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A Review of the *Stern Review on the Economics of Climate Change*

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How much and how fast should we react to the threat of global warming? The Stern Review *argues that the damages from climate change are large, and that nations should undertake sharp and immediate reductions in greenhouse gas emissions. An examination of the* Review's *radical revision of the economics of climate change finds, however, that it depends decisively on the assumption of a near-zero time discount rate combined with a specific utility function. The* Review's *unambiguous conclusions about the need for extreme immediate action will not survive the substitution of assumptions that are consistent with today's marketplace real interest rates and savings rates.*

1. *Opposite Ends of the Globe*

It appears that no two places on earth are further apart on global warming policies than the White House and 10 Downing Street. In 2001, President George W. Bush announced his opposition to binding constraints on greenhouse gas emissions. In his letter of opposition, he stated, "I oppose the Kyoto Protocol because it exempts 80 percent of the world, including major population centers such as China and India, from compliance, and would cause serious harm to the U.S. economy" (Bush 2001). This policy, much like the war in Iraq, was undertaken with no discernible economic analysis.[1]

In stark contrast, the British government in November 2006 presented a comprehensive new study, the *Stern Review on the Economics of Climate Change* (hereafter the *Review*).[2] Prime Minister Tony Blair painted a dark picture for the globe at its unveiling, "It is not in doubt that if the science is right, the consequences for our planet are literally disastrous . . . . [W]ithout radical international measures to reduce carbon emissions within

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[1] There is no record of a fact sheet or other economic analysis accompanying the letter. The Bush Administration's economic analysis was contained in the *Economic Report of the President and the Council of Economic Advisers* (2002), chapter 6, published almost a year after President Bush's letter to the Senators. The *Economic Report*'s analysis suggests that the Kyoto Protocol is costly, but its analysis does not show that binding action is economically unwarranted.

[2] The printed version is Nicholas Stern (2007). Also, see the electronic edition at that reference. It is assumed that the printed version is the report of record, and all citations are to the printed version. The printed version contains a "Postscript" which is in part a response to the early critics, including a response to the November 17, 2006, draft of this review.

the next 10 to 15 years, there is compelling evidence to suggest we might lose the chance to control temperature rises" (Blair 2006).

The summary in the *Review* was equally stark: "[T]he *Review* estimates that if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more . . . . Our actions now and over the coming decades could create risks . . . on a scale similar to those associated with the great wars and the economic depression of the first half of the 20th century" (p. xv).

These results are dramatically different from earlier economic models that use the same basic data and analytical structure. One of the major findings in the economics of climate change has been that efficient or "optimal" economic policies to slow climate change involve modest rates of emissions reductions in the near term, followed by sharp reductions in the medium and long term. We might call this the *climate-policy ramp,* in which policies to slow global warming increasingly tighten or ramp up over time.[3]

The findings about the climate-policy ramp have survived the tests of multiple alternative modeling strategies, different climate goals, alternative specifications of the scientific modules, and more than a decade of revisions in integrated assessment models. The logic of the climate-policy ramp is straightforward. In a world where capital is productive, the highest-return investments today are primarily in tangible, technological, and human capital, including research and development on low-carbon technologies. In the coming decades, damages are predicted to rise relative to output. As that occurs, it becomes efficient to shift investments toward more intensive emissions reductions. The exact mix and timing of emissions reductions depend upon details of costs, damages, and the extent to which climate change and damages are nonlinear and irreversible.

There are many perils, costs, and uncertainties—known unknowns as well as unknown unknowns—involved in unchecked climate change.[4] Economic analyses have searched for strategies that will balance the costs of action with the perils of inaction. All economic studies find a case for imposing immediate restraints on greenhouse gas emissions, but the difficult questions are how much and how fast. The *Review* is in the tradition of economic cost–benefit analyses, but it has strikingly different conclusions from the mainstream economic models.[5] Because it has conclusions that are so different from most economic studies, the present note examines the reasons for this major difference. Is this radical revision of global-warming economics warranted? What are the reasons for the difference?[6]

[3] This strategy is a hallmark of virtually every study of intertemporal efficiency in climate-change policy. It was one of the major conclusions in a review of integrated-assessment models: "Perhaps the most surprising result is the consensus that given calibrated interest rates and low future economic growth, modest controls are generally optimal" (David L. Kelly and Charles D. Kolstad 1999). A survey of the results of greenhouse-gas stabilization in several models in contained in Energy Modeling Forum Study 19 (2004). This result has been found in all five generations of the Yale/DICE/RICE global-warming models developed over the 1975–2007 period; see the references in footnote 28.

[4] See James Hansen et al. (2006) for a recent warning.

