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The Impact of Learning-By-Doing on the Timing and Costs of CO_2 Abatement

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Executive Summary

A particular ceiling on atmospheric CO_2 concentrations can be maintained through a variety of emission pathways. Over the past decade, there has been considerable debate over the characteristics of a least-cost pathway. Some have suggested that a gradual departure from the emissions baseline will be the most cost-effective because it reduces the pressure for premature retirement of the existing capital stock, and it provides valuable time to develop low-cost, low-carbon emitting substitutes. Others counter that a major flaw in analyses that support this line of reasoning is that they ignore learning-by-doing (LBD).

In this paper, we examine the impact of LBD on the timing and costs of emissions abatement. With regard to timing, we find that including learning-by-doing does *not* significantly alter the conclusions of previous studies that treated technology cost as exogenous. The analysis supports the earlier conclusion that for a wide range of stabilization ceilings, a gradual transition away from the "no policy" emissions baseline is preferable to one that requires substantial near-term reductions. We find that the major impact of including learning-by-doing is on the costs of emission abatement. Depending upon the sensitivity of costs to cumulative experience, LBD can substantially reduce the overall costs of emissions abatement.

The Impact of Learning-By-Doing on the Timing and Costs of CO_2 Abatement

Alan S. Manne and Richard G. Richels

I. Introduction

The issue of learning-by-doing (LBD) has become an integral part of the climate debate. LBD is the process by which the costs of new technologies decline as a function of cumulative experience. Although a number of studies have addressed the potential role of learning-by-doing in the context of climate policy, the effect of LBD on the timing and costs of emissions abatement remains unclear.[1–8] The objective of the current paper is to help clarify the role of LBD as it relates to the choice of emissions abatement strategy.

The ultimate goal of the UN Framework Convention on Climate Change (UNFCCC) is “the stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.”[9] Although what constitutes “dangerous” has yet to be determined, for most concentration ceilings there is likely to be flexibility in terms of the emissions pathway for achieving stabilization. This is because future CO_2 concentrations are determined more by cumulative emissions rather than year-by-year emissions.[10]

Although little attention is placed on abatement costs in the selection of a concentration ceiling, cost-effectiveness does come into play in determining how to meet a prescribed target. In particular, the UNFCCC states that “… policies and measures to deal with climate change should be cost-effective so as to insure global benefits at the lowest possible cost” (ref. 9). Hence, once a concentration ceiling has been chosen, the issue then becomes one of how to stay beneath the ceiling in a cost-effective manner.

Some have suggested that the least-cost emissions pathway is one that departs only gradually from the emissions baseline.[11] A gradual departure avoids premature obsolescence of the existing capital stock, and it provides more time to develop low-cost low-carbon emitting substitutes. These analyses are based on models that typically treat the decline in technology costs as a function of time, ignoring the potential contribution of learning-by-doing.

The exclusion of LBD has led others to question the conclusions of such models.[12] They argue that an effective way to reduce abatement costs is to accelerate learning-by-doing. This can be accomplished through mandating a sharp near-term departure from the emissions baseline. This would raise the price of energy from existing carbon-intensive technologies. Currently uneconomical technologies would then become attractive. As their costs drop, so would the overall costs of emissions abatement.

Still others suggest that learning-by-doing has an ambiguous impact on the timing of emissions abatement (refs. 2 and 5). LBD reduces the costs of future abatement. This suggests delaying abatement activities. However, there is added value to current abatement. It contributes to cumulative experience and hence helps reduce the costs of future abatement. It is unclear which of these two effects dominates.

In evaluating the desirability of one emissions pathway over another, we need to consider both the near-term costs to the economy and also the benefits of having low-cost substitutes earlier than might otherwise be the case. The near-term costs will be determined, in large part, by the inertia in the energy system. Much of the existing capital stock is long lived (buildings, power plants, and motor vehicles). This places constraints on the rate at which new technologies can be introduced. The switch to a less carbon-intensive economy cannot happen overnight. Tight near-term constraints can accelerate the process, but at a cost. Whether these near-term costs are warranted will depend upon how the costs of low-emitting substitutes respond to learning-by-doing.

Before turning to the analysis, some caveats are in order. First, the present paper focuses exclusively on learning-by-doing. Another important channel for inducing technical change is R&D. Because knowledge is not fully appropriable, private markets probably underinvest in R&D. For a discussion of the role of R&D in providing low-cost substitutes to high-carbon emitting technologies, see refs. 2, 5, 13–15. For a general overview of the issue of induced technical change, see ref. 16.

Second, the focus of the current work is on the timing and the costs of emissions abatement required in order to meet a given concentrations target. We do not address the issue of how the potential impacts attributed to climate change might be affected by choosing one emission pathway over another when complying with a prescribed concentration ceiling. Previous work has suggested that the differences in terms of temperature increase and sea level rise may be small (ref. 11). Nevertheless, analysis to date has been rudimentary, and further work is required. To the extent that the choice of emissions pathways differs in terms of its impacts on climate change, these differences need to be considered.

Finally, consistent with UNFCCC, we have assumed that once a concentration ceiling is adopted, the goal is to achieve it in a cost-effective manner. If we were conducting a cost-benefit rather than a cost-effectiveness analysis, the reduction in abatement costs brought about by learning-by-doing would lead to more abatement in the future relative to that which might take place in the absence of LBD (ref. 5).

