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Bryan K. Mignone

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Technological Scarcity, Compliance Flexibility and the Optimal Time Path of Emissions Abatement

Bryan K. Mignone[1,2*]

[1]*Foreign Policy Program, The Brookings Institution, Washington, D.C., USA*

[2] *Centre for Applied Macroeconomic Analysis, The Australian National University, Canberra, Australia*

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* Corresponding author's E-mail: bmignone@brookings.edu

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Abstract

The overall economic efficiency of a quantity-based approach to greenhouse gas mitigation depends strongly on the extent to which such a program provides opportunities for compliance flexibility, particularly with regard to the timing of emissions abatement. Here I consider a program in which annual targets are determined by choosing the optimal time path of reductions consistent with an exogenously prescribed cumulative reduction target and fixed technology set. I then show that if the availability of low-carbon technology is initially more constrained than anticipated, the optimal reduction path shifts abatement toward later compliance periods. For this reason, a rigid policy in which fixed annual targets are strictly enforced in every year yields a cumulative environmental outcome identical to the optimal policy but an economic outcome worse than the optimal policy. On the other hand, a policy that aligns actual prices (or equivalently, costs) with expected prices by simply imposing an explicit price ceiling (often referred to as a "safety valve") yields the opposite result. Comparison among these multiple scenarios implies that there are significant gains to realizing the optimal path but that further refinement of the actual regulatory instrument will be necessary to achieve that goal in a real cap-and-trade system.

Keywords: *Environmental regulation; climate policy; energy modeling.*

1. Introduction

Article 2 of the Framework Convention on Climate Change (UNFCCC) states that the ultimate objective of climate policy is "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference (DAI) with the climate system" (*UNFCCC, 1992*). Although the exact meaning of DAI remains the subject of some controversy (*O'Neill and Oppenheimer, 2002*), a growing body of scientific literature suggests that global targets in the 450-550 ppm range (and perhaps even lower) will be necessary to avoid a significant risk of dangerous and irreversible damage (*IPCC, 2007*). Achieving the most stringent of these targets would require a sustained, global reversal of emissions growth within the next several years, while achieving the more modest targets would likely require such a reversal within the next one or two decades, depending on how quickly mitigation proceeds once the growth in emissions is reversed (*Mignone et al., 2008*).

Because atmospheric stabilization will require a continuous mitigation effort over the next century and beyond, a common element of policies informed by this paradigm is the preference for an explicit set of mandated targets and timetables. Although the concept of stabilization is poorly defined in the national context (since action by any one country alone cannot yield stabilization), national-level policies may nonetheless be viewed as *consistent with* stabilization if the relative domestic reductions are comparable to the relative reductions required globally (*WRI, 2008*). These considerations explain the tendency of the scientific and environmental establishment to advocate for a system of national caps, ultimately coordinated through international negotiation.

The economics community has had a more difficult relationship with the idea of quantity-based mechanisms in the climate policy context, largely because economists tend to see economic efficiency (realized through policy instruments that promote compliance flexibility) as the most important objective in sound policymaking (e.g. *Aldy et al., 2003*). By this standard, a strict quantity-based mechanism (i.e. a fixed schedule of caps) is relatively inefficient, because it lacks "when-flexibility" or the ability for regulated entities to shift their compliance obligations across time in response to real market conditions. The extra effort required to make quantity-based systems economically efficient, combined with the arguable assumption that the slope of the marginal damage function is less steep than the slope of the marginal cost function in the carbon abatement context, has led many economists to favor a carbon tax over a cap-and-trade system (e.g. *Newell and Pizer, 2002*).

Despite this theoretical preference for price-based regulation, economists have generally supported cap-and-trade proposals when they have emerged in the political arena, under the condition that such proposals contain explicit mechanisms to facilitate compliance flexibility and overall economic efficiency. Generally speaking, mechanisms to promote flexibility in the timing of compliance must account for two contingencies: (1) the possibility that initial targets are *not stringent enough* with respect to later targets, in which case the optimal path would require shifting abatement toward the present, and (2) the possibility that initial targets are *too stringent* with respect to later targets, in which case the optimal path would require shifting abatement toward the future.

The first of these concerns is generally easy to address by allowing firms to bank permits for later use. Because firms do not have unilateral incentives to overcomply beyond the optimal amount, there is no reason to place further restrictions on the quantity of permits a firm may bank in any given year or on the size of the total bank of permits it may accumulate. Indeed, the existence of an accumulated allowance bank on the part of regulated industry may actually enhance the political constituency in support of the long-run continuity of the system, because banked permits will only be valuable if the program remains viable in the future (c.f. *McKibbin and Wilcoxen, 2008*).

