least cost by using the 86 green cells shown (the cell used with highest present value, $25.46 in 2041, is only needed for 54 of the 100 mmts available in it). In other words, the least cost solution that a market would choose is to undertake reductions in cells with present value of $25.46 or less. The red cells in the same table show more expensive cells that are used if following the regulator-specified compliance path (the least cost way of achieving each year's goal).[34]

The linear path in Table A2 requires a reduction of 9096 mmts, so it requires that more cells be used than under CAR. If there were no boundary conditions, this would require 91 cells. However, one of the least expensive green cells is on the boundary—the $26.02 cell in 2050 at $80 undiscounted marginal cost, where there are only 37 mmts of emissions left to take. So we actually need a 92nd green cell to reach the correct reduction total; we use all cells with costs up to $26.22, with the 92nd cell contributing a reduction of 59 mmts. Finally, the CDE path in Table A3 requires reductions that total 10,435 mmts. It requires using all cells that have present value of $28.28 or less, again due to boundary conditions. Limited 37 mmt reductions are available in the 3 cells for years 2048-2050 at $80 nominal marginal cost; this means 107 cells must be used to reach the correct total (103 at 100mmts each, 3 at 37mmts each, and 1 at 24 mmts).

For any of the three illustrative compliance paths, the cells used in each year to meet it sum to the total reductions undertaken for that year, and these totals are the least-cost way of meeting the path's aggregate reduction goal. The regulator's path tells us how many allowances are issued for that year, and the least-cost path tells us how many allowances will actually be used in that year if unrestricted saving and borrowing are allowed. The difference between these two numbers reveals the pattern of borrowing and lending that we would expect to observe in the allowance marketplace. Table A4 contains these numbers.

[34] Note that cells are not always used in their entirety. On the regulator-specified compliance path, cells are routinely used only in part; on the least-cost path they generally are not since this path always selects the lowest-cost cell available. Therefore, more cells are used in part on the regulator's path than on the least cost path. This explains how there are cells used by the regulator's path but not the least-cost path (the red cells), but not the reverse—cells used by the least-cost path and not the regulator's path.

If one looks at the annual borrowing and saving amounts, the numbers do not appear to be problematic. That is, years of borrowing and saving are pretty well interspersed along the compliance pathway for any of the three illustrative paths. Furthermore, the amounts borrowed or saved in any one year usually are less than 25% of the amount shown on the corresponding regulatory path for that year. However, the cumulative amount of saving suggests some concerns, as there is substantial net borrowing along each of the three illustrative pathways. Along the linear pathway, for example, cumulative emissions always exceed the cumulative total along the regulator's path until the final year of the period. Total borrowing reaches its peak in 2033 at 562 mmts, after which it gradually declines to zero. The pattern is similar for the CAR path, where total borrowing is generally greater than the linear path for about the first 20 years and reaches a peak of 575 in 2034. Along the CDE path, however, there is net saving from 2015-2022, then net borrowing that reaches a peak of 687 mmts in 2037 after which it declines to zero. Recall that the CDE path requires the least reductions initially, so it is not surprising that the cost-minimizing market finds that additional reductions in these early years (i.e. savings) are relatively inexpensive. Of course this result depends upon our cost and discount rate assumptions that, while plausible, may turn out to differ significantly from actuality.

Table A1: The Least-Cost Path Meeting the Linear Total Reduction (Green Cells; Red cells are more expensive and used if no borrowing or saving is allowed)