II. The Model[d]

In this section, we provide a brief overview of MERGE (a model for evaluating regional and global effects of greenhouse gas reductions). MERGE is an intertemporal general equilibrium model of the global economy, which incorporates perfect foresight. Although we will focus on global results, the underlying model is based on a world divided into nine geopolitical regions: 1) the USA, 2) OECDE (Western Europe), 3) Japan, 4) CANZ (Canada, Australia and New Zealand), 5) EEFSU (Eastern Europe and the Former Soviet Union), 6) China, 7) India, 8) MOPEC (Mexico and OPEC) and, 9) ROW (the rest of the world). MERGE is calibrated to the year 2000. Future periods are modeled in 10-year intervals. Hence, the Kyoto Protocol's first commitment period (2008-2012) is represented as 2010.[17] Economic values are reported in US dollars of constant 1997 purchasing power.

MERGE provides a bottom-up perspective of the energy supply system. A distinction is made between electric and nonelectric energy. Table 1 identifies the alternative sources of electricity supply. The first five technologies represent sources in operation during the base year, 2000. The second group of technologies includes candidates for serving electricity needs in 2010 and beyond.

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[d] For a detailed description of MERGE and its key assumption, see our website: http://www.stanford.edu/group/MERGE/.

TABLE 1. ELECTRICITY GENERATION TECHNOLOGIES AVAILABLE TO U.S. [a]

Technology name	Identification/ Examples	Earliest possible introduction date	Costs in 2000 [b] (Mills/kWh)	Potential cost reduction due to learning by doing (Mills/kWh)	Carbon emission coefficients (Billion tons per TWH)
HYDRO	Hydroelectric and geothermal	Existing	40.0		0.0000
NUC	Remaining initial nuclear	Existing	50.0		0.0000
GAS-R	Remaining initial gas fired	Existing	35.7		0.1443
OIL-R	Remaining initial oil fired	Existing	37.8		0.2094
COAL-R	Remaining initial coal fired	Existing	20.3		0.2533
GAS-N	Advanced combined cycle	2010	30.3		0.0935
GAS-A	Fuel cells with capture and sequestration–gas fuel	2030	47.7		0.0000
COAL-N	Pulverized coal without CO_2 recovery	2010	40.6		0.1955
COAL-A	Fuel cells with capture and sequestration–coal fuel	2040	55.9		0.0068
IGCC	Integrated gasification and combined cycle with capture and sequestration–coal fuel	2020 [c]	62.0		0.0240
ADV-HC	Carbon-free technologies; costs do not decline with learning by doing	2010	95.0		0.0000
LBDE-HC [d]	Carbon-free technologies; costs decline with learning by doing (high cost)	2010	95.0	40.0	0.0000
LBDE-LC [d]	Carbon-free technologies; costs decline with learning by doing (low cost)	2010	95.0	60.0	0.0000

[a] Introduction dates and costs may vary by region.

[b] Except for oil and gas costs and the learning by doing component, we assume that the costs of all technologies decline at a rate of 0.5% per year beginning in 2000. Note that this column is used to calculate the autonomous learning component. The earliest possible introduction date is specified in the previous column.

[c] IGCC is currently available; however, without capture and sequestration.

[d] For the LBDE technologies, it is necessary to specify an initial quantity. We assume that the cumulative experience prior to 2000 is only 0.2 tkWh global.

Previous versions of MERGE have included two electric "backstop" technologies: ADV-HC and ADV-LC. These refer to advanced high and low-cost carbon-free electricity generation, respectively. The low-cost variant is not available until well after the high-cost one. Their distinguishing characteristic is that once introduced, they are available at a constant marginal cost. Any of a number of technologies could be included in these categories: wind, solar, advanced nuclear, biomass, coal-based generation with carbon capture and sequestration, and others. Given the enormous disagreement as to which of these technologies or combination of technologies will succeed in terms of economic attractiveness and public acceptability, we refer to them generically rather than attempt to pick specific winners.

In the current version of the model (MERGE 4.5), we continue to refer to these technologies generically, but follow a somewhat different approach. We assume that the decline in the cost of backstops will be a function of cumulative experience.[e] To do this, we have replaced ADV-LC with LBDE (learning-by-doing, electric). Its total costs are initially identical to ADV-HC (95 mills/kWh), but its learning costs decline by 20% for every doubling of cumulative experience.[18] The potential for reducing costs through learning-by-doing; however, is limited. Given the uncertainties, we explore two alternatives. For a pessimistic case (LBDE-HC), we assume that costs can be reduced to 55 mills/kWh through learning-by-doing. For our optimistic case (LBDE-LC), we assume that these costs can be reduced to 35 mills/kWh. In addition, we assume that due to autonomous technical progress, the time-dependent electricity generating costs decline at the rate of 0.5% per year.

Figure 1 illustrates how the LBDE costs might decline in the absence of a carbon constraint. The top two lines are based upon the two alternative assumptions about learning-by-doing. We also show how the costs of COAL-N might change over time in two different regions. Due to coal transportation costs, the costs of coal-fired electricity are higher in OECD Europe (OECDE) than in the US. As a result, OECDE begins investing in LBDE-LC and LBDE-HC, in 2010 and 2030, respectively. Our cost curves reflect the

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[e] See ref. 7 for a description of the approach used in the present study. A heuristic is employed to deal with the problem of isolated, local optima.

assumption that learning-by-doing is based on global diffusion. That is, experience in one region will reduce the costs of a technology in all regions. Notice that those technologies that do not benefit from learning-by-doing, for example COAL-N, still experience some decline in costs due to autonomous technical progress.