The second concern is more difficult to resolve. In theory, one could allow unlimited borrowing in the same way that one allows unlimited banking. In a world with perfect foresight and perfect regulatory certainty, firms would borrow the optimal number of permits when responding to actual market conditions. However, in the real world, if firms have imperfect information about the future, doubts about the ability of regulators to enforce long-term targets, or concerns about the continuity of the system itself, they may borrow more than the optimal amount, thereby exacerbating the risk of future default. Moreover, if such defaults do occur (or appear imminent), regulators may face pressure to revise the reduction targets, leading to the paradoxical conclusion that the more one tries to encourage the optimal outcome (by enhancing compliance flexibility), the more likely it is that the program will in fact fail to achieve that optimal outcome (because the cumulative target will be exceeded to account for defaults).

The problems that surround borrowing suggest several possible responses. First, one could prohibit borrowing altogether. This would be the recommended course of action if the efficiency gains from additional compliance flexibility were determined to be small relative to the risk-adjusted costs associated with the possibility of default. Another alternative would be to implement a price ceiling (known as a "safety valve") that would cap the price of CO_2 in the permit market (*Jacoby and Ellerman, 2004; McKibbin and Wilcoxen, 2004; Pizer, 2002; Roberts and Spence, 1976*). If the safety valve price mirrored the expected price path, then it would be triggered only if the compliance obligation in a given year turned out to be more onerous than anticipated when the reduction path was codified into an annual reduction schedule. In this way, the conditions under which undercompliance would occur under a safety valve would be identical to the conditions under which undercompliance would occur in a more conventional specification of borrowing. The critical difference between a safety valve and borrowing *per se* is that the former would not require borrowed emissions to be repaid in later years. This outcome might be acceptable if the cumulative environmental target were ultimately regarded as flexible but could be far more problematic if the cumulative target were decided through prior negotiation. In that case, the mechanism proposed to enhance flexibility – to the extent that it threatened a fragile political coalition over targets – could once again jeopardize the system itself.

With these considerations as a backdrop, we examine, in the remainder of this paper, the economic and environmental implications of several policies designed to capture the different ways in which compliance flexibility could be implemented in a real cap-and-trade system. In particular, we use a well-known computable model to show that if low-carbon technology turns out to be more scarce than anticipated, inflexible annual targets would drive up the economic costs of mitigation well beyond the costs of a policy with optimal borrowing. The value of this difference provides one measure of the benefits of enhancing compliance flexibility that can be compared to any proposed measure of the risk-adjusted costs of default.

While the benefits of providing flexibility and achieving the when-efficient outcome are significant, we show that attempting to realize these benefits by applying a conventional safety valve (to align the actual cost of the policy with the anticipated cost) threatens the cumulative environmental integrity of the program by an amount that is likely to jeopardize the political coalition around targets. A safety valve policy may even be economically suboptimal if the cumulative target is decided through a separate balancing of costs and benefits and if the emissions overages are sufficient to drive down the level of avoided damages (benefits). Together, these simulations suggest that there are real economic and environmental gains to developing a credible policy instrument that can achieve a when-efficient response to a cumulative emissions reduction target.

2. Model Description and Baseline Results

In order to quantitatively evaluate the tradeoff between economic efficiency and environmental integrity under cap-and-trade, we make use of the MERGE model, a well-documented computable general equilibrium (CGE) model of the energy-economic system that combines a top-down specification of the macroeconomy with a bottom-up specification of the energy sector (*Manne et al., 1995*). In the simplified configuration used for this study, we reduce the number of distinct world regions in the model to one (the United States) and the number of carbon abatement technologies to two, one deployable in the power sector and one deployable in the fuels sector.

In the power sector, this single aggregate technology is meant to represent the larger set of low-carbon technologies like coal equipped with carbon capture and storage (CCS), advanced nuclear, wind, solar and geothermal, among others. Both aggregate abatement technologies are assumed to be available at a marginal (levelized) cost premium of $50 per ton CO_2, but because the large-scale availability of these sources remains the subject of some debate, the time at which they are assumed to be available for deployment is one of the adjustable parameters in this study, along with the details of the regulatory system itself. In addition to technology substitution, the model also includes an explicit demand response to price (over and above autonomous improvements in energy efficiency), with a long-run elasticity of 0.3. Together these two features allow the model to capture, in an aggregate manner, both supply and demand-side responses to carbon mitigation policy.

