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Managing the Transition to Climate Stabilization*

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Executive Summary

This paper builds upon recent work by the US Climate Change Science Program (CCSP). Among its products, the CCSP developed new emission projections for the major man-made greenhouse gases, explored the effects of emission limits on the energy system, and calculated the costs of various stabilization constraints to the economy. This paper applies one of the models used for that analysis to explore the sensitivity of the results to three potentially critical factors: the stabilization level, the policy design, and the availability and costs of low- to zero-emitting technologies.

The major determinant of costs is likely to be something over which we have little control – Mother Nature. The choice of stabilization level will reflect our understanding of the science of global climate change. We have little control over many of the key bio-geophysical processes which, to a major extent, will determine what constitutes dangerous anthropogenic interference with the climate system.

We consider two limits on radiative forcing, corresponding to stabilizing CO_2 concentrations at approximately 450 ppmv and 550 ppmv. These levels have been chosen because of the fundamentally different nature of the challenge posed by each. In the case of the lower concentration limit, emission reductions will be required virtually immediately and annual GDP losses to the US could approach 5%. With the higher concentration limit, the pressure for a sharp reduction in near-term emissions is not as great. This offers some potential to reduce GDP losses.

Indeed, we find that depending upon the concentration limit, implementing market mechanisms which take advantage of "where" and "when" flexibility can markedly reduce GDP losses, perhaps by as much as an order of magnitude. However, for a variety of reasons, our ability to realize such savings may be compromised. One possible impediment relates to the proximity to the target. If the limit is imminent, flexibility will be greatly reduced. The nature of the coalition and our willingness to permit "borrowing" emission rights from the future will also affect the magnitude of the potential savings. As a result, the reduction in GDP losses from where and when flexibility may turn out to be only a small fraction of what has been previously estimated.

Fortunately, the biggest opportunity for managing costs may come from something over which we do have considerable control. We find that investments in climate friendly technologies can reduce GDP losses to the US by a factor of two or more. At present, we have insufficient economically competitive substitutes for high carbon emitting technologies. The development of low- to zero-emitting alternatives will require both a sustained commitment on the part of the public sector upstream in the R&D chain and incentives for the private sector to bring the necessary technologies to the marketplace. Aside from helping to assure that environmental goals are met in an economically efficient manner, climate policy can also serve as an enabler of new technologies. By recognizing the acute shortage of low-cost substitutes, the long lead times required for development and deployment, and the market failures that impede technological progress, climate policy can play an important role in reducing the long-term costs of the transition.

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1. Introduction

Among the products of the US Climate Change Science Program (CCSP) is an updated set of emission scenarios. These describe future emission trajectories for the major man-made greenhouse gases (GHGs), the effects of limiting emissions on the energy system and the economy, and the economic costs of stabilization.[i] The prospectus for the report specified that with the exception of the first commitment period, stabilization targets would be met in a manner that allowed for "when" and "where" flexibility.[ii] That is, there would be flexibility across both space and time as to where and when reductions would be made. The implication is that reductions will take place both when and where it is economical to do so. The realism of this assumption was questioned by reviewers and authors alike, and the report recommended that the sensitivity of the results to this assumption be the subject of further study.[iii] This extension is a major focus of the present analysis.

We apply one of the three models used in the CCSP update of emission scenarios to examine the costs of straying from the economically efficient scenarios specified in report's prospectus. We also explore the relative importance of other assumptions, including choice of stabilization levels and the availability and costs of low to zero emitting technologies in the energy sector. The analysis is designed to address three questions: What are the determinants of costs? Over which factors do we have control? And, are there steps that make sense despite the differences in perception about what is at stake – in other words, are there some actions that we can all agree upon?

Ideally, policy makers would account for not only the costs of an action, but also the damages avoided by taking the action. Unfortunately, calculating the benefits of action to address climate change is a far more daunting task than calculating the costs. Placing a value on environmental goods and services is always difficult; some would question whether given our current state of knowledge quantifying benefits is even possible. In the past, most economic analyses which attempted to get at the issue of benefits used a surrogate for damages avoided; e.g., reductions in temperature change or sea level rise. In any event, the CCSP limited the focus of the scenario analysis to mitigation costs, while holding benefits constant at a given stabilization level. Accordingly, ***the current analysis is limited to an examination of mitigation costs and not the ensuing benefits.***

In the next section, we briefly describe the modeling framework used both in the CCSP exercise and the current effort. We then discuss the nature of the stabilization challenge and the choice of limits to be explored. Particular attention is paid to how a constraint on GHG emissions can alter the future shape of the energy system. For each stabilization level, we examine marginal and total costs of abatement and the relative importance of major contributing factors. We conclude with some final comments.

2. The model

The analysis is based on the MERGE model (a **m**odel for **e**valuating the **r**egional and **g**lobal **e**ffects of greenhouse gas reduction policies). MERGE is an intertemporal general equilibrium model. Like its predecessors, the current version (MERGE 5.5) is designed to be sufficiently transparent so that one can explore the implications of alternative viewpoints in the greenhouse debate. The current analysis utilizes those submodels that provide a reduced-form description of the economy, the energy sector, emissions, concentrations, and radiative forcing.

MERGE provides a bottom-up representation of the energy supply sector. For a particular scenario, a choice is made among specific activities for the generation of electricity and for the production of non-electric energy. Oil, gas and coal are viewed as exhaustible resources. There are introduction constraints on new technologies and decline constraints on existing technologies.

Geographically, the world is divided into nine geopolitical regions: 1) the USA, 2) WEUR (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) OILX (oil exporting will be captured countries, and 9) ROW (the rest of world). Note the OECD (regions 1-4) together with EEFSU constitute Annex B of the UN Framework Convention on Climate Change. The remaining four regions comprise non-Annex B. 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.[iv] Economic values are reported in US dollars of constant 2000 purchasing power.

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. Note that rather than try to identify the means by which CO_2 will be captured, for the present analysis it is sufficient to refer to the process as carbon capture and sequestration (CCS).

We assume that most existing nuclear power plants are retired during the first half of the 21^{st} century. For those scenarios where new nuclear power plants are introduced, we assume that the cost has both a market and nonmarket component (see Table 1). The latter, which is calibrated to current usage, rises proportionally to market share and is intended to represent public concerns about environmental risks in the technology and associated nuclear fuel cycle.
MERGE includes an electric "backstop" category labeled RNW-HC to indicate high-cost renewable options. The distinguishing characteristics of the backstop category are 1) a zero GHG emissions rate and 2) that once introduced, it is available at a constant marginal cost. Any of a number of technologies could be included in this category, e.g., solar photovoltaics, high cost wind, and biotechnology. It is intended to represent the fact that we will not run out of energy, but as conventional sources are exhausted there are more expensive sources waiting in the wings. A number are identified explicitly in the model. However, as we move further out in time and further up the supply cost curve, specificity can be sacrificed at little cost. Uncertainty about backstop costs are typically dealt with through sensitivity analysis.

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: BFUEL (low-cost biofuels such as ethanol from biomass) and RNW-NE (a high cost renewable backstop category including, for example, hydrogen produced via electrolysis using solar photovoltaics or hydrogen from thermonuclear dissociation). The key distinction is that BFUEL is in limited supply, but RNW-NE is available in unlimited quantities at a constant but considerably higher marginal cost.

Table 1. Electricity Generation Technologies Available to US (introduction dates and costs may differ by region)

Technology Name	Identification/ Examples	Earliest Possible Introduction Date	Market Cost (Mills/ kWh)	Non-Market Cost in 2000 (Mills/ kWh)	Carbon Emission Coefficients (Million tons C/TWh)
HYDRO	Hydroelectric	Existing	40		0.0
NUC-R	Remaining initial nuclear	Existing	50		0.0
GAS-R	Remaining initial gas fired	Existing	32		136.0
OIL-R	Remaining initial oil fired	Existing	37		193.0
COAL-R	Remaining initial coal fired	Existing	20		227.0
COAL-RCS	Remaining coal with carbon capture and sequestration	2020	35		87.0
NUC-N	New nuclear	2010	50	10	0.0
GAS-N	Advanced combined cycle	2010	45		93.5
GAS-NCS	Advanced combined cycle with CCS	2020	65		5.4
COAL-N	New coal without CCS	2010	40		195.5
COAL-NCS	New coal with CCS	2020	55		11.0
RNW-LC	Low cost carbon free renewables, e.g., wind (quantity constrained)	2010	60		0.0
RNW-HC	High cost carbon free renewables, e.g., PV (unlimited quantity)	2010	150		0.0

Table 2. Nonelectric Energy Supplies Available to US (introduction dates and costs may differ by region)

Technology Name	Description	Cost ($/GJ)	Carbon Emission Coefficients (kg C/GJ)
CLDU	Coal – direct uses	2.50	24.1
OIL-1-10	Oil – 10 cost categories	5.00-7.25	19.9
GAS-1-10	Gas – 10 cost categories	4.00-6.25	13.7
BFUEL	Biofuels (e.g., ethanol, biodiesel)	10.00	0.0
SYNF	Coal based synthetic fuels	8.33	40.0
RNEW-NHC	Nonelectric high cost carbon free renewables, e.g. hydrogen via electrolysis using PV (unlimited quantity)	25.00	0.0

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 3.5% 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 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.