Table 2 identifies alternative sources of *non*electric energy within the model. Notice that oil and gas supplies for each region are divided into 10 cost categories. The higher cost groups have been added to reflect the potential use of nonconventional sources. With regard to carbon-free alternatives, the choices have been divided into two broad categories: RNEW (low-cost renewables such as ethanol from biomass) and NEB-HC (high cost backstops such as hydrogen produced through photovoltaics and electrolysis). The key distinction is that RNEW is in limited supply, but NEB-HC is available in unlimited quantities at a constant but considerably higher marginal cost. As in the case of electric energy, we have added a new category of technologies. This is termed LBDN (learning-by-doing, non-electric). As with its counterpart in the electric sector, costs are a function of cumulative experience. In essence, LBDN adds a learning component to NEB-HC. In addition, all nonelectric technologies enjoy autonomous technical progress.

TABLE 2. NONELECTRIC ENERGY SUPPLIES AVAILABLE TO US [a]

Technology name	Description	Cost in 2000 ($/GJ) [b]	Potential cost reduction due to learning by doing ($/GJ)	Carbon emission coefficients (tons of carbon per GJ)
CLDU	Coal—direct uses	2.50		0.0241
OIL-1-10	Oil—10 cost categories	3.00-5.25		0.0199
GAS-1-10	Gas—10 cost categories	2.00-4.25		0.0137
RNEW	Renewables	6.00		0.0000
NEB-HC	Nonelectric backstop	14.00		0.0000
LBDN [c]	Carbon free technologies; costs decline with learning-by-doing	14.00	6.00	0.0000

[a] Costs may vary by region.

[b] Except for the learning by doing component, we assume that the costs of all technologies decline at a rate of 0.5% per year beginning in 2000.

[c] We assume that the cumulative global experience prior to 2000 is only one GJ.

Typically, the energy producing and consuming capital stock is long lived. In MERGE, introduction and decline constraints are placed on *new* technologies. We assume that the production from new technologies in each region is constrained to 1% of total production in the year in which it is initially introduced and can increase by a factor of three for each decade thereafter. The decline rate is limited to 2% per year for new technologies, but there is no decline rate limit for existing technologies. This is to allow for the possibility that some emission ceilings may be sufficiently low to force premature retirement of the existing capital stock.

Turning from the supply to the demand side of the model, we use nested production functions[f] to determine how aggregate economic output depends upon the inputs of capital, labor, electric and non-electric energy. In this way, the model allows for both price-induced and autonomous (non-price) energy conservation and for interfuel substitution. Since there is a “putty-clay” formulation, short-run elasticities are smaller than long-run elasticities. This increases the costs of rapid short-run adjustments. The model also allows for macroeconomic feedbacks. Higher energy and/or environmental costs will lead to fewer resources available for current consumption and for investment in the accumulation of capital stocks.

It is assumed that there can be international trade in emission rights. This allows regions with high marginal abatement costs to purchase emission rights from regions with low marginal abatement costs. There is also trade in oil, gas, and energy-intensive goods. Each of the model’s nine regions maximizes the discounted utility of its consumption subject to an intertemporal budget constraint. Each region’s wealth includes not only capital, labor and exhaustible resources, but also its negotiated international share in global emission rights.

III. The Effect of Learning-By-Doing on Reference Case Emissions

We begin the analysis by examining how CO_2 emissions might grow in the absence of policy intervention. We explore three scenarios. In the first, there is no learning-by-

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[f] These production functions represent an additional opportunity for induced technical change. As the cost of carbon emitting technologies changes, there will be interfuel substitution between electric and nonelectric energy. Similarly, as the price of energy changes, there will be substitution between energy and capital-labor.

doing. The costs of all technologies are specified exogenously. The second and third scenarios incorporate learning-by-doing, but differ in their potential for cumulative experience to lower costs.

Figure 2 illustrates how the inclusion of learning can affect baseline projections of CO_2 emissions over the 21st century. The top line shows the "no LBD" baseline. That is, neither the costs of the ADV-HC nor of NEB-HC decline as a function of cumulative experience. Their costs depend only on the passage of time. The other two trajectories incorporate learning-by-doing. They differ, however, with regard to the potential for cost reductions in the electric sector.[g]

Under the assumptions adopted in the present analysis, learning-by-doing has a negligible effect on the baseline during the first half of this century. However, the effect can be substantial in the second half. In the absence of a carbon constraint, the transition to a low-carbon economy is governed by the exhaustion of conventional oil and gas resources, the relative cost and availability of each technology, and the inertia in the energy system.

With LBDE-LC, the technology's ultimate cost is sufficiently attractive so that there is an incentive to start the learning-by-doing process early. For this case, global emissions peak in the middle of the century and then turn downward - even in the absence of a carbon constraint. Concentrations eventually stabilize in the range of 650 ppmv. Conversely, with LBDE-HC, the relatively high cost provides little incentive for its introduction prior to 2040. As a result, we observe little change from the "no LBD" baseline throughout the time horizon under study.

Figure 3 illustrates the importance of the expansion constraints. Suppose for example, that there is no constraint on the rate at which the LBDE technologies can enter the energy system. In the case of LBDE-LC, the percent of global electricity generation increases. This is a reflection of the technology's ultimate economic attractiveness. Conversely, the expansion constraint has little impact on the rate of introduction of the

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[g] Assumptions regarding LBDN (learning-by-doing, nonelectric) remain the same in both cases. Because of its high initial costs, this technology does not begin to play a significant role, i.e., providing 10% of nonelectric energy supply, until 2070.

LBDE-HC technology. Even after allowing for learning effects, this technology has a high cost, and is unattractive in most regions.

These results highlight the potential importance of learning-by-doing in determining the baseline. If learning-by-doing can lead to technologies that are both low carbon emitters *and* economically competitive, then it can substantially reduce the need for external intervention. Carbon emissions will decline naturally in response to market forces.