Model simulations begin in 2010, with (forecast) data in that year supplied by the US Energy Information Administration (*EIA, 2008*). Under business-as-usual conditions (no policy constraints), economic output (GDP) in the US starts in 2010 at about 12.5 trillion USD and grows at approximately 2.4% per year to 32 trillion USD in 2050, consistent with the EIA growth forecast over the 2006-2030 horizon. Over the same period, total energy consumption (or more precisely, the total energy contained in the fuels used for such consumption) grows from 110 EJ in 2010 to 143 EJ in 2050, representing an annual growth of energy demand of approximately 0.7%, which is also broadly consistent with EIA projections through 2030. The difference between the growth rate of economic output and the growth rate of energy consumption provides a measure of the rate of autonomous energy efficiency improvement. Using the numbers above, we find that the overall energy intensity of the economy decreases by about 1.7% per year, a trend that is assumed to continue in the future with or without explicit policy intervention.

The future fuel mix under business-as-usual also continues to reflect historical trends, with coal dominating the power sector and oil dominating the fuels sector. Over the course of the (baseline) simulation, coal, natural gas, nuclear and renewables (including hydropower) account for approximately 51%, 17%, 20% and 11% of energy supplied in the power sector, respectively, whereas oil, natural gas, coal and renewables account for 65%, 28%, 3.3% and 4.4% of energy supplied in the fuels sector, respectively. Because consumption of all fossil fuels continues to grow under business-as-usual, CO_2 emissions also continue to rise, from 6.0 Pg CO_2 in 2010 to 8.0 Pg CO_2 in 2050, an increase of approximately 0.7% per year. The business-as-usual emissions trend is shown by the black markers in panel (a) of **Figure 1**.

3. Policy Simulations

The energy system response to applied CO_2 targets can be modeled in a number of different ways. Typically, modelers working within the intellectual framework of constrained dynamic optimization have preferred to specify a constraint on cumulative emissions over a predetermined period of time, or similarly, a constraint on the ultimate atmospheric CO_2 concentration.[1] In either case, the imposition of a single aggregate constraint, as opposed to an ordered set of annual constraints, allows the model to endogenously solve for the economically efficient (least-cost) time path of abatement, thus providing a trajectory of annual targets that can be used to further develop concrete policy recommendations. However, to the extent that annual targets have already been codified in legislative or regulatory language, this approach essentially assumes full when-flexibility during compliance (i.e. unlimited banking and borrowing by regulated entities), an assumption whose importance will be analyzed in greater detail below.

To make this problem as concrete and as simple as possible, we begin by imposing a cumulative emissions target equal to the sum of annual targets (between 2012-2050) specified in the Lieberman-Warner Climate Security Act, a bill that was

[1] If CO_2 were a perfect stock pollutant, so that the total atmospheric stock equalled the sum of prior annual inflows, a cumulative emissions constraint would be identical to a concentration stabilization constraint. In fact, CO_2 is gradually removed from the atmosphere by natural ocean and land processes (see, e.g., *Mignone et al., 2008*), meaning that the annual *net* inflow (and resulting atmospheric stock) is determined by a more complex balance between sources and sinks. Nevertheless, the basic qualitative insight that the underlying environmental objective depends strongly on the cumulative emissions release, and less so on the details of the trajectory, remains valid for the scenarios considered in this study.

considered on the floor of the US Senate in June 2008.[2] The model-derived optimal time path of emissions abatement under "core technology" assumptions (that is, assuming both abatement technologies are available for deployment from the start of the simulation) is shown by the dark blue markers in panel (a) of **Figure 1**. It is worth noting that the emissions constraint is sufficiently stringent to require an immediate reversal in emissions growth, at least when technology to enable these reductions is assumed to be readily available from the start.

We next apply the same cumulative emissions constraint to a world in which the introduction of low-carbon technology is delayed by 10 years (i.e. until after 2020). The adjusted optimal emissions path is shown by the green markers in panel (a) of **Figure 1**. Not surprisingly, the emissions reductions in this case are delayed with respect to the core technology case, with less stringent reductions in early years and more stringent reductions in later years. The shift in abatement toward later compliance periods in the delayed technology case is most apparent in panel (b) of **Figure 1**, which shows the difference in annual emissions relative to the core technology case. The difference is positive for approximately the first half of the simulation and negative for the remainder. By design, the integral of this difference over the entire simulation must be equal to zero in order to satisfy the cumulative emissions constraint, which is identical in the core and delayed technology policy cases.

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[2] We take the numerical targets from S. 3036, the Boxer substitute to the Committee-reported version of the Lieberman-Warner bill (S. 2191). Full text of these bills is available at http://www.thomas.gov. In this study, we make the additional assumption that emissions from covered sources are equivalent to energy-related CO_2 emissions, allowing us to apply the targets verbatim. For more detailed economic analyses of this legislation, see the reports by the US Environmental Protection Agency (available at http://www.epa.gov) and the US Energy Information Administration (available at http://www.eia.doe.gov).