[5] An early precursor of this Review is the study by William R. Cline (1992). Cline's analysis of discounting was virtually identical to that in the *Review.*

[6] There is by spring 2007 a large body of commentary on the *Stern Review,* including the companion article by Martin Weitzman in this issue. A critical discussion of key assumptions is provided in Richard S. J. Tol and Gary W. Yohe (2006) and Robert O. Mendelsohn (2006). A particularly useful discussion of discounting issues is contained in Partha Dasgupta (2007). An analysis which focuses on the extreme findings of the *Review* is S. Niggol Seo (2006). A discussion of ethics is in Wilfred Beckerman and Cameron Hepburn (2007). A sensitivity analysis of the ethical parameters with much the same message as the present article is Sergey Mityakov (2007). A wide-ranging attack on various elements is contained in Robert M. Carter et al. (2006) and Ian Byatt et al. (2006). Insurance issues and discounting are discussed in Christian Gollier (2006).

2. *Overview of the Issues*

I will not summarize the basic findings of the *Review*—a clear summary is found in its introduction—nor will I review the many reviews of the *Review.* Instead, I begin with some summary reactions.

First, the *Review* should be read primarily as a document that is political in nature and has advocacy as its purpose. The *Review* was officially commissioned when British Chancellor of the Exchequer Gordon Brown "asked Sir Nick Stern to lead a major review of the economics of climate change, to understand more comprehensively the nature of the economic challenges and how they can be met, in the UK and globally" (*Stern Review* Web Page 2007). The scientific ground rules of government reports produced by professional scientists and economists are not codified. My vantage point, having been both producer and consumer of government reports, is that we expect them to be factually correct, present a professionally accurate representation of the technical scientific issues, support the government's policies, but not necessarily to be a textbook with a balanced view of all competing theories. By this definition of the ground rules, the *Review* fits well within the boundaries. For the most part, it accurately describes the basic economic questions involved in global warming. However, it tends to emphasize studies and findings that support its policy recommendations, while reports with opposing views of the dangers of global warming are ignored. Such are the rules of the game, but we should be alert in reading the *Review* that—even though it was published by a university press—it is not standard academic analysis.

Putting this point differently, we might evaluate the *Review* in terms of the ground rules of standard science and economics. The central methodology by which science, including economics, operates is peer review and reproducibility. By contrast, the *Review* was published without an appraisal of methods and assumptions by independent outside experts. Nor can its results be easily reproduced.

These may be seen as minor points, but they are fundamental for good science. The British government is not infallible in questions of economic and scientific analysis on global warming, any more than it was in its white paper on weapons of mass destruction in Iraq (UK White Paper on WMD 2002). External review and reproducibility cannot remove all error, but they are essential for ensuring logical reasoning and a respect for opposing arguments. From a practical point of view, these cannot be undertaken after the government and scholars involved have publicly staked out a position, so they also protect the authors from correctible mistakes. This deviation from the norm of modern science does not necessarily discredit the *Review*, but it does mean that fatal flaws in evidence and reasoning, which might have been caught in the early stages under normal ground rules, may emerge after the report has been published.

A related issue is the difficulty that readers may have in understanding the chain of reasoning. The *Review* was prepared in record speed. One of the unfortunate consequences of haste is that the *Review* is a thicket of vaguely connected analyses and reports on the many facets of the economics and science of global warming. Readers will find it difficult to understand or reproduce the line of reasoning that goes from background trends (such as population and technology) through emissions and impacts, to the finding about the 20 percent cut in consumption, now and forever.

In reflecting upon the haste and bulk, I am reminded of a remark by Mark Twain, who said he could write two pages in thirty days or thirty pages in two days, but he could not write two pages in two days. We could only wish that the *Review*'s authors had taken a few more months and written a more concise and consistent treatise.

On a more positive note, while we can question some of the *Review*'s modeling and economic assumptions, it makes an important contribution in selecting climate-change policies with an eye to balancing economic priorities with environmental dangers. By linking climate-change policies to both economic and environmental objectives, in principle if not in practice, the *Review* has corrected one of the fundamental flaws of the Kyoto Protocol, which had no such linkage. By contrast, the parallel analysis of the Bush Administration, cited in footnote 2 above, provided no support for the Bush Administration's rejection of binding emissions constraints on greenhouse gas emissions.