IV. The Effect of Learning-By-Doing on Least-Cost Abatement Pathways

We now examine the impact of learning-by-doing on the timing and costs of emission abatement policies. Two types of constraints are explored: those on ultimate concentrations and those on year-by-year emissions. The former is more in the spirit of the UNFCCC. The latter is more nearly consistent with the Kyoto Protocol. It prescribes a constraint on emissions in each commitment period.

We are far from reaching agreement on what might constitute "dangerous anthropogenic interference with the climate system". This will likely be the subject of intense scientific and political debate for some time to come. For illustrative purposes, this section is based on the goal of stabilizing atmospheric CO_2 concentrations at 550 ppmv (SCC-550). We also assume that the criterion is to achieve this concentration target in an economically efficient manner.[h] To do this will require full "where" and "when" flexibility. That is, emissions are reduced both where and when it is economical to do so. This is apart from the issue of who pays the bill. If there is full international trade in emission rights, equity and efficiency issues may be separated.

There are three distinct phases in the transition to a low-carbon energy system. Figure 4 suggests that with full "where" and "when" flexibility, the least-cost abatement trajectory stays very close to the baseline through 2020. This is true both with and without learning-by-doing. Roughly speaking, a concentration ceiling places a limit on the cumulative amount of carbon that can be emitted into the atmosphere. But how do we allocate this carbon budget over time? Not surprisingly, the least-cost emissions pathway involves dependence on

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[h] We stress, however, that to the extent that "command and control" approaches are chosen over "market mechanisms", abatement costs will be higher.

inexpensive high-carbon emitting technologies in the early years, and a gradual shift to lower-carbon emitting technologies in the future once their decline in costs makes them more economically attractive.

In the case of LBDE-LC, future costs are sufficiently low to warrant some early investment even though it is presently uneconomical. However, the inertia in the energy system limits how quickly the LBDE-LC technologies can expand. In the case of LBDE-HC, learning-by-doing in the early years results in a less dramatic reduction in future costs. As a result, there is less inducement for early investment.

In the second phase (2020-2060), incorporating learning-by-doing has what initially appears to be a counter intuitive influence on the least-cost pathway. Figure 5 compares the three emission profiles for stabilizing CO_2 concentrations at 550 ppmv. Although all three cases eventually show a substantial reduction in emissions, note that emissions are lower in phase II in the “no LBD” case. This is because, based upon the assumptions about technology cost and availability, there is no concern about locking into technologies that will soon prove to be economically inferior. With LBD, however, investors are reluctant to commit to low-cost, low-carbon emitting substitutes when even lower-cost, lower-carbon emitting substitutes will soon be available. For example, in the “no LBD” case, COAL-A (e.g., the solid oxide fuel cell) becomes available in 2040 and is the technology of choice. However, when we incorporate learning-by-doing, the LBDE technologies win out even though their costs remain noncompetitive for another decade or so. The final phase (2060-2100) is the time frame in which the LBDE technologies have a clear economic advantage over all other electric technologies.

Although learning-by-doing has little impact on the timing of near-term emission reductions, it has a major impact on costs. Figure 6 shows cumulative discounted global abatement costs for stabilizing concentrations at 550 ppmv, assuming full “where” and “when” flexibility. Compared with no LBD, the LBDE-HC and LBDE-LC scenarios show a reduction in costs by 42 and 72%, respectively. Although learning-by-doing has little impact on the timing of emission reductions during the early decades of the 21st century, it has a major impact on total abatement costs.

V. Some Additional Sensitivity Analysis

The Impact of Learning-By-Doing Under Alternative Concentration Targets. Up to this point, we have assumed that the goal was to stabilize atmospheric CO_2 concentrations at 550 ppmv. Now let us consider alternative concentration targets: 450 and 650 ppmv. Figure 7 compares the least-cost stabilization pathway for these ceilings. With a target of 450 ppmv, we see an immediate departure from the emissions baseline—regardless of the LBD assumption. With such a tight ceiling, it is necessary to introduce major near-term changes in the energy system if we are to stay below the prescribed concentration level. The incremental value of carbon emission rights rises high enough to induce sufficient fuel switching and price-induced conservation to stay on the least-cost trajectory. See Table 3. The implicit tax is roughly an order of magnitude higher than that required for a ceiling of 550 ppmv or above. For a ceiling of 650 ppmv, very little is required in the early decades, hence the implicit tax is negligible.

TABLE 3. INCREMENTAL VALUE OF CARBON EMISSION RIGHTS ($ PER TON OF CARBON) FOR ALTERNATIVE STABILIZATION CEILINGS

	No LBD		LBDE-HC		LBDE-LC	
	2010	2020	2010	2020	2010	2020
450 ppmv	75	134	70	126	72	129
550 ppmv	9	16	7	12	6	11
650 ppmv	2	4	0	2	0	0

Figure 8 shows the implications for discounted abatement costs over the 21st century. As one would expect, the costs are highest with a 450 ppmv target. The benefits from learning-by-doing will come too late to offset these increases in near-term costs.

The Impact of Learning-By-Doing on a Kyoto-Type Target. We now turn to a case closer to that suggested by the Kyoto Protocol. There is not “when” flexibility, nor is there complete “where” flexibility. This scenario is designed to achieve approximately the same level of concentrations in 2100 as SCC-550, but is more aggressive in terms of emission reductions in the early decades of the present century. We refer to this case as “Kyoto plus” (Kyoto+).