If low-carbon technology is assumed to be widely available during the development of a regulatory program, then policymakers will tend to codify the optimal path from the core technology policy case into binding annual targets (blue markers in **Figure 1**). If low-carbon technology later turns out to be less widely available than anticipated, then the optimal response to such technological scarcity (green markers in **Figure 1**) can only be realized if regulated entities are allowed to borrow permits from future periods. As discussed above, implementing such provisions in the context of a real cap-and-trade system is fraught with difficulty, because borrowing enhances the risk of future default and jeopardizes the viability of the underlying program.

To address these issues, we have examined two additional policy cases – a safety valve case and a no-borrowing case – intended to simulate possible real-world responses to the default risk problem. The addition of a safety valve essentially institutionalizes a limited amount of default by releasing regulated entities from the obligation to repay borrowed permits. On the other hand, the elimination of borrowing is a rather blunt response to the default risk problem that eliminates the risks associated with a particular mechanism by eliminating the mechanism itself. In effect, these two policy cases represent two extreme responses to the default risk problem, with the first sanctioning some amount of future default and the latter adopting a draconian precautionary approach toward default risk.

Both of these additional cases are variations on the delayed technology policy case considered above, in the sense that both assume that the entry of low-carbon technology is delayed by 10 years. The first is modeled by applying the annual targets derived from the core technology policy case together with a safety valve that caps permit prices in each year at the corresponding value from the core technology case. This particular setup reflects the assumption in this paper that the purpose of a safety valve is to align actual prices with expected prices during the initial phases of a new regulatory program.[3] Ultimately, a safety valve enhances compliance flexibility by allowing emissions targets to be exceeded in the early years when technology is more scarce than initially anticipated, but it does so without requiring such "borrowed" emissions to be paid back in later periods, thus favoring compliance flexibility at the expense of environmental integrity.

The second additional policy scenario – the no-borrowing case – is essentially the mirror image of the safety valve case, in the sense that it represents an extreme attachment to (annual) environmental goals at the expense of compliance flexibility. This scenario is modeled by applying the annual targets derived from the core technology policy case together with an additional constraint that the cumulative bank of stored permits must never drop below zero. Under this condition, emissions in a given year may only rise above the prescribed annual target when regulated entities are drawing down an existing accumulated bank of allowances resulting from overcompliance in an earlier period.

The simulated emissions trajectories for the two additional policy cases are shown by the red and light blue markers, respectively, in panel (a) of **Figure 1**, and the annual differences from the core technology policy case are shown in panel (b) of

[3] Of course, other assumptions about the purpose of a safety valve are possible. While the US policy discussion has often focused on the threat posed by near-term technological scarcity, a safety valve could also be used to protect against other contingencies, like shorter-term volatility unrelated to technology (e.g. swings in emissions driven by the business cycle) or the possibility that long-run mitigation costs are simply higher, on average, than policymakers anticipate or would be willing to pay. Note that the former problem can be addressed through other forms of compliance flexibility, like borrowing, while the latter cannot. Some will argue that this versatility provides an additional reason to consider the safety valve over alternative flexibility mechanisms, while others will view a long-term mismatch between expected and actual prices as reason to revisit the underlying details of the program, including the strategic targets.

Figure 1. Emissions from the safety valve case roughly track emissions of the delayed technology policy case (green markers) during the 10-year period when low-carbon technology is scarce, but significantly exceed emissions from the delayed technology case in later years. In effect, because payback is not required, the reductions do not steepen sufficiently in later years to make up the early overages, meaning that the cumulative emissions in the safety valve case significantly exceed the cumulative emissions associated with the applied targets, when integrated over the entire 40-year window. The magnitude of this difference (~20 Pg CO_2) is equal to the area under the red markers in panel (b) of **Figure 1**.

Finally, under the no-borrowing case, regulated entities slightly overcomply (i.e. bank permits) in the very earliest periods and then draw down this bank in the periods immediately following, as shown by the light blue markers in panels (a) and (b) of **Figure 1**. While the difference in any given year between the applied targets and the actual emissions is relatively small (to first order, the emissions simply track the emissions in the core technology policy case), it is worth exploring this deviation, because banking (overcompliance) is counterintuitive in a scenario in which the targets are extremely strict. The result is actually considerably less perplexing when one examines the simulated allowance prices for these scenarios, which we consider next.