The next comment concerns the *Review*'s emphasis on the need for increasing the price of carbon emissions. The *Review* summarizes its discussion here as follows, "Creating a transparent and comparable carbon price signal around the world is an urgent challenge for international collective action" (p. 530). In plain English, it is critical to have a harmonized carbon tax or the equivalent both to provide incentives to individual firms and households and to stimulate research and development in low-carbon technologies. Carbon prices must be raised to transmit the social costs of greenhouse gas emissions to the everyday decisions of billions of firms and people. This simple economic insight is virtually absent from most political discussions of climate change policy (including the presentation by Al Gore in *An Inconvenient Truth*).

But these points are not the nub of the matter. Rather, the *Review*'s radical view of policy stems from an extreme assumption about discounting. Discounting is a factor in climate-change policy—indeed in all investment decisions—that involves the relative weight of future and present payoffs. At first blush, this area would seem a technicality. Unfortunately, it cannot be buried in a footnote, for discounting is the central to the radical revision. The *Review* proposes ethical assumptions that produce very low discount rates. Combined with other assumptions, this magnifies impacts in the distant future and rationalizes deep cuts in emissions, and indeed in all consumption, today. If we substitute more conventional discount rates used in other global-warming analyses, by governments, by consumers, or by businesses, the *Review*'s dramatic results disappear, and we come back to the climate-policy ramp described above. The balance of this discussion focuses on this central issue.

3. *Discounting in Growth and Climate Change*

Questions of discounting are central to understanding economic growth theory and policy. They also lie at the heart of the *Review*'s radical view of the grave damages from climate change and the need for immediate steps to reduce greenhouse gas emissions sharply. This section reviews some of the core issues, while the next section provides an empirical application of alternative approaches.

3.1 *Alternative Discount Concepts*

Debates about discounting have a long history in economics and public policy. Discounting involves two related and often confused concepts. One is the idea of a discount rate on goods, which is a positive concept that measures the relative price of goods at different points of time. This is also called the real return on capital, the real interest rate, the opportunity cost of capital, and the real return. The real return measures the yield on investments corrected by the change in the overall price level. In principle, this is observable in the marketplace. For example, the real return on twenty-year U.S. Treasury securities in spring 2007 was 2.4 percent per year. Similarly, the real pretax return on U.S. corporate capital over the last four decades has averaged about 6.6 percent per year. Estimated real returns on human capital range from 6 percent per year to 20-plus percent per year depending upon country and time period. The IPCC second assessment report discussed actual returns and reported real returns on investment ranging from 5 to 26 percent per year (Arrow et al. 1996). In my empirical work with aggregated and regional models, based on returns from many studies, I generally use a benchmark real return on capital of around 6 percent per year. Since taxes are excluded, this is the real discount rate on consumption as well.

The second important discount concept involves the relative weight of the economic welfare of different households or generations over time. This is sometimes called the pure rate of social time preference, but I will denote it the "time discount rate" for brevity. It is calculated in percent per unit time, like an interest rate, but refers to the discount in future welfare, not future goods or dollars. A zero time discount rate means that future generations into the indefinite future are treated symmetrically with present generations; a positive time discount rate means that the welfare of future generations is reduced or "discounted" compared to nearer generations. Philosophers and economists have conducted vigorous debates about how to apply time discount rates in areas as diverse as economic growth, climate change, energy policy, nuclear waste, major infrastructure programs such as levees, and reparations for slavery.[7]

The sections that follow examine the analytical and philosophical arguments about intergenerational equity, how discounting affects the measurement of damages, the role of discounting in economic modeling of climate change, saving behavior, and behavior under uncertainty.

[7] Many of the issues involved is discounting, particularly relating to climate change, are discussed in the different studies in Paul R. Portney and John P. Weyant (1999). A useful summary is contained in Arrow et al. (1996). A discussion of the philosophical aspects of Frank P. Ramsey's approach is contained in Dasgupta (2005).

3.2 *The Analytical Background of Optimal Economic Growth*

Like many other economic studies of the economics of global warming, the *Review* puts policy decisions about how to balance emissions reductions with climate damages in the framework of economic growth theory. In this framework, the economies of the world begin with reference paths for consumption, capital, population, emissions, climate, and so on. Policies change the trajectory of emissions, greenhouse gas concentrations, impacts, and consumption. Alternative paths of climate policies and consumption are then evaluated using a social-welfare function that ranks different paths.

The specific approach used to model the economy and to evaluate the outcomes is the Ramsey–Koopmans–Cass model of optimal economic growth.[8] In this theory, a central decisionmaker desires to maximize a social welfare function that is the discounted value of utility of consumption over some indefinite time period. The economic units in the economy are generations or cohorts. We represent their economic activity by a single variable, $c(t)$, which is interpreted as the consumption resources devoted to that generation or cohort on a per capita basis and is discounted to a particular year. (We suppress the details of the decision making of the generation such as the time profile of consumption, life span, working and leisure, as well as individual preferences such as personal risk aversion and time preference as distinct elements not specifically related to the social choices.)