Year	$30	$40	$50	$60	$70	$80	Least-Cost Emission **Linear**	Emissions **Linear**
2012	$30.00	$40.00	$50.00	$60.00	$70.00	$80.00	537	537
2013	$29.13	$38.83	$48.54	$58.25	$67.96	$77.67	537	523
2014	$28.28	$37.70	$47.13	$56.56	$65.98	$75.41	537	510
2015	$27.45	$36.61	$45.76	$54.91	$64.06	$73.21	537	496
2016	$26.65	$35.54	$44.42	$53.31	$62.19	$71.08	537	482
2017	$25.88	$34.50	$43.13	$51.76	$60.38	$69.01	437	468
2018	$25.12	$33.50	$41.87	$50.25	$58.62	$67.00	437	455
2019	$24.39	$32.52	$40.65	$48.79	$56.92	$65.05	437	441
2020	$23.68	$31.58	$39.47	$47.36	$55.26	$63.15	437	427
2021	$22.99	$30.66	$38.32	$45.99	$53.65	$61.31	437	416
2022	$22.32	$29.76	$37.20	$44.65	$52.09	$59.53	437	404
2023	$21.67	$28.90	$36.12	$43.35	$50.57	$57.79	437	393
2024	$21.04	$28.06	$35.07	$42.08	$49.10	$56.11	437	381
2025	$20.43	$27.24	$34.05	$40.86	$47.67	$54.48	437	370
2026	$19.83	$26.44	$33.06	$39.67	$46.28	$52.89	437	359
2027	$19.26	$25.67	$32.09	$38.51	$44.93	$51.35	337	347
2028	$18.70	$24.93	$31.16	$37.39	$43.62	$49.85	337	336
2029	$18.15	$24.20	$30.25	$36.30	$42.35	$48.40	337	324
2030	$17.62	$23.50	$29.37	$35.24	$41.12	$46.99	337	313
2031	$17.11	$22.81	$28.51	$34.22	$39.92	$45.62	337	302
2032	$16.61	$22.15	$27.68	$33.22	$38.76	$44.29	337	290
2033	$16.13	$21.50	$26.88	$32.25	$37.63	$43.00	337	279
2034	$15.66	$20.88	$26.09	$31.31	$36.53	$41.75	237	267
2035	$15.20	$20.27	$25.33	$30.40	$35.47	$40.54	237	256
2036	$14.76	$19.68	$24.60	$29.52	$34.44	$39.35	237	245
2037	$14.33	$19.10	$23.88	$28.66	$33.43	$38.21	237	233
2038	$13.91	$18.55	$23.18	$27.82	$32.46	$37.10	237	222
2039	$13.51	$18.01	$22.51	$27.01	$31.51	$36.02	237	210
2040	$13.11	$17.48	$21.85	$26.22	$30.60	$34.97	178	199
2041	$12.73	$16.97	$21.22	$25.46	$29.70	$33.95	137	188
2042	$12.36	$16.48	$20.60	$24.72	$28.84	$32.96	137	176
2043	$12.00	$16.00	$20.00	$24.00	$28.00	$32.00	137	165
2044	$11.65	$15.53	$19.42	$23.30	$27.18	$31.07	137	153
2045	$11.31	$15.08	$18.85	$22.62	$26.39	$30.16	137	142
2046	$10.98	$14.64	$18.30	$21.96	$25.62	$29.28	37	131
2047	$10.66	$14.22	$17.77	$21.32	$24.88	$28.43	37	119
2048	$10.35	$13.80	$17.25	$20.70	$24.15	$27.60	37	108
2049	$10.05	$13.40	$16.75	$20.10	$23.45	$26.80	37	96
2050	$9.76	$13.01	$16.26	$19.51	$22.77	$26.02	0	85
Totals							11847	11847

Table A2: The Least-Cost Path Meeting the CDE Total Reduction (Green Cells; Red cells are more expensive and used if no borrowing or saving is allowed)