Panel (c) of **Figure 1** shows the simulated allowance prices for the four scenarios described above. In the core technology case, the allowance price begins at ~$23 per ton CO_2 in 2011 and rises at the interest rate (~6%) to almost $200 per ton in 2050. It is worth noting that, even though advanced technology is deployed immediately, the initial carbon price is lower than the assumed technology crossover price ($50 per ton CO_2), because the price of a permit in any given year represents the opportunity cost associated with a marginal unit of emissions. When the climate constraint is applied as an upper bound on the allowable cumulative emissions, the opportunity cost of a unit of emissions in the first period is the discounted value of an additional unit of abatement in a future period, which must always be less than the instantaneous value ($50 in this case) (*Mignone, 2008*).

When low-carbon technology is initially scarce, the optimal transition path shifts abatement toward later periods. Again, because the price of a permit in the first year represents the opportunity cost of an additional unit of future abatement, the price in the first year must reflect the discounted value of this future action. That price is the sum of the technological crossover price and the additional adjustment cost associated with the more rapid decline of emissions (and energy capital) in later years. In other words, the allowance price path in the delayed technology policy case sits above the allowance price path for the core scenario (starting in the former at about $35 per ton CO_2) because there is a premium associated with the steeper reductions mandated by the early deferral of abatement.

Having considered the full-flexibility cases, it is worth examining the simulated allowance price trajectories in the remaining two policy scenarios. The price path under the safety valve case is reasonably intuitive. Because the applied price ceiling reflects the prices required to generate the prescribed abatement path when low-carbon technology is widely available, it underestimates the prices required to support the same level of abatement when technology is more limited. For this reason, the safety valve binds in each period, and the allowance prices remain pegged to the values associated with the safety valve.

In the no-borrowing case, the prices start very high (at ~$100 per ton CO_2) but fall dramatically in later periods to values consistent with the core technology case. The very high initial prices result from the fact that borrowing is prohibited at a time when technology is extremely scarce, meaning that the required abatement must come from demand destruction. However, this does not explain the observed banking in early periods. Indeed, the apparent overcompliance seems to suggest that the same targets could be met at lower carbon prices, and thus lower overall economic cost. However, this conclusion neglects the full extent of the prohibition on borrowing. While lower prices would be consistent with the targets in the very earliest periods, it would drive up emissions in the periods immediately following, leading to cumulative emissions overages that would exceed the earlier amount banked, thus violating the no-borrowing constraint. In other words, prices lower than those observed would not generate a bank sufficiently large to cover the overages that immediately follow.

Finally, changes in economic output for each of the scenarios are shown in panel (d) of **Figure 1**. In the core technology case and in the safety valve case, the relative loss of GDP relative to business-as-usual increases over the simulation to a maximum of about 1.5% annually. In the delayed technology case, economic losses peak at ~2% at the end of the 10-year period in which technology is constrained (i.e. in 2020), while in the no-borrowing case, the economic losses reach a maximum of ~3% over that period. The difference between these latter two scenarios – that is, between the optimal borrowing case (green markers) and the no-borrowing case (light blue markers) – provides one measure of the economic benefit of compliance flexibility.

Because the availability of low-carbon technology is so uncertain, **Figure 2** shows the sensitivity of the environmental and economic results to assumptions about the time at which low-carbon technology enters the market, with the point of entry varying between 2010 (i.e. technology available immediately) and 2030 (i.e. 20 year delay before technology is available). Each point in these figures represents an aggregate result from a separate model simulation. Panels (a) and (b) of **Figure 2** show the (undiscounted) cumulative GDP loss, relative to the core technology optimum for the 2010-2030 and 2010-2050 periods, respectively. A quick inspection of these figures reveals that, while the magnitude of the economic loss increases with the number of years until low-carbon technology is introduced, the relative ranking of the different policies is robust to such assumptions and to the period over which costs are integrated. As one might expect, the no-borrowing scenarios are always the most expensive, the safety valve scenarios are always the least expensive and the optimal borrowing scenarios are always less expensive than the former but more expensive than the latter.

Panels (c) and (d) of **Figure 2** show the cumulative emissions overages, relative to the core technology optimum, for the 2010-2030 and 2010-2050 periods, respectively. Over the near-term (2010-2030), the overages in panel (c) vary inversely with the costs in panel (a), in the sense that the scenarios with the greatest near-term emissions overages (safety valve scenarios) are the ones achieved at least cost, while the scenarios with the lowest near-term emissions overages (no-borrowing scenarios) are the ones achieved at greatest cost. Again, as one might expect, the scenarios with near-term emissions overages in between the other two (the optimal borrowing scenarios) achieve costs that also fall in between the other two sets of scenarios.