Where international trade in emission rights is permitted, regions with high marginal abatement costs can purchase emission rights from regions with low marginal abatement costs.[v] There is also trade in oil, and gas. 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.

3. Definition of reference case and constrained scenarios

With the exception of Eastern Europe and the former Soviet Union (EEFSU), participating countries are assumed to meet the targets imposed by the Kyoto Protocol during the first commitment period. Because the decline in economic activity in EEFSU during the 1990s has led to a decrease in their carbon dioxide emissions, their Kyoto limits are expected to exceed their actual emissions. Hence, these countries will have excess emission rights. In the parlance of the climate debate this is commonly referred to as "hot air" or "Russian hot air" denoting the country expected to receive the largest number of excess rights. At present, the Protocol permits these rights to be sold to countries in search of low-cost options for meeting their own targets. We eliminate this unintended possibility by constraining the countries of EEFSU to their 2000 rather than 1990 emission levels during the first commitment period. Finally, for the US, currently a non participant in the protocol, we apply the constraint on GHG intensity adopted by the Bush Administration for 2010. For the remaining periods in our time horizon, reference case emissions are unconstrained.

For comparison with the reference case, two alternative long-term climate stabilization goals are analyzed. These goals are represented as constraints on the total radiative forcing from the Kyoto suite of gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), the hydrofluorocarbons (HFCs), the perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). Analysis of climate policy has gradually evolved from a focus on stabilizing CO_2 emissions only, to stabilizing CO_2 concentrations, to multigas concentration targets. The CCSP moved one step further down the causal chain connecting human activities to the things that we care about by focusing on stabilizing changes in the earth's energy balance, or radiative forcing (RF).

In accordance with "what flexibility," all gases are considered when identifying the least cost strategy for meeting a particular RF constraint. This raises the issue of establishing equivalence among multiple gases. Comparison is difficult because each gas has its own lifetime and effect on instantaneous forcing. The IPCC has suggested the use of global warming potentials (GWPs) to represent the relative contribution of *emissions* of the different greenhouse gases to long term atmospheric radiative forcing.[vi] However, a number of studies have pointed out the arbitrary nature of GWPs and called for an approach that recognizes the relative contribution of each gas over time as it relates to achieving a particular target.[vii] Thus the RF target approach represents an improvement over concentration targets in that it avoids the need to choose an arbitrary measure for making tradeoffs among multiple greenhouse gases.

Of the four RF targets chosen by the CCSP, the present analysis focuses on the lower two: 3.4 watts/m^2 and 4.7 watts/m^2. These were found to be consistent with atmospheric CO_2 concentrations on the order of 450 and 550 ppmv, respectively, stabilization levels that have received considerable attention in the debate. Moreover, as the results of our study will demonstrate the frontier between "immediate and rapid" action and a "more gradual" approach lies in the range defined by these two goals.

As noted earlier, the CCSP adopted the assumption that reductions would be allocated across space and time in an economically efficient manner. This is referred to in the present study as a "1st best" policy case. We note, however, that many consider this assumption to be difficult to implement. Indeed, most proposals currently under consideration do not allow for the possibility of borrowing emission rights from the future and place limits on the degree to which we might have trading across space.

For comparison to the 1st best case, we will also examine scenarios in which specific constraints are placed on Annex B's year-by-year emissions during the first half of the 21st century. In an attempt to mimic the types of proposals currently under discussion while avoiding singling out any specific proposal for analysis, we arbitrarily assume that Annex B carbon dioxide emissions are reduced by two percent per year between 2010 and 2050. Furthermore we assume that non-Annex B does not join the coalition until 2060 and behaves as if the price of carbon is zero through 2050. Figure 1 shows the nature of the constraints. Because neither Annex B nor non-Annex B countries pursue least cost emission pathways from a global perspective during the transition period, we refer to these as "3rd best" policy scenarios. Note that the arbitrary constraint placed on annual emissions is *in addition* to the long-term constraint on global radiative forcing.

Finally, in order to isolate the benefits from the availability of certain low or zero carbon emitting technologies, we explore scenarios with and without the option of new nuclear power plants *and* carbon capture and sequestration (CCS) technologies in coming decades. These two scenarios are referred to as "Optimistic" and "Pessimistic," respectively. Thus we have identified eight cases as distinguished by target, policy and technology availability. These are summarized in Figure 2. We now turn to the examination of the modeling results.

4. <u>The implications of the long-term goal for near-term emissions</u>

The sharp distinction between the two radiative forcing targets chosen for analysis becomes immediately apparent from Figure 3. The figure shows the time path for total radiative forcing under reference case emissions. Notice that with the tighter target (3.4 watts/m^2), the constraint becomes binding within the next few decades, whereas with a constraint of 4.7 watts/m^2, the constraint does not become binding until the second half of the century. This has implications for how quickly we must act - that is, the potential benefits from "when" flexibility.

Figure 4 shows global carbon emissions under the reference or business-as-usual (BAU) case and the constrained cases. The figure suggests with a 3.4 watts/m^2 constraint there is little room for when flexibility. From a global perspective, the 3rd best policy is only barely more aggressive during the first half of the 21st century than the 1st best policy.

Conversely, with a radiative forcing constraint of 4.7 watts/m^2, there is a clear distinction between the emission pathways under the 1st best and 3rd best policies. In this case, the 2% per annum transition constraint causes Annex B to reduce its emissions below that required by the long-term constraint in the early decades. That is, there is still some flexibility in the choice of emissions pathway.

By definition, the 3rd best policy will be more costly than the 1st best policy in meeting our environmental goals. The question is how much more costly. The analysis suggests that the fewer the degrees of freedom in terms of the timing of emission reductions, that is the closer we are to hitting the constraint, the more the 3rd best policy must resemble the 1st best policy. However, we note that even if the two paths were identical, the costs of the policies will differ. This is because in the case of the 3rd best policy non-Annex B countries do not join the coalition until post-2050. Hence, we have limited where flexibility. But before pursuing the matter of costs further, it will be useful to look at the implications of the various constraints for the energy system.

5. Alternative energy futures

In this section, we explore how a constraint on near-term GHG emissions or on long-term radiative forcing may alter the future shape of the energy system. Previously, we discussed some of the crucial characteristics of the technologies which will drive investment decisions, including costs, availability and public acceptance. It is often said when referring to emissions abatement that there will be no "silver bullet," and that the solution will be comprised of a number of technologies on both the supply and demand side of the energy system. This is likely to be so, but nonetheless, some technologies may play a larger role than others in the management of costs. Two candidates high up on many lists are carbon capture and sequestration (CCS) and nuclear power. Although each confronts substantial hurdles, if successful they could make an important contribution to our energy future.

These zero- to low-emitting technologies can serve as alternatives to electric technologies that freely emit CO_2 into the atmosphere (see Table 1). They also can have an impact through interfuel substitution on the nonelectric sector. Hence, it is necessary to look at the entire energy system to understand their potential roles in reducing greenhouse gas emissions. The two panels which comprise Figure 5 show the electric and nonelectric sectors under the assumptions that both CCS and nuclear power will be available. The figure is for the 3rd best policy case. That is, we have annual limits on Annex B emissions through 2050 and non-Annex B joins the coalition in 2060.

Let's begin with the electricity reference case. Notice that in the absence of a constraint on carbon emissions, coal (without CO_2 capture and sequestration) continues to be the major source of electric power in the US. Indeed, production triples over the course of the century with coal maintaining a 50% market share. As the natural gas share diminishes, nuclear power and low cost renewables, mainly wind power, become major sources of electricity.

The results indicate that with the 4.7 watts/m^2 constraint on radiative forcing, the price of carbon will rise sufficiently that it becomes economical to generate electricity from new coal plants with carbon capture and sequestration technology. Indeed, there is even some retrofitting of existing coal with post-combustion removal and sequestration technology. *Note that whereas nuclear power is economical in its own right in the base case, CCS requires a price on carbon to be competitive.*

Interestingly, the share of CCS declines relative to that of nuclear as we move to the 3.4 watts/m^2 constraint on radiative forcing. Recall that we assume that 95% of the CO_2 is removed with this technology. Nevertheless, the remaining 5% proves to be too much to adhere to the target. Hence, in comparison with the 4.7 watts/m^2 constraint, some of the CCS must be replaced by nuclear.

Notice in the lower panel of Figure 5 that the reference case includes substantial reliance on coal-based synthetic fuels which replace oil as supplies are exhausted and its price rises. In the stabilization scenarios, coal-based synthetics are no longer a viable alternative. Whereas they may be a relatively inexpensive alternative to oil in a world which places zero price on carbon, they become uneconomical as the price of carbon rises. The alternatives are increased dependence on natural gas which was previously used to produce electricity, biofuels which are in limited supply, the high cost non electric backstop, e.g., hydrogen produced via electrolysis using photovoltaics, and substituting electricity for nonelectric energy where economical. The latter provides at least a partial explanation for the negligible fall in electricity demand in Figure 5.