Specifically, we assume that all Annex B countries (with the exception of the US) adopt the Protocol during the first commitment period. Further, with an intertemporal general equilibrium model like MERGE, it is necessary to make assumptions about requirements for emission reductions in subsequent commitment periods. Here for illustrative purposes, we assume that Kyoto will be followed by subsequent protocols in which all Annex B countries agree to reduce emissions by an additional 10% per decade starting in 2020. For the US, this constraint in 2020 is assumed to be the same as if it had eventually adopted the Kyoto Protocol. Finally, we assume that all countries adopt binding targets and timetables by 2050. Clearly, the nature and timing of these future constraints are highly speculative, and they need to be subjected to extensive sensitivity analysis. The one adopted here provides an alternative emissions pathway to stabilization at 550 ppmv in 2100.

Figure 9 shows that regardless of the assumption about learning-by-doing, Kyoto+ results in an immediate departure from the baseline. In order to induce sufficient reductions, the incremental value of carbon emission rights must again be an order of magnitude higher than that associated with a 550 ppmv ceiling with complete "where" and "when" flexibility. See Table 4.

TABLE 4. THE INCREMENTAL VALUE OF CARBON EMISSION RIGHTS ($ PER TON OF CARBON) FOR TWO ALTERNATIVE EMISSION PATHWAYS FOR A CEILING OF 550 PPMV

	No LBD		LBDE-HC		LBDE-LC	
	2010	2020	2010	2020	2010	2020
550 ppmv	9	16	7	12	6	11
Kyoto+	99	164	101	168	102	170

Finally Figure 10 compares cumulative discounted abatement costs for SCC-550 and Kyoto+. In all cases, Kyoto+ represents a substantial increase in the overall costs relative to SCC-550.

VI. Concluding Comments

A particular concentration target can be achieved through a variety of emission pathways. Over the past decade, there has been considerable debate over the characteristics of a least-cost pathway. Some have suggested that a gradual departure from the emissions baseline will be the most cost-effective because it avoids premature retirement of the existing capital stock, and it provides valuable time to develop low-cost, low-carbon emitting substitutes. Others counter that a major flaw in this line of reasoning is that it ignores learning-by-doing. In this paper, we examine the impact of LBD on the timing and costs of emissions abatement.

We find that including learning-by-doing does *not* alter the conclusions of earlier studies that focused on the timing of emission reductions. For ceilings of 550 ppmv and above, a gradual near-term departure from the emissions baseline is still preferred. For concentration targets in the neighborhood of 450 ppmv, a more rapid near-term departure is still required—with or without LBD.

Although learning-by-doing may not accelerate the timing of the transition to a less carbon intensive infrastructure, it can have a major impact on the overall costs of the transition. This is particularly so for concentration ceilings of 550 ppmv and above. Cumulative discounted abatement costs are substantially lower relative to the "no LBD" case. However, for a 450 ppmv ceiling, most of the costs are associated with premature retirement of the existing capital stock. LBD can do little to reduce these costs.

We emphasize that a gradual departure from the baseline is not a "do nothing" or "wait and see" strategy. The emissions baseline incorporates considerable technical progress on both the supply and demand sides of the energy sector. We also assume that to the extent that there are "no regrets" options, they will be incorporated in both the reference case and the policy case. For example, we do not need climate policy to take advantage of efficiency improvements that make sense in their own right.

Finally, although emissions abatement represents immediate action, the choices are not confined to emissions abatement. The response to the threat of climate change suggests a portfolio of responses. These include: 1) emissions abatement, 2) adaptation, 3) reducing scientific uncertainty, and 4) the development and deployment of low-cost substitutes. The issue is not one of "either-or", but what constitutes the right balance. This paper examines the interaction between two of the options in the portfolio: emissions abatement, and technology development and deployment, and it examines their relative contributions over time.

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Figure 1. Electricity Generating Costs for Three Technologies in the Absence of a Carbon Constraint