We find similar results in panel (d), with one critical difference, namely that the emissions overages associated with the optimal borrowing scenarios are eliminated when the period of integration is extended to 2050. Thus, in comparing panels (d) and (b), we find the same inverse relationship between costs and emissions in the safety valve and no-borrowing scenarios, but an interesting and important asymmetry in the optimal borrowing scenarios. By design, the cumulative emissions releases are always identical to the no-borrowing emissions releases (which, in turn, are equal to the release from the core technology optimal case) but the costs of the optimal borrowing scenarios are significantly lower than the no-borrowing scenarios because of the added flexibility in the former. To the extent that the long-term (as opposed to near-term) cumulative emissions release is a more relevant measure of the benefit of the policy (so that the benefit is the same in each case), the difference in cost provides a measure of the efficiency gain (in dollar terms) associated with realizing the optimal time path of abatement.

4. Conclusions

Ultimately, decisions about the design of a greenhouse gas regulatory program will hinge on judgments about the proper tradeoff between environmental integrity and economic certainty in the climate policy context, together with additional judgments about the practical and political viability of the instruments designed to achieve such a balance. This paper primarily sheds light on the first of these two questions. In particular, the simulations discussed here suggest that if the true objective of climate policy is to achieve a particular cumulative amount of emissions abatement at least cost, then a policy instrument that allows regulated entities to endogenously shift their compliance obligation across time significantly outperforms instruments in which such compliance flexibility is constrained or imperfect. Our results therefore provide some measure of the environmental and economic benefit of realizing compliance flexibility.

The four simulations discussed in this study are summarized compactly in **Table 1**. A close inspection of these results suggests that when regulated entities are allowed to shift abatement across time in response to actual technological circumstances, the cumulative environmental goals of the program can be preserved with only modest increases in the overall economic cost (compare the core technology and delayed technology cases). However, if regulated entities must instead achieve strict annual goals in the face of severe technological scarcity, then the costs of the program rise dramatically to satisfy the very difficult early targets, while the added benefit is negligible given that the cumulative target remains unchanged relative to the delayed technology optimum. Finally, if a safety valve is applied in lieu of borrowing, then actual costs track expected costs over the duration of the simulation, but the cumulative environmental target is exceeded by an amount that is likely to jeopardize the political coalition around targets and potentially the environmental benefit itself.

The magnitude of the efficiency gain associated with optimal borrowing (and more generally, the differences between scenarios) varies with assumptions about the availability of low-carbon technology. However, the existence of such a benefit is robust to the technology assumptions, and on a relative basis, the gain is always significant, with a reduction in total (cumulative cost) of perhaps 40% relative to the no-borrowing case. This finding suggests that there are real economic gains to adopting policies that provide mechanisms to achieve flexibility in the timing of abatement.

Given the magnitude of this potential efficiency gain, the second question about feasibility is obviously paramount. For reasons discussed at greater length earlier, borrowing is difficult to implement because it exposes the trading system to significant default risk. Some recent analyses have suggested ways to mitigate default risk by incorporating specific features of the safety valve (i.e. price triggers) into mechanisms that would preserve the cumulative environmental integrity of the system. One such example is a "reserve auction" that would inject a limited number of permits "borrowed" from future compliance periods into earlier periods, as a supplement to the primary permit distribution mechanism (*Murray et al., 2008*). Future work will need to further evaluate such mechanisms to determine whether borrowing can in fact be implemented in ways that enable regulated entities (and thus consumers) to realize the efficiency benefits associated with compliance flexibility, and if so, to determine which of these mechanisms would be optimal in the context of a real regulatory program.