Year	$30	$40	$50	$60	$70	$80	$90	Least-Cost Emissions **CDE**	Emissions **CDE**
2012	$30.00	$40.00	$50.00	$60.00	$70.00	$80.00	$90.00	537	537
2013	$29.13	$38.83	$48.54	$58.25	$67.96	$77.67	$87.38	537	522
2014	$28.28	$37.70	$47.13	$56.56	$65.98	$75.41	$84.83	513	507
2015	$27.45	$36.61	$45.76	$54.91	$64.06	$73.21	$82.36	437	493
2016	$26.65	$35.54	$44.42	$53.31	$62.19	$71.08	$79.96	437	479
2017	$25.88	$34.50	$43.13	$51.76	$60.38	$69.01	$77.63	437	465
2018	$25.12	$33.50	$41.87	$50.25	$58.62	$67.00	$75.37	437	452
2019	$24.39	$32.52	$40.65	$48.79	$56.92	$65.05	$73.18	437	439
2020	$23.68	$31.58	$39.47	$47.36	$55.26	$63.15	$71.05	437	427
2021	$22.99	$30.66	$38.32	$45.99	$53.65	$61.31	$68.98	437	405
2022	$22.32	$29.76	$37.20	$44.65	$52.09	$59.53	$66.97	437	383
2023	$21.67	$28.90	$36.12	$43.35	$50.57	$57.79	$65.02	437	363
2024	$21.04	$28.06	$35.07	$42.08	$49.10	$56.11	$63.12	337	344
2025	$20.43	$27.24	$34.05	$40.86	$47.67	$54.48	$61.29	337	326
2026	$19.83	$26.44	$33.06	$39.67	$46.28	$52.89	$59.50	337	309
2027	$19.26	$25.67	$32.09	$38.51	$44.93	$51.35	$57.77	337	293
2028	$18.70	$24.93	$31.16	$37.39	$43.62	$49.85	$56.09	337	278
2029	$18.15	$24.20	$30.25	$36.30	$42.35	$48.40	$54.45	337	263
2030	$17.62	$23.50	$29.37	$35.24	$41.12	$46.99	$52.87	337	249
2031	$17.11	$22.81	$28.51	$34.22	$39.92	$45.62	$51.33	337	236
2032	$16.61	$22.15	$27.68	$33.22	$38.76	$44.29	$49.83	237	224
2033	$16.13	$21.50	$26.88	$32.25	$37.63	$43.00	$48.38	237	212
2034	$15.66	$20.88	$26.09	$31.31	$36.53	$41.75	$46.97	237	201
2035	$15.20	$20.27	$25.33	$30.40	$35.47	$40.54	$45.60	237	191
2036	$14.76	$19.68	$24.60	$29.52	$34.44	$39.35	$44.27	237	181
2037	$14.33	$19.10	$23.88	$28.66	$33.43	$38.21	$42.98	237	171
2038	$13.91	$18.55	$23.18	$27.82	$32.46	$37.10	$41.73	137	162
2039	$13.51	$18.01	$22.51	$27.01	$31.51	$36.02	$40.52	137	154
2040	$13.11	$17.48	$21.85	$26.22	$30.60	$34.97	$39.34	137	146
2041	$12.73	$16.97	$21.22	$25.46	$29.70	$33.95	$38.19	137	138
2042	$12.36	$16.48	$20.60	$24.72	$28.84	$32.96	$37.08	137	131
2043	$12.00	$16.00	$20.00	$24.00	$28.00	$32.00	$36.00	37	124
2044	$11.65	$15.53	$19.42	$23.30	$27.18	$31.07	$34.95	37	117
2045	$11.31	$15.08	$18.85	$22.62	$26.39	$30.16	$33.93	37	111
2046	$10.98	$14.64	$18.30	$21.96	$25.62	$29.28	$32.94	37	105
2047	$10.66	$14.22	$17.77	$21.32	$24.88	$28.43	$31.98	37	100
2048	$10.35	$13.80	$17.25	$20.70	$24.15	$27.60	$31.05	0	95
2049	$10.05	$13.40	$16.75	$20.10	$23.45	$26.80	$30.15	0	90
2050	$9.76	$13.01	$16.26	$19.51	$22.77	$26.02	$29.27	0	85
Totals								10508	10508

Table A3: The Least-Cost Path Meeting the CAR Total Reduction (Green Cells; Red cells are more expensive and used if no borrowing or saving is allowed)