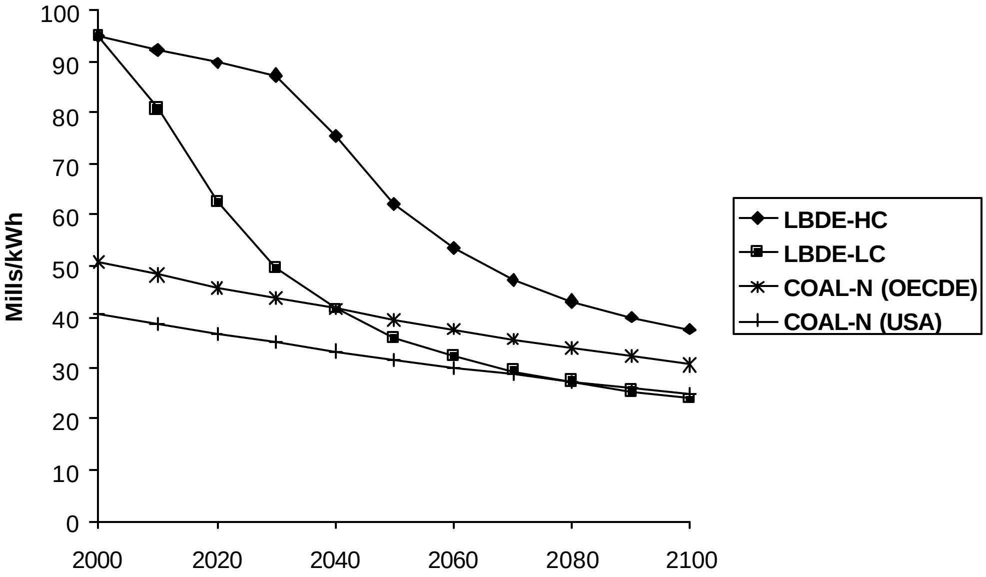


Figure 2. Global Carbon Emissions – no carbon constraints

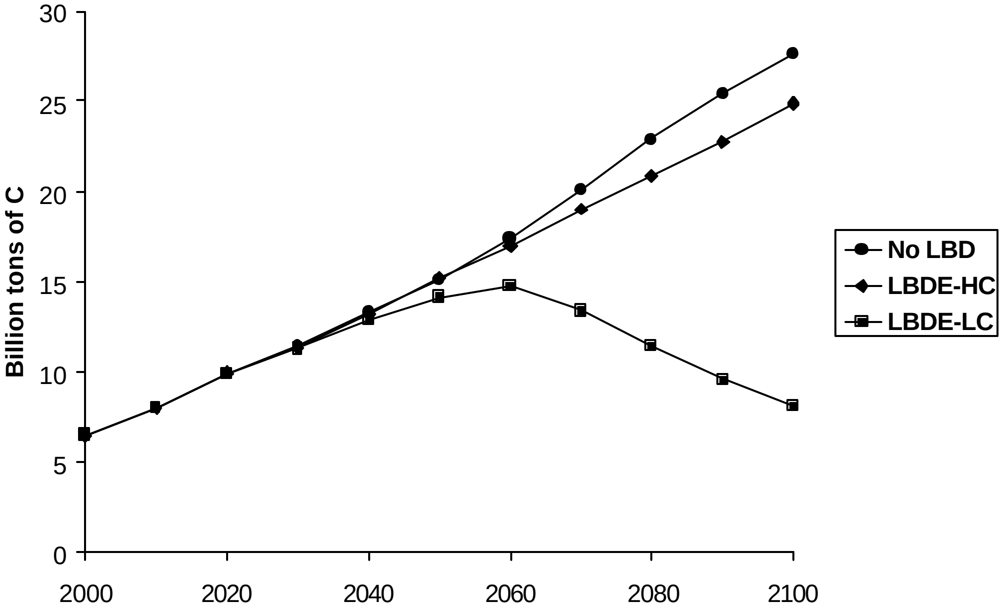


Figure 3. Percent of Global Electricity Generation Supplied by LBDE – no carbon constraints

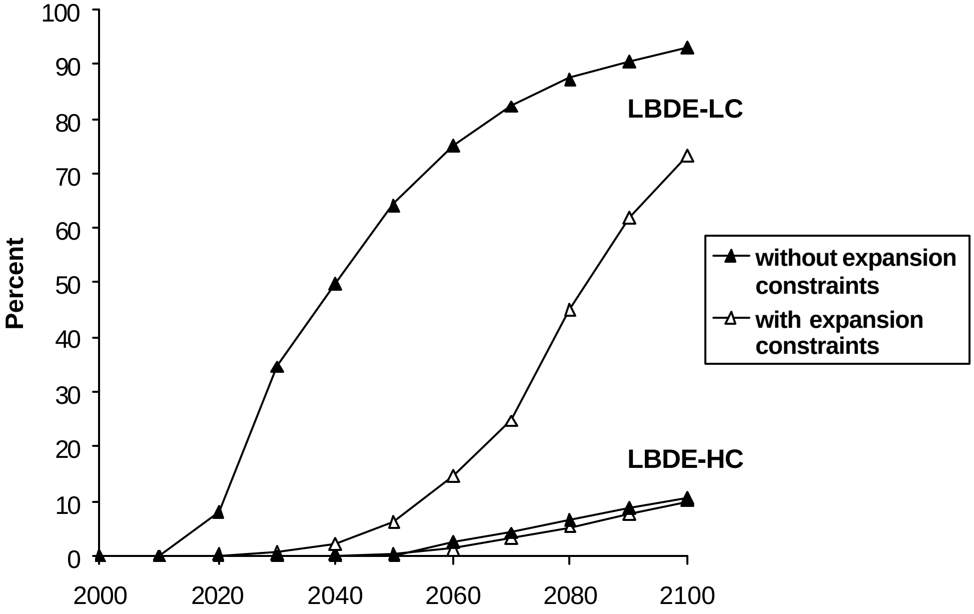


Figure 4. Global Emission Reductions Required to Stabilize Concentrations at 550 ppmv