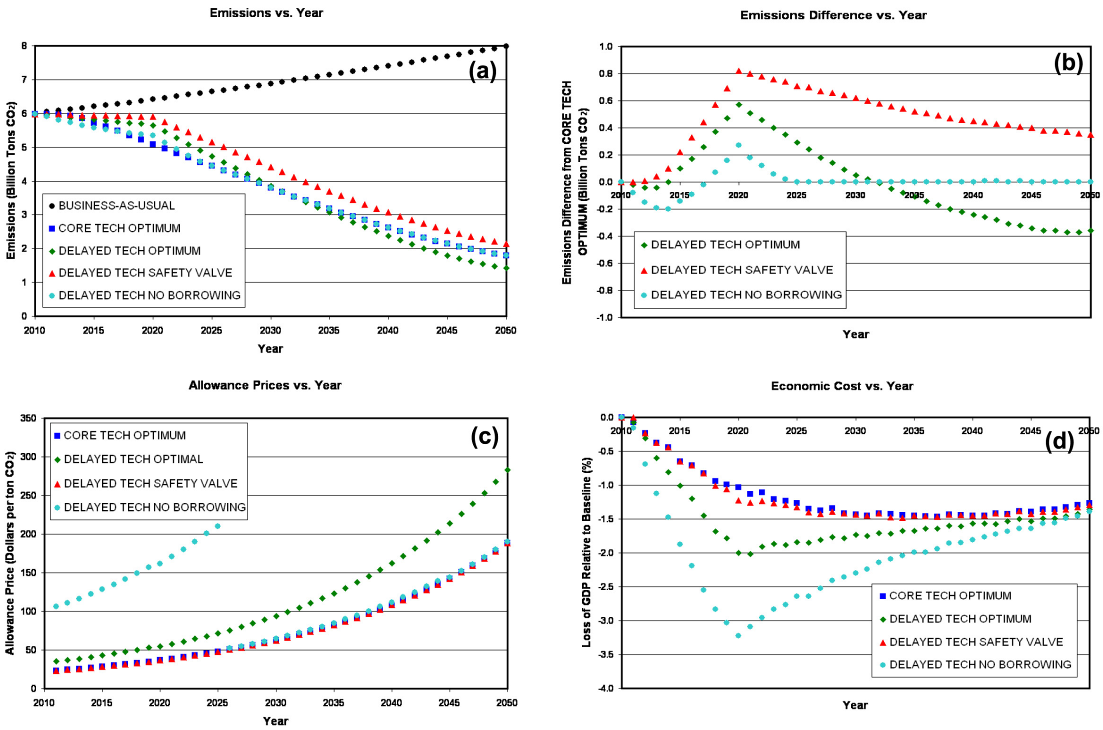

Figure 1

Environmental and economic diagnostics for the four simulations discussed in the text. Panel (a) shows CO_2 emissions as a function of time, and panel (b) shows differences in annual emissions from the core technology policy case as a function of time, with positive values representing undercompliance and negative values representing overcompliance with respect to the core technology policy case. Panel (c) shows simulated allowance prices as a function of time, and panel (d) shows economic losses as a function of time, calculated as the relative GDP difference between each policy scenario and the business-as-usual path.