	$30	$40	$50	$60	$70	$80	Least-Cost Emissions	Emissions
Year							**CAR**	**CAR**
2012	$30.00	$40.00	$50.00	$60.00	$70.00	$80.00	537	537
2013	$29.13	$38.83	$48.54	$58.25	$67.96	$77.67	537	525
2014	$28.28	$37.70	$47.13	$56.56	$65.98	$75.41	537	512
2015	$27.45	$36.61	$45.76	$54.91	$64.06	$73.21	537	499
2016	$26.65	$35.54	$44.42	$53.31	$62.19	$71.08	537	485
2017	$25.88	$34.50	$43.13	$51.76	$60.38	$69.01	537	471
2018	$25.12	$33.50	$41.87	$50.25	$58.62	$67.00	437	457
2019	$24.39	$32.52	$40.65	$48.79	$56.92	$65.05	437	442
2020	$23.68	$31.58	$39.47	$47.36	$55.26	$63.15	437	427
2021	$22.99	$30.66	$38.32	$45.99	$53.65	$61.31	437	419
2022	$22.32	$29.76	$37.20	$44.65	$52.09	$59.53	437	410
2023	$21.67	$28.90	$36.12	$43.35	$50.57	$57.79	437	402
2024	$21.04	$28.06	$35.07	$42.08	$49.10	$56.11	437	393
2025	$20.43	$27.24	$34.05	$40.86	$47.67	$54.48	437	384
2026	$19.83	$26.44	$33.06	$39.67	$46.28	$52.89	437	374
2027	$19.26	$25.67	$32.09	$38.51	$44.93	$51.35	437	365
2028	$18.70	$24.93	$31.16	$37.39	$43.62	$49.85	337	355
2029	$18.15	$24.20	$30.25	$36.30	$42.35	$48.40	337	346
2030	$17.62	$23.50	$29.37	$35.24	$41.12	$46.99	337	336
2031	$17.11	$22.81	$28.51	$34.22	$39.92	$45.62	337	325
2032	$16.61	$22.15	$27.68	$33.22	$38.76	$44.29	337	315
2033	$16.13	$21.50	$26.88	$32.25	$37.63	$43.00	337	304
2034	$15.66	$20.88	$26.09	$31.31	$36.53	$41.75	337	293
2035	$15.20	$20.27	$25.33	$30.40	$35.47	$40.54	237	282
2036	$14.76	$19.68	$24.60	$29.52	$34.44	$39.35	237	271
2037	$14.33	$19.10	$23.88	$28.66	$33.43	$38.21	237	259
2038	$13.91	$18.55	$23.18	$27.82	$32.46	$37.10	237	247
2039	$13.51	$18.01	$22.51	$27.01	$31.51	$36.02	237	235
2040	$13.11	$17.48	$21.85	$26.22	$30.60	$34.97	237	223
2041	$12.73	$16.97	$21.22	$25.46	$29.70	$33.95	183	211
2042	$12.36	$16.48	$20.60	$24.72	$28.84	$32.96	137	198
2043	$12.00	$16.00	$20.00	$24.00	$28.00	$32.00	137	185
2044	$11.65	$15.53	$19.42	$23.30	$27.18	$31.07	137	171
2045	$11.31	$15.08	$18.85	$22.62	$26.39	$30.16	137	158
2046	$10.98	$14.64	$18.30	$21.96	$25.62	$29.28	137	144
2047	$10.66	$14.22	$17.77	$21.32	$24.88	$28.43	37	129
2048	$10.35	$13.80	$17.25	$20.70	$24.15	$27.60	37	115
2049	$10.05	$13.40	$16.75	$20.10	$23.45	$26.80	37	100
2050	$9.76	$13.01	$16.26	$19.51	$22.77	$26.02	37	85
Totals							12389	12389

Table A4: Annual and Cumulative Amount of Allowances Saved (Borrowed)

Year	Annual Saving Linear	Cumulative Saving Linear	Annual Saving CDE	Cumulative Saving CDE	Annual Saving CAR	Cumulative Saving CAR
2012	0	0	0	0	0	0
2013	-14	-14	-15	-15	-12	-12
2014	-28	-41	-6	-21	-25	-37
2015	-41	-83	56	35	-38	-76
2016	-55	-138	42	77	-52	-127
2017	31	-106	28	105	-66	-193
2018	18	-89	15	120	20	-173
2019	4	-85	2	122	5	-167
2020	-10	-95	-10	112	-10	-177
2021	-21	-116	-32	80	-18	-196
2022	-33	-149	-54	27	-27	-223
2023	-44	-193	-74	-47	-35	-258
2024	-56	-249	7	-40	-44	-302
2025	-67	-316	-11	-51	-53	-356
2026	-78	-394	-28	-78	-63	-418
2027	10	-384	-44	-122	-72	-490
2028	-1	-385	-59	-182	18	-472
2029	-13	-398	-74	-256	9	-464
2030	-24	-422	-88	-343	-1	-465
2031	-35	-457	-101	-444	-12	-477
2032	-47	-504	-13	-457	-22	-499
2033	-58	-562	-25	-482	-33	-532
2034	30	-532	-36	-518	-44	-575
2035	19	-513	-46	-564	45	-530
2036	8	-505	-56	-621	34	-496
2037	-4	-509	-66	-687	22	-474
2038	-15	-524	25	-662	10	-464
2039	-27	-551	17	-645	-2	-465
2040	21	-530	9	-636	-14	-479
2041	51	-479	1	-636	28	-451
2042	39	-440	-6	-642	61	-391
2043	28	-412	87	-555	48	-343
2044	16	-396	80	-475	34	-309
2045	5	-391	74	-400	21	-288
2046	94	-297	68	-332	7	-282
2047	82	-215	63	-269	92	-189
2048	71	-144	95	-174	78	-111
2049	59	-85	90	-85	63	-48
2050	85	0	85	0	48	0