Figure 6 shows the extent to which electric energy is substituted for nonelectric energy in both the optimistic and pessimistic technology scenarios. In each case, the price of nonelectric energy rises faster than that of electricity. While there may be some conservation of traditional electricity services, it is offset by increased substitution of electricity for traditionally nonelectric services. This dynamic is particularly apparent under the optimistic technology case (i.e., with CCS and nuclear power).

Figure 7 shows the energy sector in a world absent the use of CCS and nuclear power. In the upper panel, the base case again consists of continued heavy dependence on coal without capture and sequestration. Whereas the share of freely emitting coal remains high there is also greater reliance on natural gas and renewables. This is necessary to replace the contribution previously made by new nuclear power, which is prohibited in the “pessimistic technology” scenarios depicted in Figure 7. Also note the substantial drop in demand relative to the earlier base case (Figure 5). This reflects a substantial rise in electricity prices.

With the imposition of a constraint on radiative forcing, we begin to see the emergence of high cost renewables which are three to four times more costly than freely emitting coal technologies. With such a sharp rise in the price of electricity, the role of price induced conservation rises considerably. Hence, we see a major decline in electricity demand. This decline is further exacerbated by the disincentive for interfuel substitution due to the higher electricity prices.

6. Marginal and total costs

We next take a closer look at the price of carbon corresponding to the various stabilization scenarios. These carbon prices describe how much we would be willing to pay to emit an additional ton of carbon and provide important insight into the relative importance of our two constraints: the annual constraint on emissions and the long-term constraint on radiative forcing. Figure 8 shows the carbon prices for each of our eight scenarios. The top and bottom panels refer to the 3.4 watts/m^2 and the 4.7 watts/m^2 constraints, respectively.

Consider first the upper panel, which shows, as we would expect, higher prices overall than in the lower panel. With the tighter constraint, the price of emission rights rise at a constant rate during the first half of the century in each scenario. This suggests that in the 3rd best case, prices are being driven by the long-term constraint on radiative forcing and not the year-by-year constraint on Annex B emissions. When only the radiative forcing constraint is binding, carbon prices will rise until the “backstop technology” is available at constant marginal cost. With an introduction constraint on the backstop technology, there will be some overshoot followed by a decline to the carbon price dictated by the backstop cost. For each path, the *rate* at which carbon prices rise is such that the discounted marginal cost of a ton of carbon is virtually identical in each period. Notice that the price paths are higher in the 3rd best cases. This is due to the fact that non-Annex B is not participating in the coalition until the second half of the century. Hence, Annex B is initially carrying the entire burden.

The lower panel in Figure 8 contrasts sharply with the upper panel. In particular, notice the erratic price path during the transition period (2010-2050) for the 4.7 watts/m^2 constraint on radiative forcing. Here, Annex B countries are responding predominantly to the year-by-year constraint on annual carbon emissions during the first half of the century. That is, the long-term global constraint on radiative forcing would not by itself require a reduction in emissions sufficient to meet the annual emission constraint. With the carbon price path governed by the annual constraint, we no longer see gradually rising prices during the first half of the century. In 2050 Annex B faces its tightest annual constraint; hence the sharp spike in the carbon price. The peak is exacerbated by the assumption that Annex B knows that non-Annex B will join the coalition post-2050 and that there will be a relaxation in its own transition constraint at that point in time. The dramatic drop in price reflects the transition to global when and where flexibility.[viii]

It is also interesting to look at the impact of the constraint on GDP. Figure 9 shows annual US GDP losses for our various scenarios. Scenarios with the 3.4 watts/m^2 radiative forcing constraint are shown in the upper panel, with the 4.7 watts/m^2 radiative forcing constraint scenarios shown in the lower panel. Not surprisingly, the magnitude of the losses is highest for the tighter RF constraint. If we adopt the pessimistic technology scenario and assume a 3rd best policy approach, the costs of stabilization at the 3.4 watts/m^2 target rise to nearly 5 percent of annual GDP in mid-century. For a given target, GDP losses may be reduced either by introducing policy flexibility or by introducing new technology. Note that there is a temporal element to the choice of approaches to reducing losses. During the first half of the century losses are most effectively reduced by focusing on the policy design. Conversely, during the second half of the century, the benefits from the policy choice decline as those from technology availability expand. This does not imply, however, that our initial focus should be exclusively on policy design followed by one on technology. To the extent that technology leadtimes imply near-term R&D, our initial focus needs to be both on policy design and technological innovation.

7. A “2nd best” policy

The 3rd best policy case represents two separate departures from the 1st best policy during the transition period (the first half of the present century). The first is the non-participation of developing countries, who behave as if the carbon price is zero through 2050. The second is the constraint on Annex B, overlaid on the long-term stabilization target, requiring a continuation of “Kyoto-style” reductions (annual targets) for the first half of the century. It is interesting to examine the relative importance of these two suboptimal components. We therefore construct an intermediate “2nd best” policy scenario, in which developing countries remain outside the transition coalition but Annex B is no longer bound by the year-by-year reduction constraints. However, to facilitate comparison, we impose the constraint that global radiative forcing by 2050 must not exceed the level achieved by that time period in the 3rd best policy case. In other words, we apply the transition policies shown in Figure 1 only in terms of their end result, the radiative forcing at mid-century, and not in terms of a prescribed timetable of reductions, allowing Annex B *when* flexibility in meeting the intermediate target. Thus the effects of bearing the burden alone can be separated from the effects of an arbitrary timetable.

The results of the 2nd best analysis depend entirely on the choice of stabilization target. In the case of the tighter 3.4 watts/m^2 target, the transition constraints on Annex B are barely binding, so removing them makes little difference; the 2nd and 3rd best policy scenarios are identical in this case. This observation highlights the importance of developing country participation in relation to the tighter target. All differences between the 3rd best and 1st best solutions in this case are due to the limited size of the transition coalition. By contrast, in the 4.7 watts/m^2 stabilization scenario, relaxation of the transition timetable makes a big difference. Figure 10 shows the carbon price with a 4.7 watts/m^2 target for all three policy scenarios (and optimistic technology assumptions). The 1st best and 3rd best price paths are the same as those shown in the lower panel of Figure 8. The 2nd best price path is only slightly higher than in the 1st best case during the transition period, demonstrating the value of even partial when flexibility. For the 4.7 watts/m^2 stabilization scenario, the remaining effects from the non-participation of developing countries are comparatively small, implying that most of the difference between the 3rd best and 1st best solutions in this case is due to the over-aggressive abatement schedule in Annex B for the higher stabilization level.

8. <u>Relative influence of various factors on cost</u>

Finally, in our last figure (Figure 11), we examine GDP losses at a global level, discounted back to the present. The figure provides a summary of our analysis. Notice that the largest determinant of losses is something over which we may have little control—Mother Nature. That is, if we assume that ultimately the RF target will be based on a better understanding of the science underlying global warming and that this understanding will determine what constitutes “dangerous anthropogenic interference with the climate system,” then the resolution of uncertainty surrounding such issues as climate sensitivity, the thermohaline circulation, sea level rise, etc. will ultimately determine the appropriate target.

The second largest determinant of costs and *the one over which we do have control* is technology. If a transformation of the global energy system turns out to be required, trillions of dollars are at stake. At the present time, there are insufficient supplies of low cost substitutes for high carbon emitting technologies. Currently we are limited primarily to fuel switching and price induced conservation, both of which will come with a sizeable price tag. To develop the technological wherewithal to do the heavy lifting in the future is essential for managing the costs of the transition. This will require both a sustained commitment on the part of the public sector upstream in the R&D chain and incentives for the private sector to bring the necessary technologies to the marketplace.

Finally, there is the issue of the design of climate policy. The cost comparison reveals that in the current formulation, policy choice plays a smaller role than either the stabilization target or the state of technology. Moreover, note that the entire gain from policy flexibility is obtained *without* developing country participation in the 2^{nd} best case with the 4.7 watts/m^2 target, while including these countries accounts for the entire gain in the 3.4 watts/m^2 stabilization scenario. Even though it ranks third in this analysis, the difference between economically efficient and inefficient policy is still on the order of trillions of dollars. But the main contribution of climate policy may be as an enabler of new technologies. By recognizing the acute shortage of low-cost substitutes, the long lead times required for development and deployment, and the market failures that impede technological progress, climate policy can play an important role in reducing the costs of the transition.

9. <u>Some final comments</u>

As climate negotiators continue the struggle to agree upon a set of goals for climate policy, the debate appears to be becoming even more polarized. This may seem surprising given the growing consensus among the scientific community that something should be done and done soon. Upon reflection, however, the widening gulf should be expected. The calls for action are being accompanied by demands for increasingly tighter constraints on greenhouse gas emissions and hence, both sides of the debate see the stakes increasing.