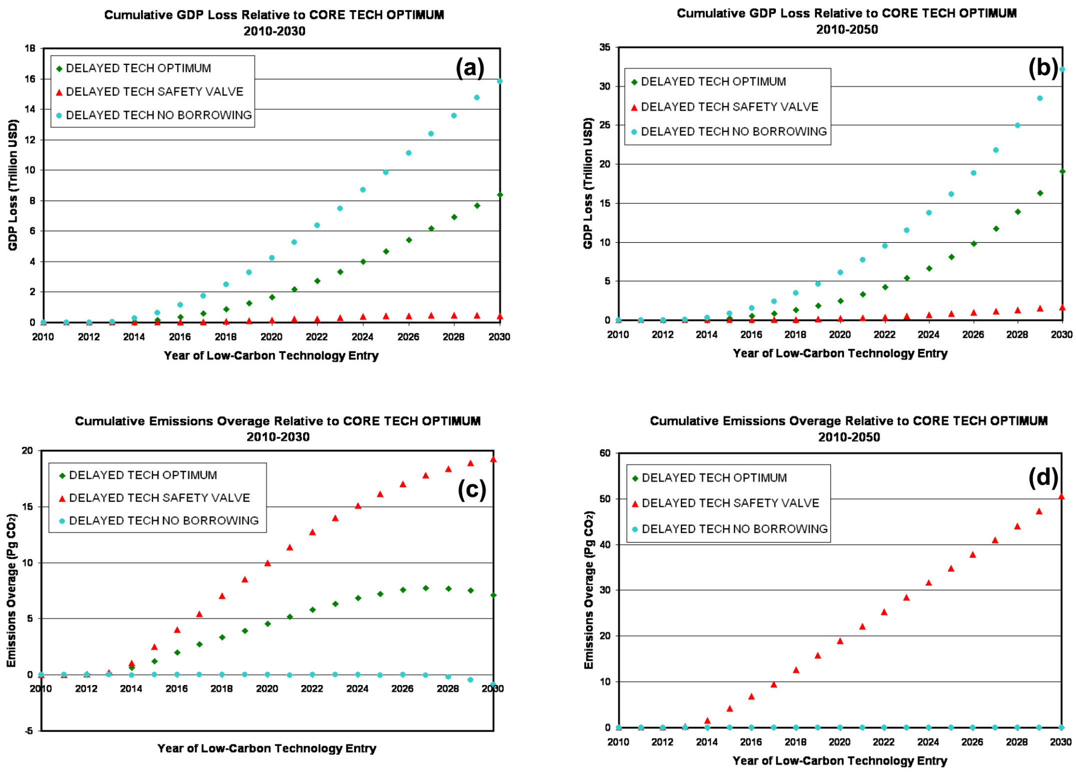

Figure 2

Environmental and economic diagnostics for a series of simulations examining the sensitivity to the technology assumptions in the model. Panel (a) shows the cumulative (undiscounted) GDP loss (relative to the core technology optimum case) between 2010-2030 as a function of the year in which low-carbon technology is first assumed to be available, while panel (b) shows the same results integrated over the 2010-2050 period. Panel (c) shows the cumulative CO_2 emissions overage (relative to the core technology case) between 2010-2030 as a function of the technology entry date, while panel (d) shows the same results integrated over the 2010-2050 period.

SCEN	TECH AVAIL.	EMISSIONS CONSTRAINT	INITIAL PRICE ($/ton CO_2)	EMISSIONS REDUCTION FROM BAU (Pg CO_2)		GDP REDUCTION FROM BAU (Trillion USD)	
				2010-2030	2010-2050	2010-2030	2010-2050
CORE	**Full set**	**Optimal path to cumulative LW Target**	**23**	**29**	**125**	**3.2**	**10.3**
DELAY	**Entry delayed by 10 yrs**	**Optimal path to cumulative LW target**	**35**	**24**	**125**	**4.8**	**12.8**
SAFETY VALVE	**Entry delayed by 10 yrs**	**Annual targets from CORE; Full Banking; SV with prices from CORE**	**23**	**19**	**106**	**3.3**	**10.5**
NO BORROW	**Entry delayed by 10 yrs**	**Annual targes from CORE; Full Banking; No Borrowing**	**106**	**29**	**125**	**7.4**	**16.4**

Table 1

Summary of the four simulations discussed in the text. Both the emissions and GDP metrics are reported as absolute differences from the business-as-usual scenario, integrated over the time horizon indicated. The GDP numbers are reported as undiscounted sums.

References

Aldy J E, Barrett S, Stavins R N. Thirteen plus one: A comparison of global climate policy architectures. Climate Policy 2003; 3; 373-397.

EIA. Annual Energy Outlook 2008. Energy Information Administration, Washington, D.C. Available at http://www.eia.doe.gov.

IPCC. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (Eds: Core Writing Team, Pachauri, R K and Reisinger, A). Geneva, Switzerland, 104 pp.

Jacoby H D, Ellerman A D. The safety valve and climate policy. Energy Policy 2004; 32; 481-491.

Manne A, Mendelsohn R, Richels R. A model for evaluating regional and global effects of GHG reduction policies. Energy Policy 1995; 23; 17-34.

McKibbin W J, Wilcoxen, P J. Estimates of the costs of Kyoto: Marrakesh versus the McKibbin-Wilcoxen blueprint. Energy Policy 2004; 32; 467-479.

McKibbin W J, Wilcoxen P J. Building on Kyoto: Towards a realistic global climate agreement. Brookings Energy Security Policy Brief 08-01, October 2008.

Mignone B K, Socolow R H, Sarmiento J L, Oppenheimer M. Atmospheric stabilization and the timing of carbon mitigation. Climatic Change 2008; 88; 251-265.

Mignone B K. Prices in emissions permit markets: The role of investor foresight and capital durability. Centre for Applied Macroeconomic Analysis Working Paper 31/2008. The Australian National University. Available at http://cama.anu.edu.au.

Murray B C, Newell R G, Pizer W A. Balancing cost and emissions certainty: An allowance reserve for cap-and-trade. Nicholas Institute Working Paper 08-03, Duke University. Available at http://www.nicholas.duke.edu.

Newell R G and Pizer W A. Regulating stock externalities under uncertainty. Journal of Environmental Economics and Management 2002; 45; 416-432.

O'Neill B C, Oppenheimer M. Dangerous climate impacts and the Kyoto Protocol. Science 2002; 296; 1971-1972.

Pizer W. Combining price and quantity certainty controls to mitigate global climate change. Journal of Public Economics 2002; 85; 409-434.

Roberts, M J, Spence M. Effluent charges and licenses under uncertainty. Journal of Public Economics 1976; 5; 193-208.

UNFCCC. United Nations Framework Convention on Climate Change 1992. Text available at http://unfccc.int.

WRI. Comparison of Legislative Climate Change Targets, September 9, 2008. World Resources Institute, Washington, D.C. Text available at http://www.wri.org.