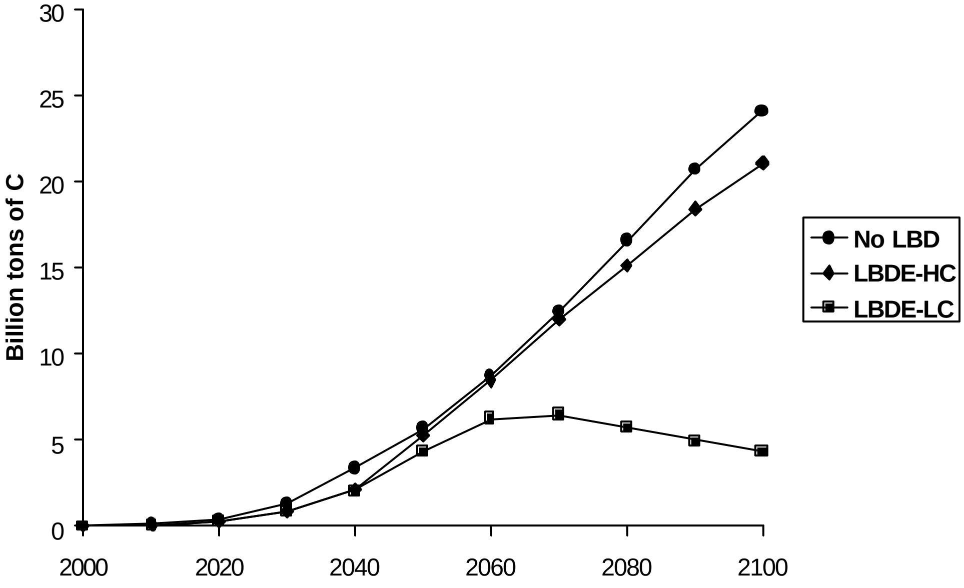


Figure 5. **Global Carbon Emissions – SCC-550**

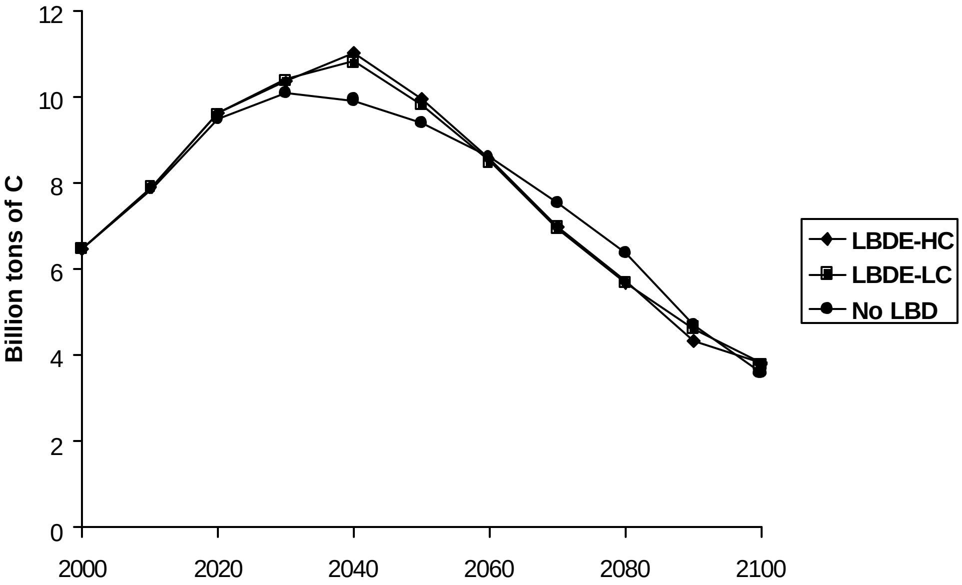


Figure 6. **Cumulative Discounted Global Abatement Costs for Stabilizing Concentrations at 550 ppmv (discounted at 5% from 2000-2100)**

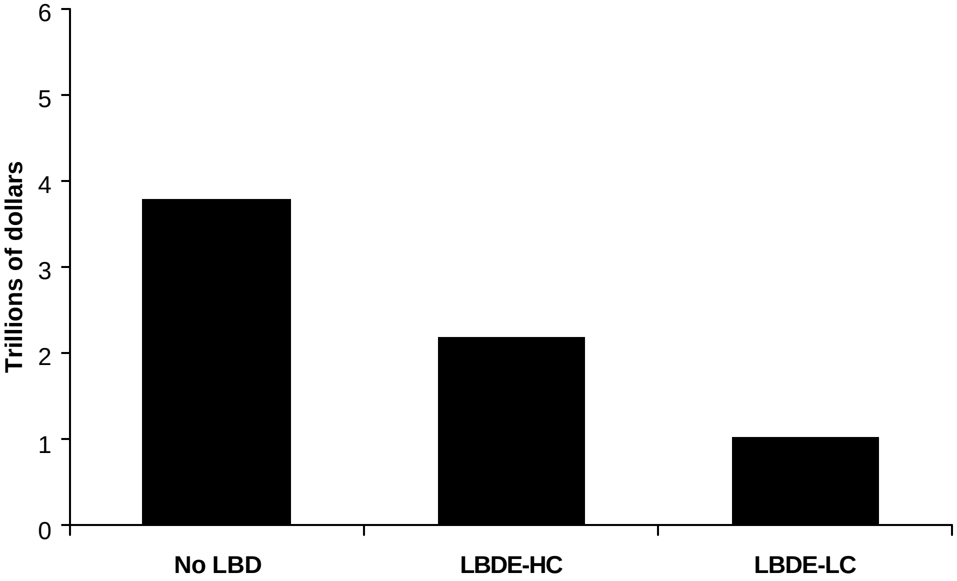
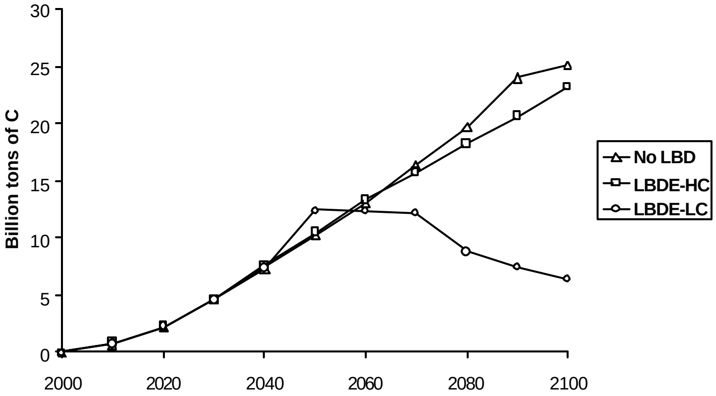
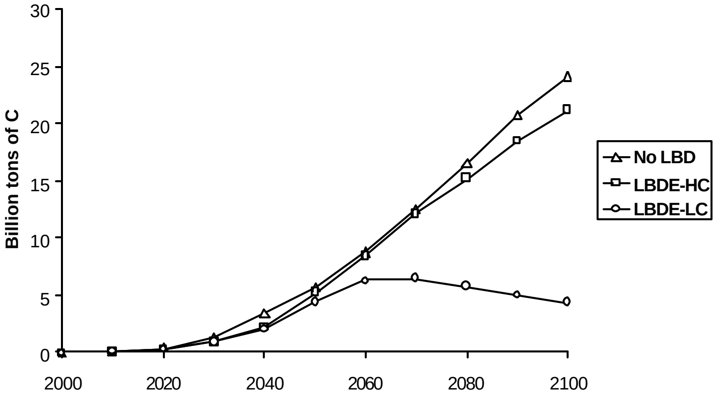