Of course, the "stakes" tend to be perceived differently depending upon one's perspective. The activists are concerned that we are imposing an unacceptable risk on the environment. To them, the very ecosystem, and its ability to provide the services to which we are accustomed, is at stake. The climate skeptics, even those who acknowledge the need for some action, fear that the types of actions that are being suggested will impose an unacceptable and unnecessary burden on our economy and in doing so will divert attention from more pressing social needs.

The real question is not *whether* to take action but *how much* action to take. Unfortunately, given the deep and pervasive uncertainties that both sides acknowledge, the problem does not lend itself to a simple solution. The issue is one of risk management, that is, how much insurance we should buy to reduce the risks associated with climate change. Here the answer will hinge upon one's perception of the stakes, the odds, and how risk averse we choose to be as a society. Our analysis focuses on one part of the risk management calculus: the costs of the insurance premium.

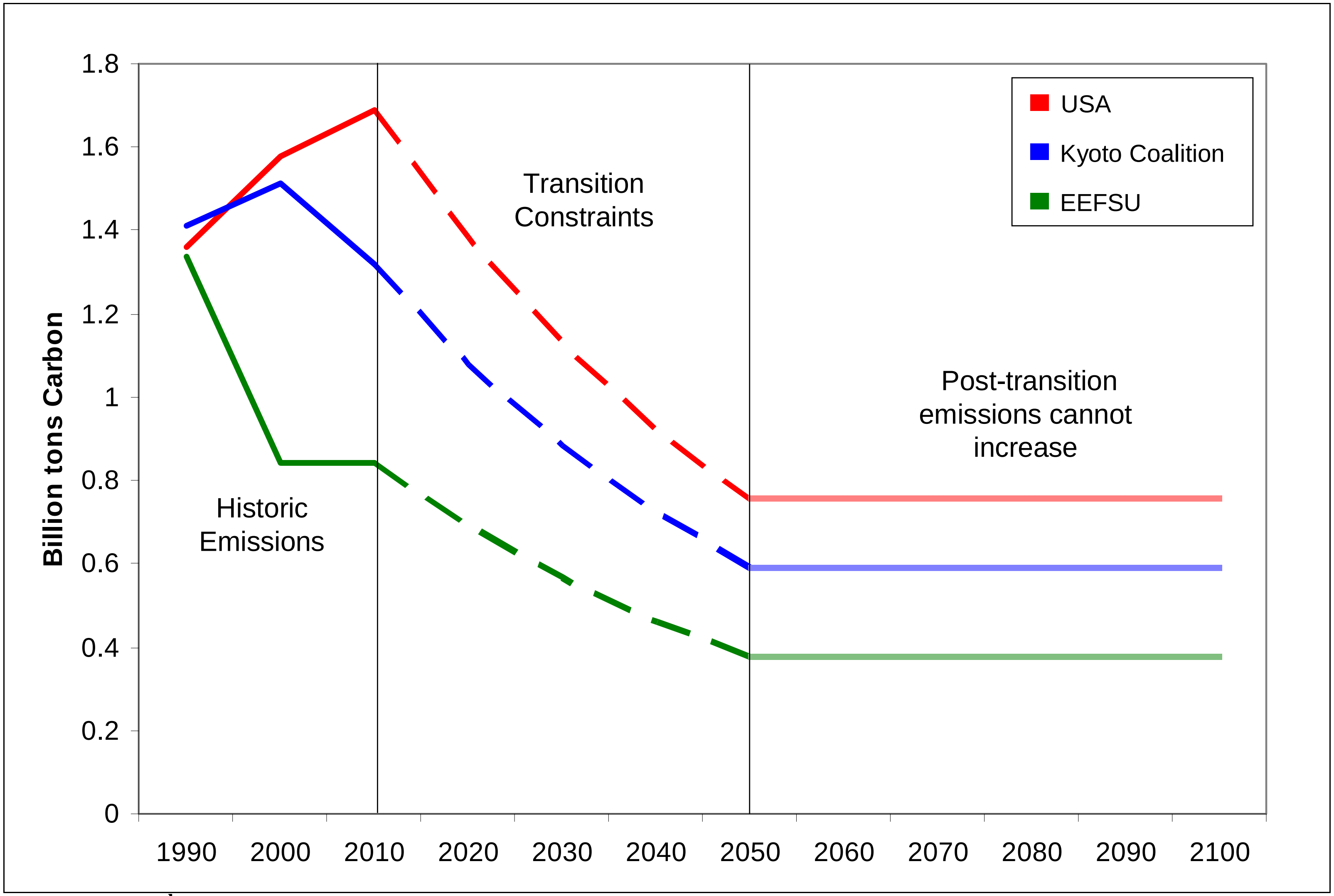

Figure 1. 3rd Best Transition Constraints for Annex B

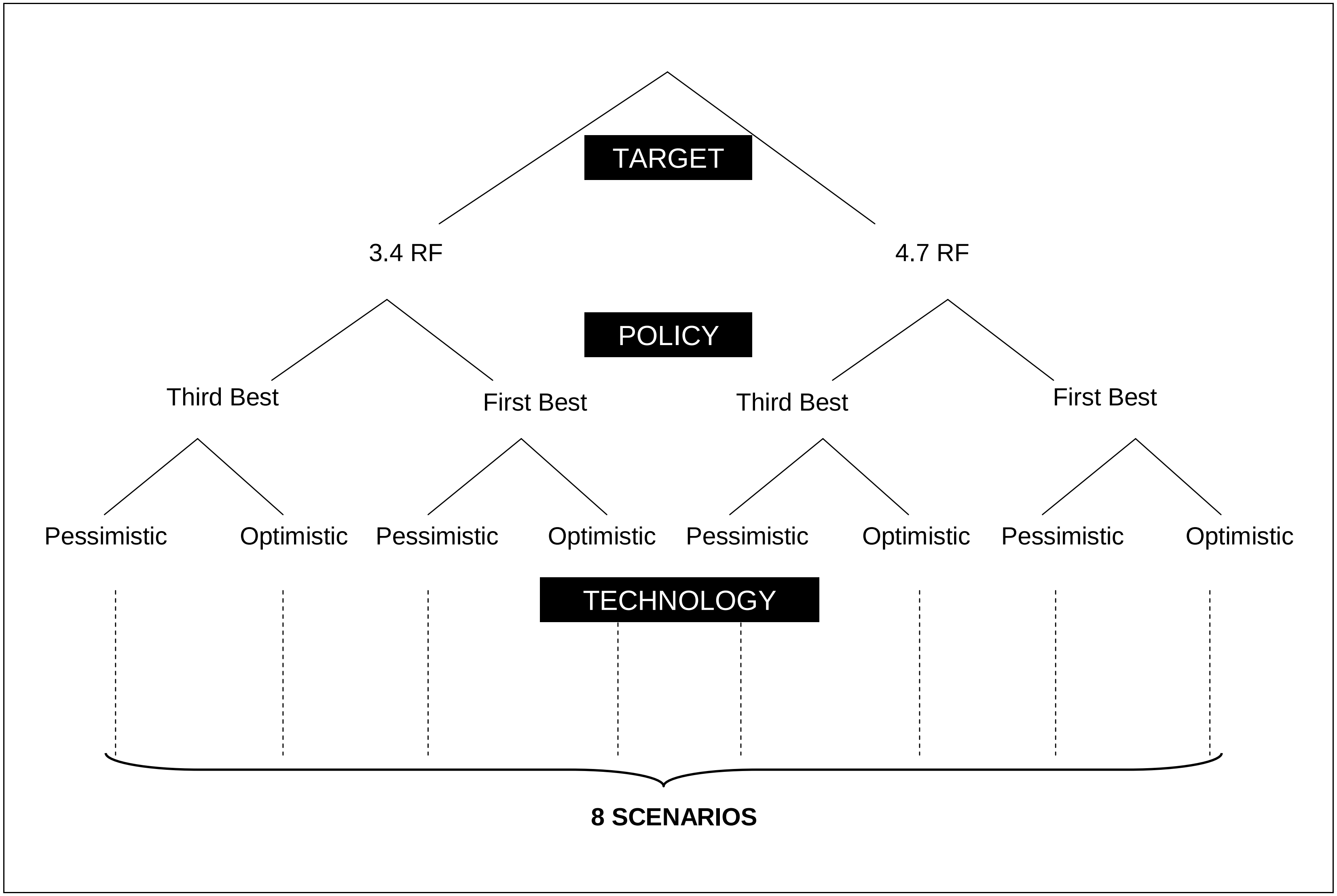

Figure 2. Scenario Design for Analysis

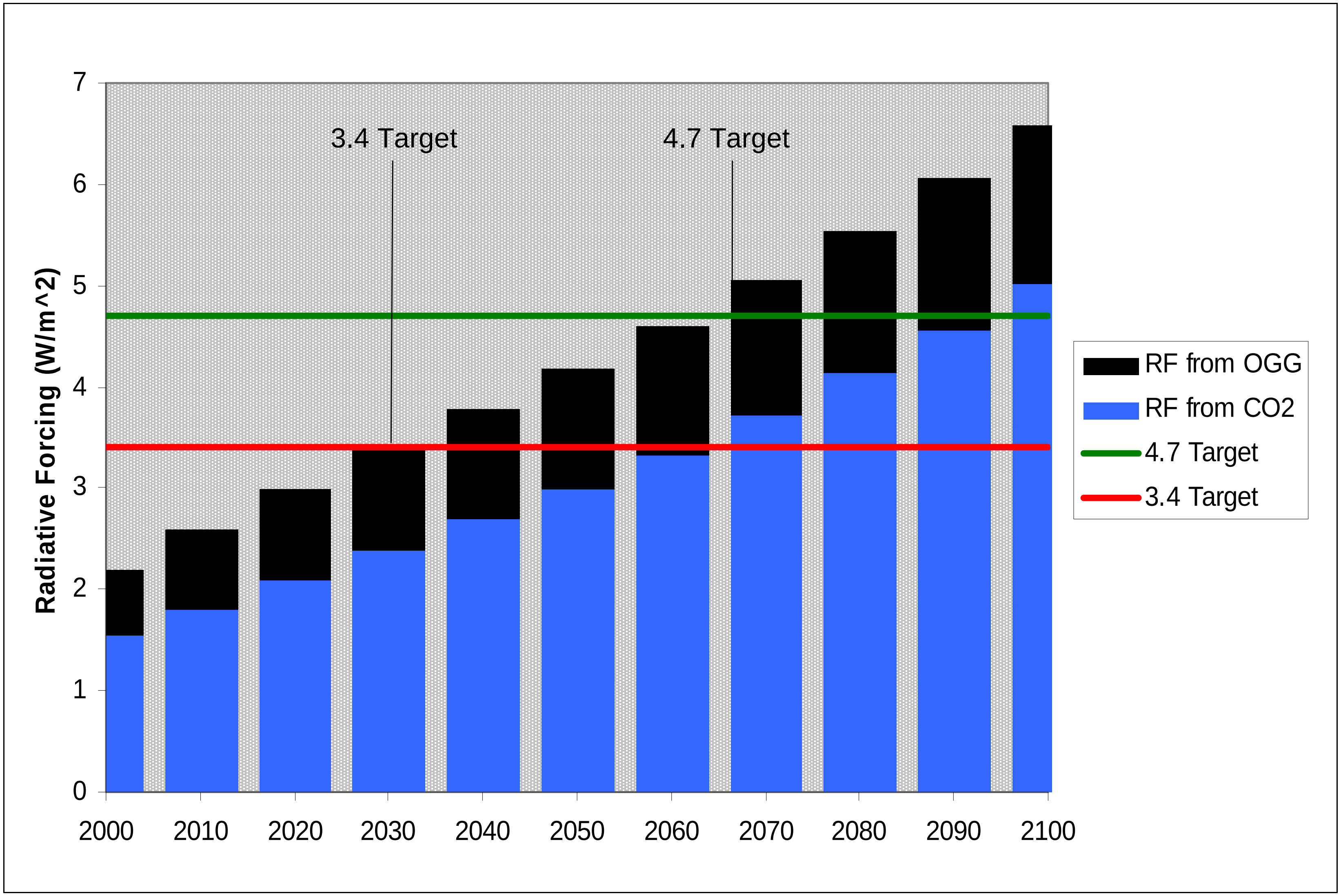

Figure 3. Global Radiative Forcing in Reference Case Relative to Stabilization Targets

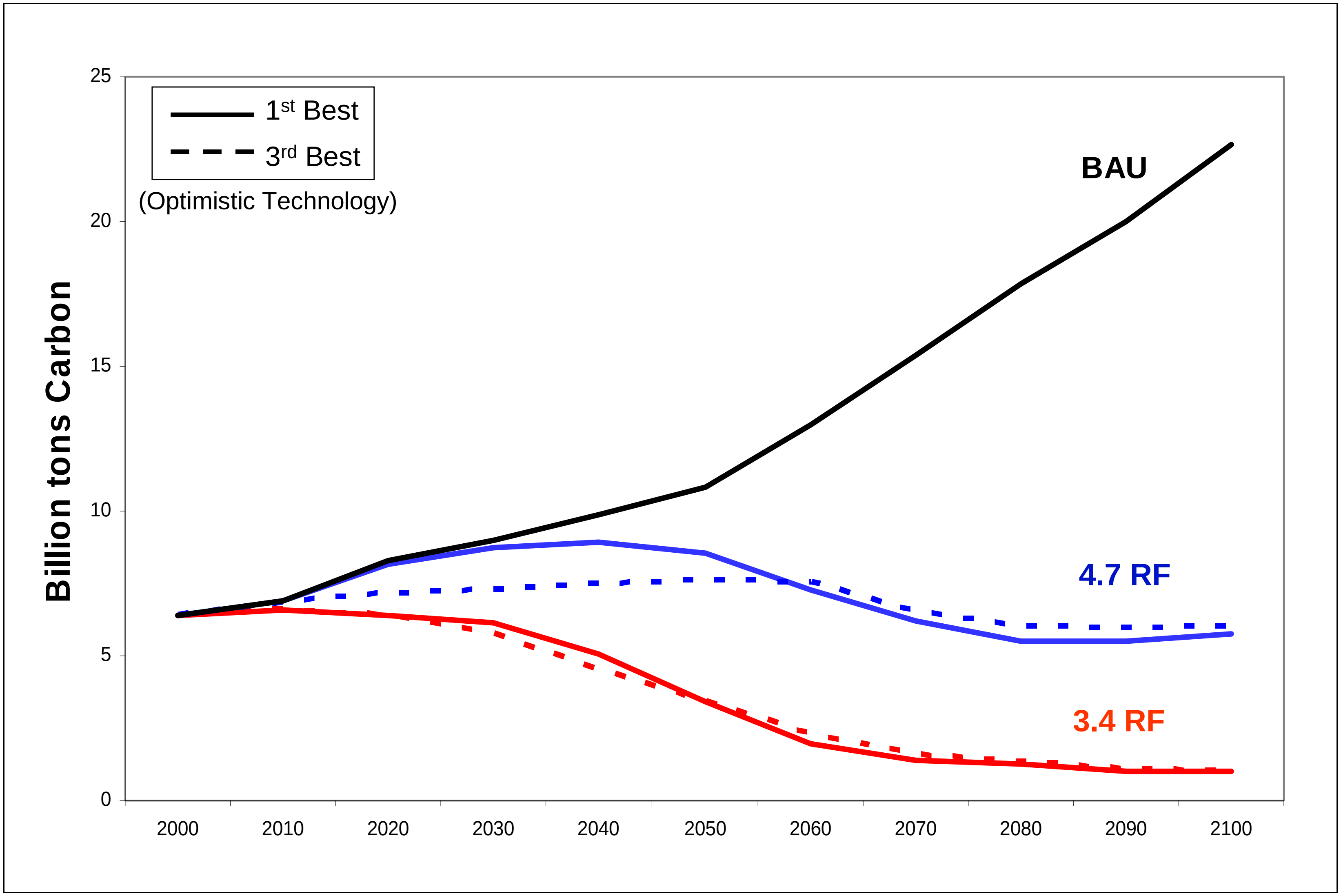

Figure 4. Global Carbon Emissions in Reference and Policy Scenarios

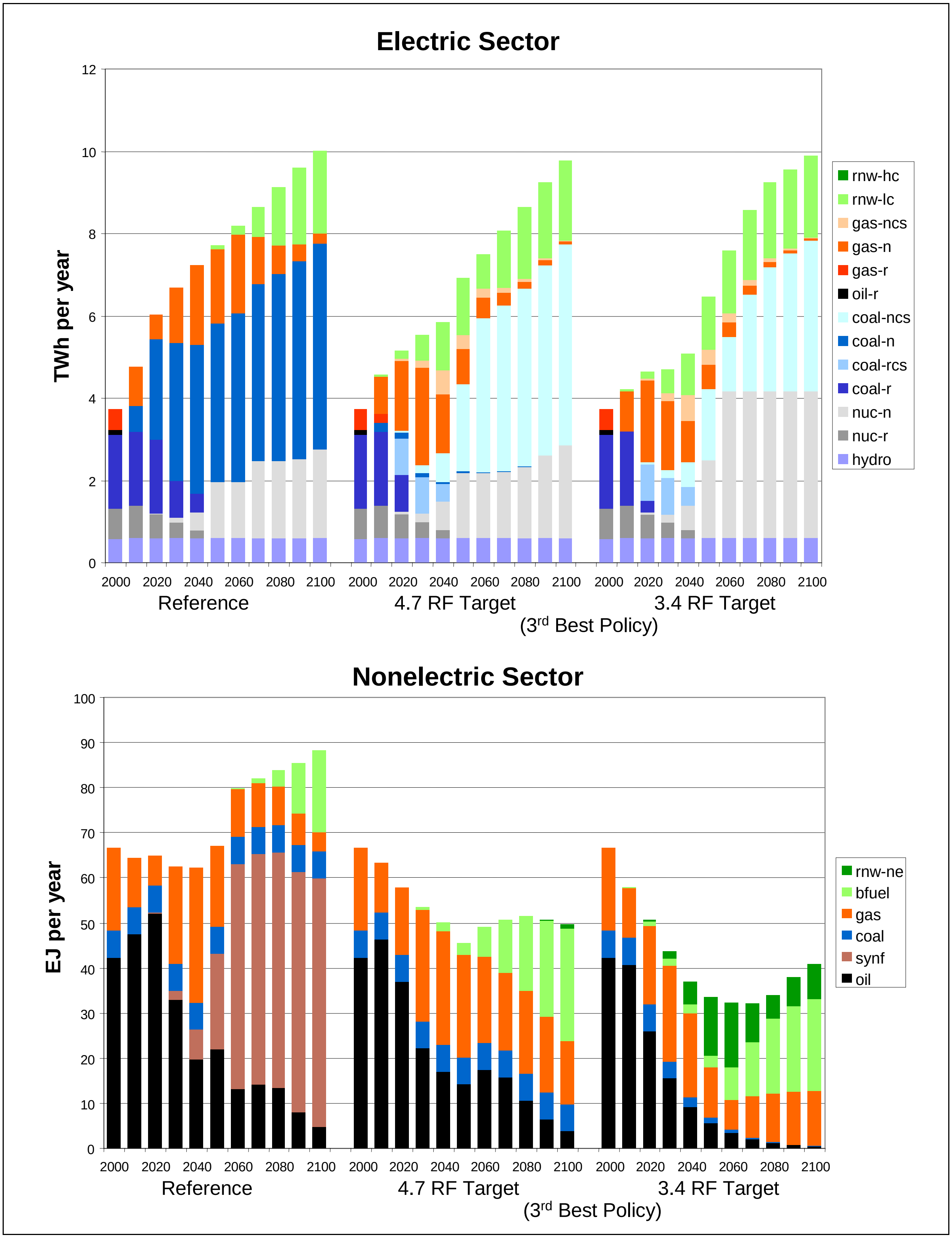

Figure 5. U.S. Energy Sector Profiles in Optimistic Technology Scenario

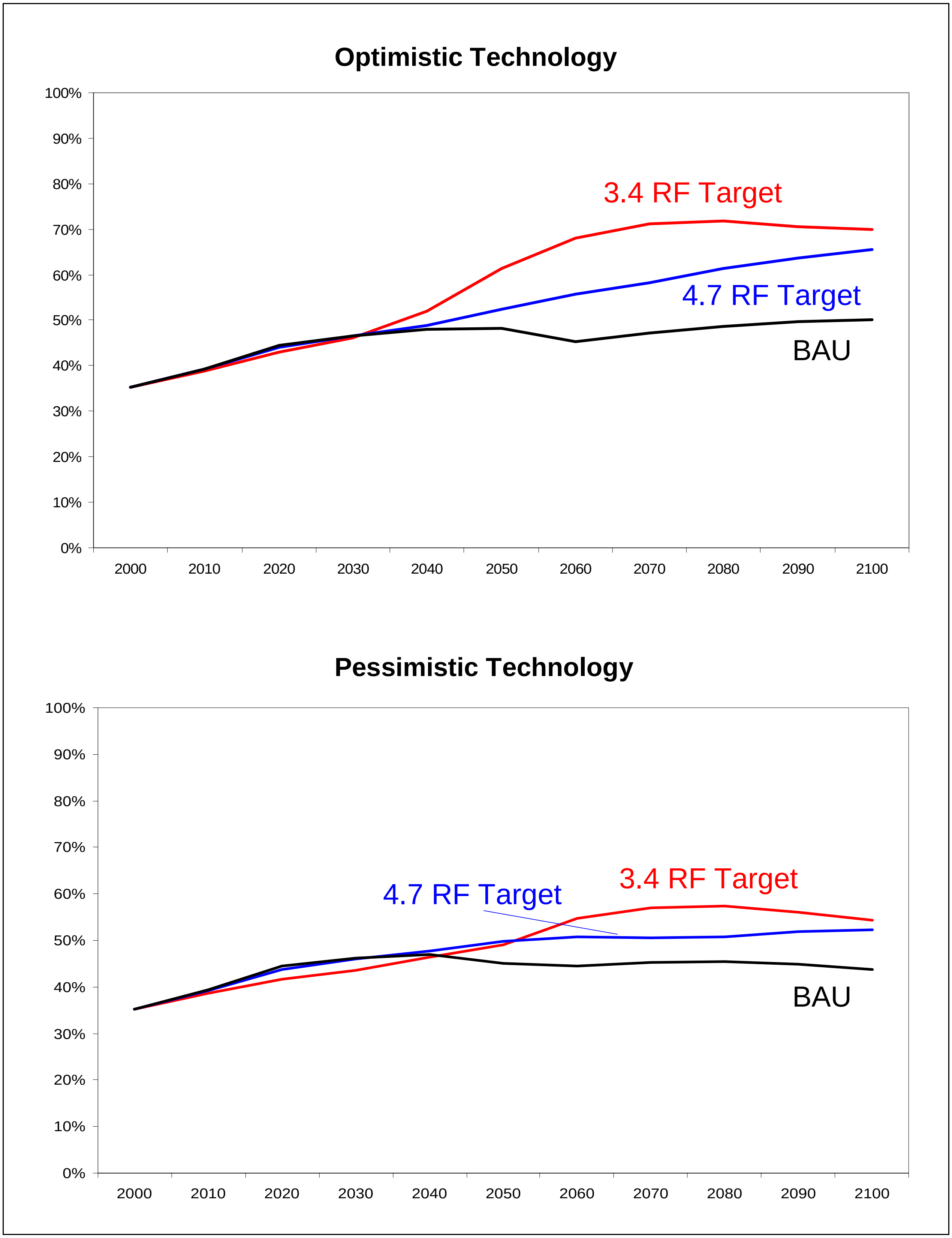

Figure 6. U.S. Electric Sector Share of Primary Energy (EJ)