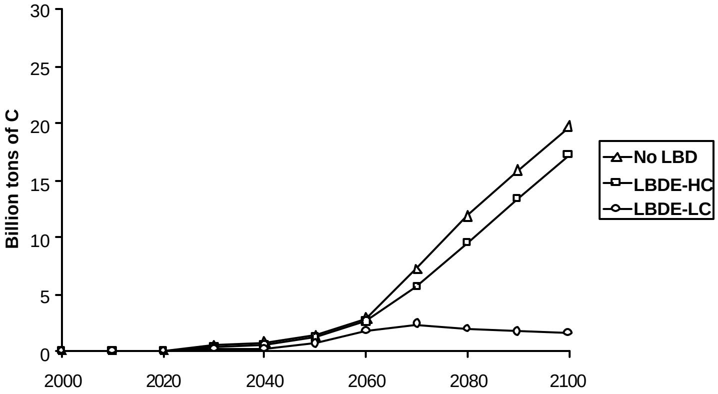
Figure 7. Global Emission Reductions from the Baseline for Three Alternative Stabilization Ceilings



a) SCC-450



b) SCC-550



c) SCC-650

Figure 8. Cumulative Discounted Global Abatement Costs (discounted at 5% from 2000-2100)

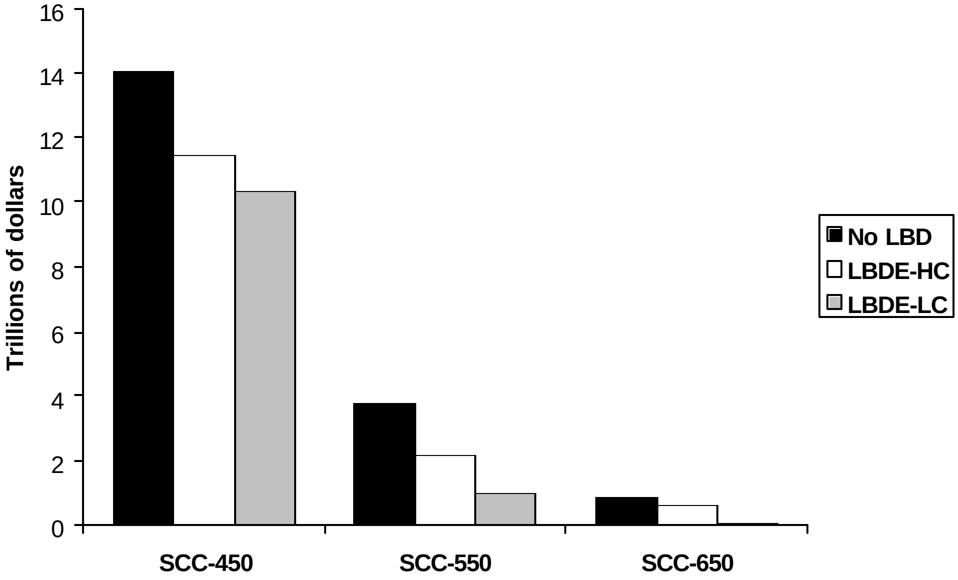


Figure 9. Global Emission Reductions Required under Kyoto+

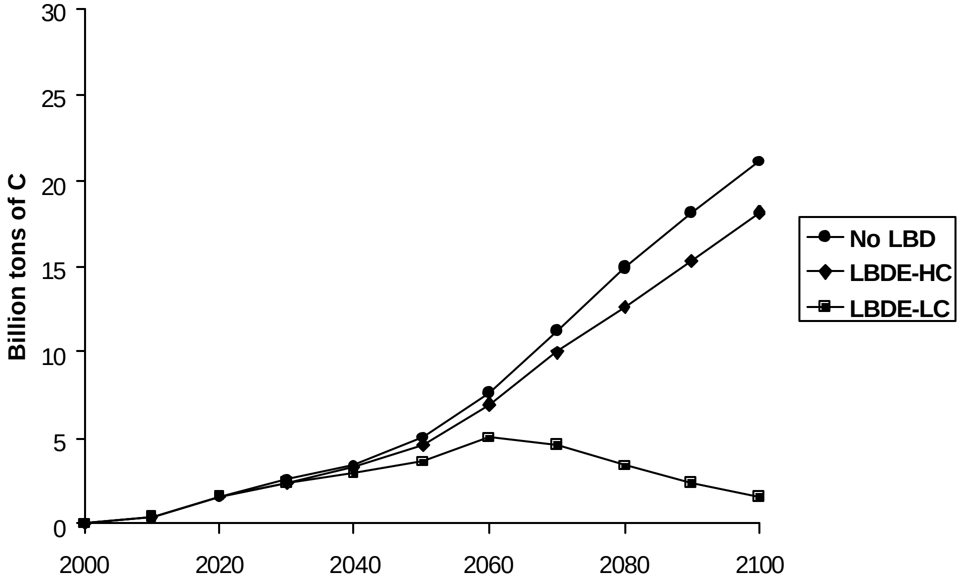


Figure 10. Cumulative Discounted Abatement Costs for SCC-550 and Kyoto+ (discounted at 5% from 2000-2100)