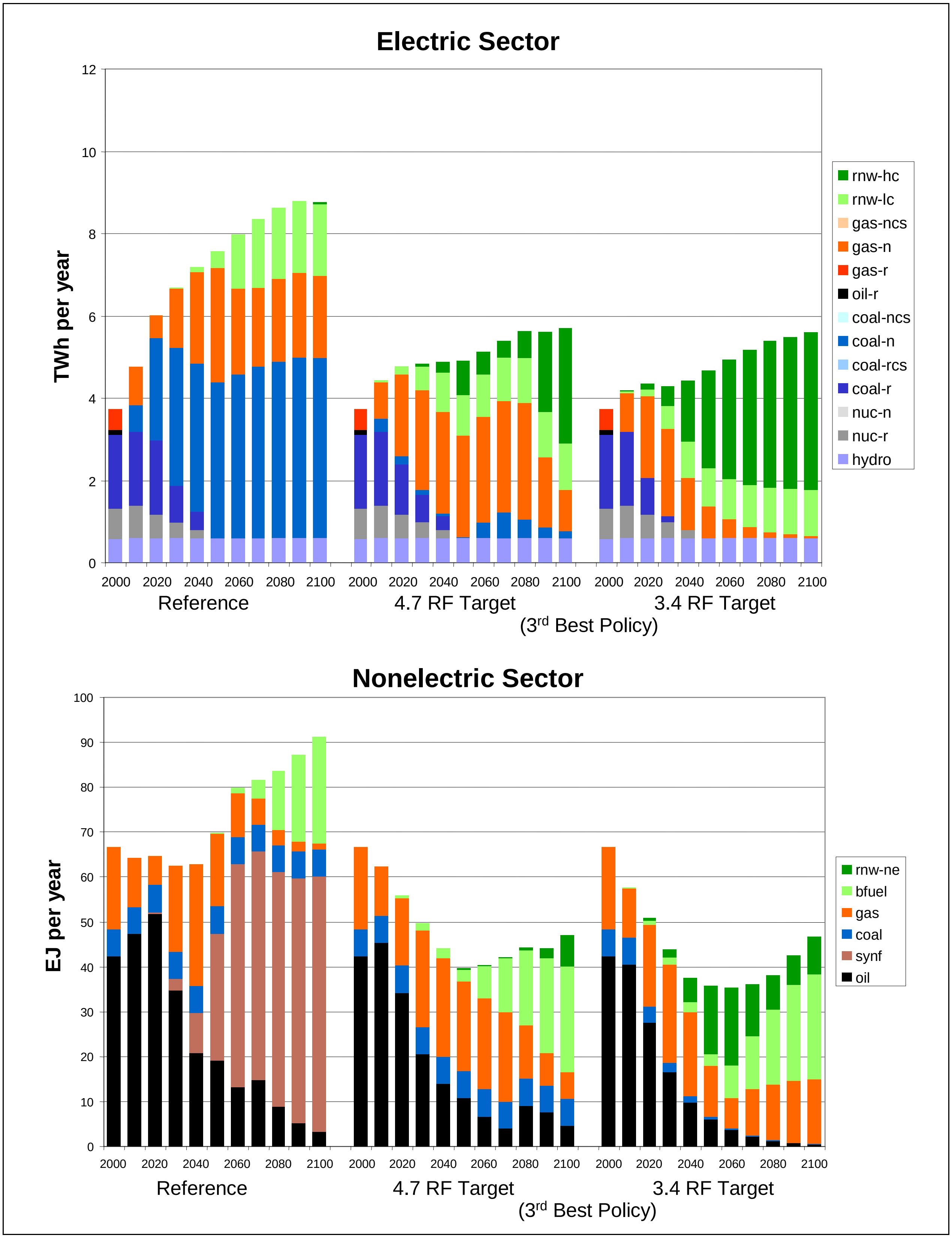

Figure 7. U.S. Energy Sector Profile in Pessimistic Technology Scenario

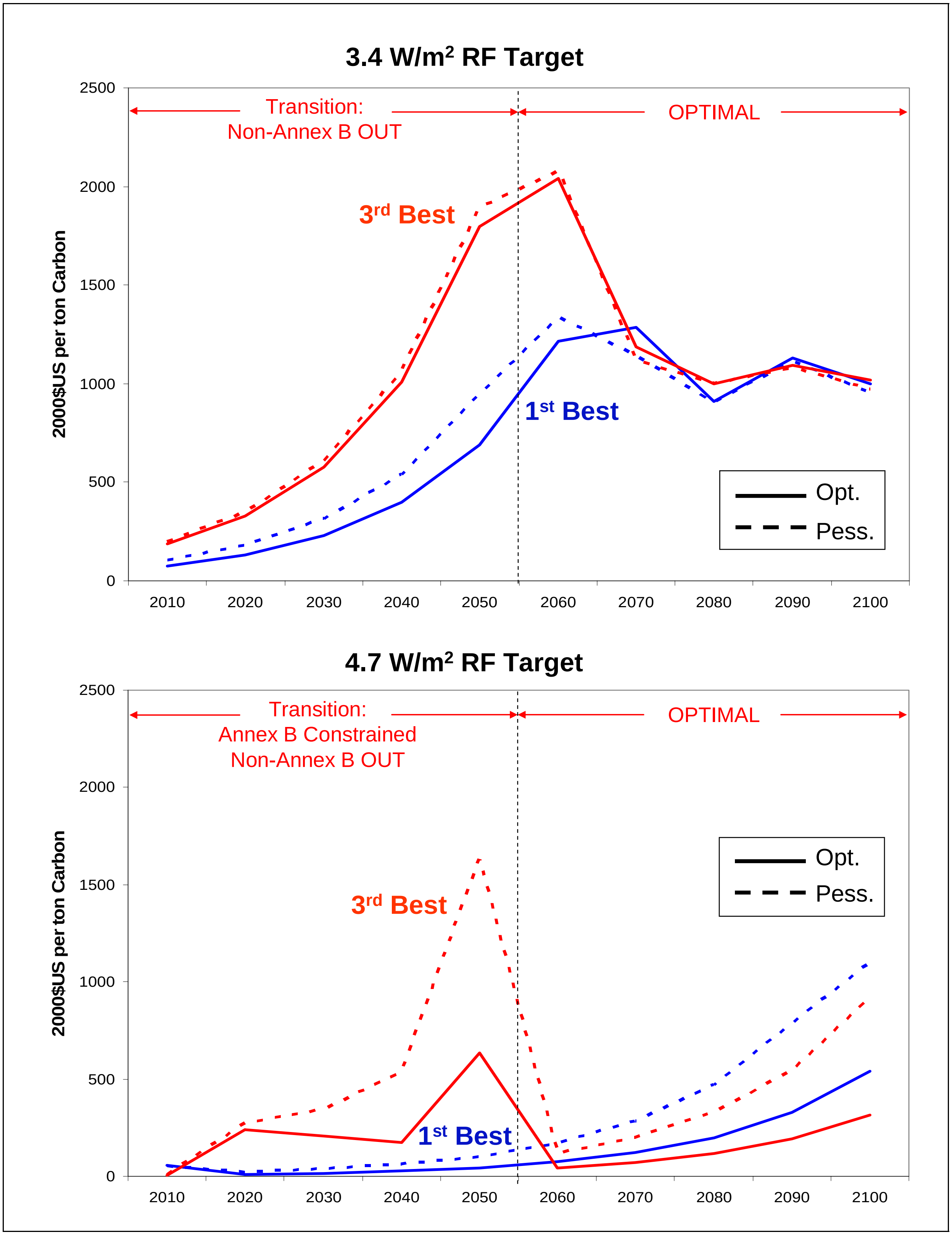

Figure 8. Annex B Carbon Price under Alternative Scenarios

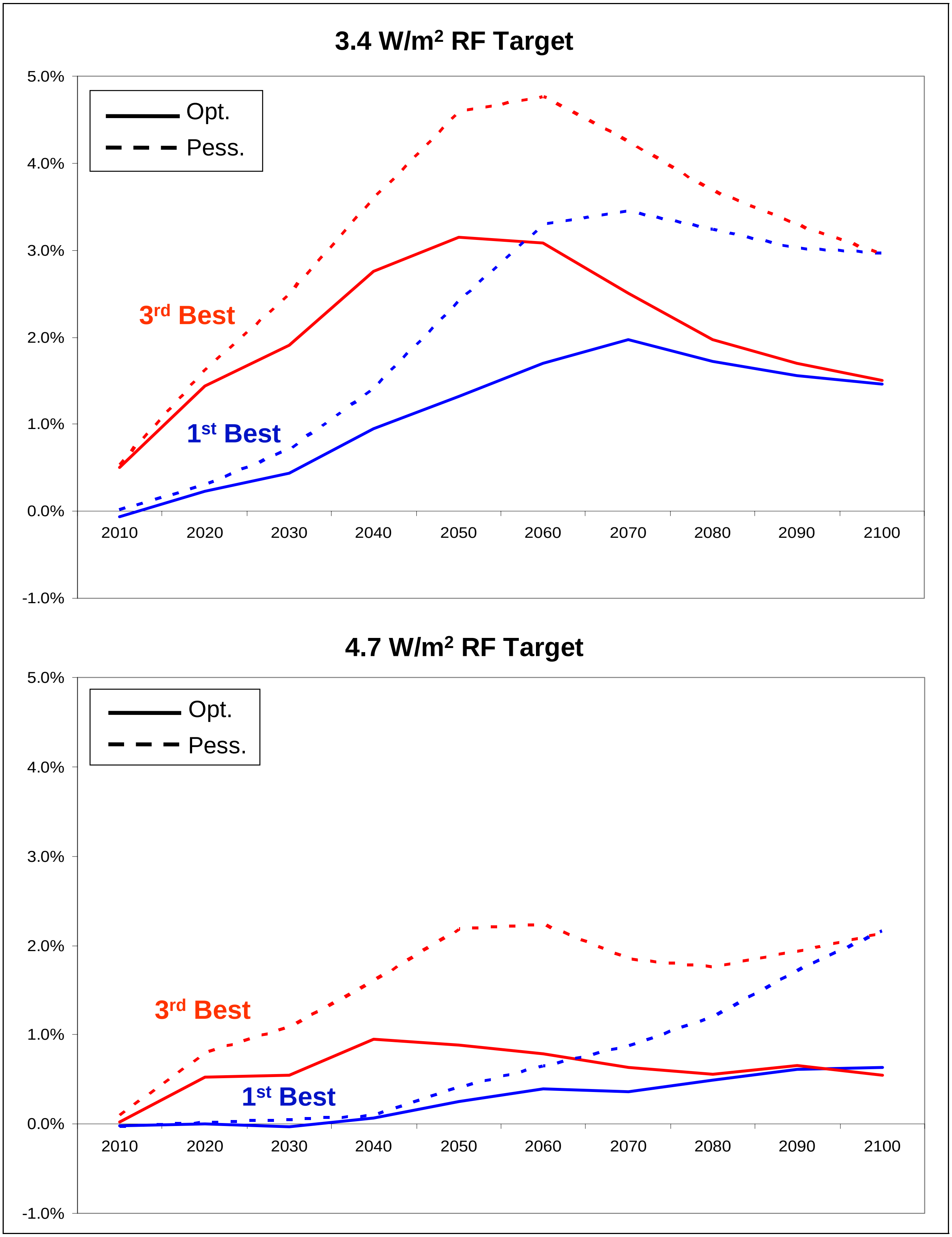

Figure 9. U.S. GDP Loss from Reference in Policy Scenarios

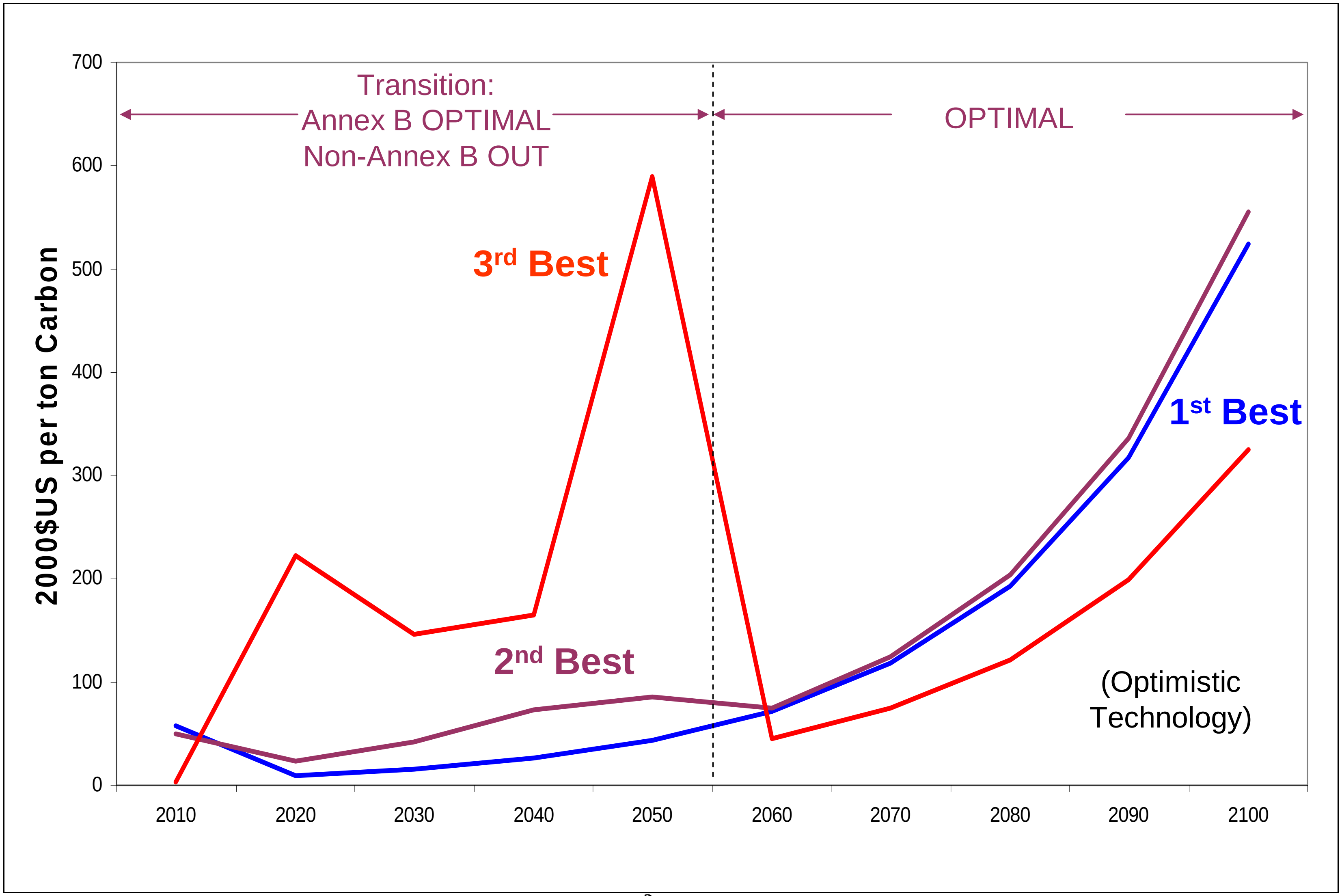

Figure 10. Annex B Carbon Price under 4.7 W/m^2 RF Target

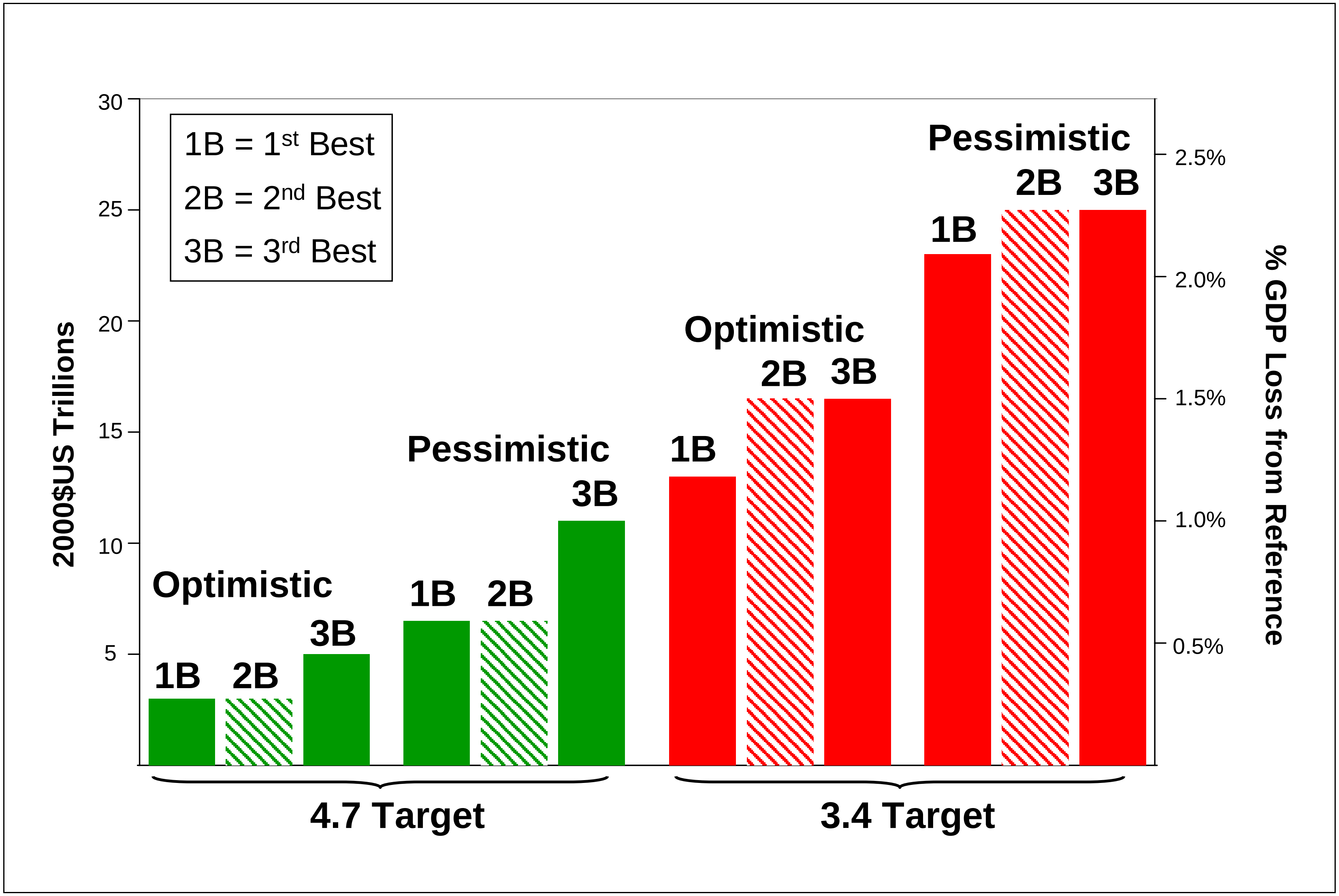

Figure 11. Total Global Economic Cost through 2200 Discounted to 2000 at 5%

[i] See http://www.climatescience.gov/Library/sap/sap2-1/default.php

[ii] See http://www.climatescience.gov/Library/sap/sap2-1/sap2-1prospectus-final.htm/

[iii] See http://www.climatescience.gov/Library/sap/sap2-1/public-review-draft/

[iv] Conference of the Parties, “Kyoto Protocol to the United Nations Framework Convention on Climate Change”, Report of the Conference of the Parties, Third Session Kyoto, 1-10 December, FCCC/CP/1997/L.7/Add1. http://www.unfccc.de.

[v] In MERGE, emissions can be limited either directly in each region or by a carbon tax with “lump sum” recycling of revenue. When the carbon taxes resulting from a particular cap and trade scheme are used as inputs to control emissions, they produce identical regional emissions that were inputs under cap and trade.

[vi] IPCC (Intergovernmental Panel on Climate Change) (1996). *Climate Change 1995, Report of Working Group III*, Cambridge University Press, UK.

[vii] Manne, A. S. and R. G. Richels (2001). “An Alternative Approach to Establishing Trade-offs Among Greenhouse Gases”, *Nature*, **410**, 675-677.

[viii] Low carbon technologies involve investments which persist for decades, and therefore the cost of new abatement measures at the end of the transition period are magnified because firms consistently anticipate that with accession of non-Annex B countries, future carbon prices will be lower. A higher carbon tax is required at the end of the transition period in order to induce abatement measures which only serve to reduce carbon emissions in one or two time periods.