For mathematical convenience, I assume that there is a continuum of generations, so that we can analyze the decisions in continuous time. In this framework, the social welfare function is taken to be an additive separable utilitarian form

[8] See Ramsey (1928), Tjalling C. Koopmans (1965), and David Cass (1965). Most advanced textbooks in macroeconomics develop this model in depth.

$$W = \int_0^\infty U[c(t)]e^{-\rho t}dt.$$

Here, $c(t)$ is the per capita consumption of the generation, $U[.]$ is the utility function used to compare the relative value of different levels of consumption per generation, and ρ is the time discount rate applied to different generations. For simplicity, I assume constant population normalized to 1.

We pause for an important cautionary point. It must be emphasized that the variables analyzed here apply to comparisons over the welfare of different generations and not to individual preferences. The individual rate of time preference, risk preference, and utility functions do not, in principle at least, enter into the discussion or arguments at all. An individual may have high time preference, or perhaps double hyperbolic discounting, or negative discounting, but this has no necessary connection with how social decisions weight different generations. Similar cautions apply to the consumption elasticity.

The *Review* argues that it is indefensible to make long-term decisions with a positive time discount rate: "[Our] argument . . . and that of many other economists and philosophers who have examined these long-run, ethical issues, is that [a positive time discount rate] is relevant only to account for the exogenous possibility of extinction" (p. 60). This point is supported on the argument, which is actually neither necessary nor sufficient, that a positive time discount rate would lead societies to ignore large costs that occur in the distant future. The actual time discount rate used in the *Review* is 0.1 percent per year, which is only vaguely justified by estimates of the probability of extinction; for our purposes, it can be treated as near-zero.

This approach makes the further convenient assumption that the utility function has a constant elasticity of the marginal utility of consumption, which I call "consumption elasticity" for short. This leads to

$$u[c(t)] = c(t)^{1-\alpha}/(1-\alpha)$$

for $0 \le \alpha \le \infty$.

Optimizing the social welfare function with a constant population and a constant rate of growth of consumption per generation, g^*, yields the standard equation for the relationship between the equilibrium real return on capital, r^*, and the other parameters, $r^* = \rho + \alpha g^*$. We call this the "Ramsey equation," which is embraced by the *Review* as the organizing concept for thinking about intertemporal choices for policies for global warming. The Ramsey equation shows that, in a welfare optimum, the rate of return on capital is determined by the generational rate of time preference, the extent to which social policies have aversion to consumption inequality among generations, and the rate of growth of generational consumption. In a growing economy, a high return to capital can arise either from a high time discount rate or high aversion to generational inequality.

How convincing is the *Review*'s argument for its social welfare function, consumption elasticity, and time discount rate? To begin with, there is a major issue concerning the views that are embodied in the social welfare function adopted by the *Review*. The *Review* takes the lofty vantage point of the world social planner, perhaps stoking the dying embers of the British Empire, in determining the way the world should combat the dangers of global warming. The world, according to Government House utilitarianism,[9] should use the combination of time discounting and consumption elasticity that the *Review*'s authors find persuasive from their ethical vantage point.

I have always found the Government House approach misleading in the context of global warming and particularly as it informs the negotiations of policies among sovereign states. Instead, I would interpret the baseline trajectory, from a conceptual point of

[9] The phrase is due to Amartya Sen and Bernard Williams (1982, p. 16), which they describe as "social arrangements under which a utilitarian elite controls a society in which the majority may not itself share those beliefs." Dasgupta (2005) discusses Government House ethics in the context of discounting.

view, as one that represents the outcome of market and policy factors as they currently exist. In other words, the baseline model is an attempt to project from a positive perspective the levels and growth of population, output, consumption, saving, interest rates, greenhouse gas emissions, climate change, and climatic damages as would occur with no interventions to affect greenhouse gas emissions. This approach does not make a case for the social desirability of the distribution of incomes over space or time of existing conditions, any more than a marine biologist makes a moral judgment on the equity of the eating habits of marine organisms in attempting to understand the effect of acidification on marine life.

The calculations of changes in world welfare from efficient climate-change policies examine potential improvements within the context of the existing distribution of income and investments across space and time. As this approach relates to discounting, it requires that we look carefully at the returns on alternative investments—at the *real* real interest rate—as the benchmarks for climatic investments. The normatively acceptable real interest rates prescribed by philosophers, economists, or the British government are irrelevant to determining the appropriate discount rate to use in the actual financial and capital markets of the United States, China, Brazil, and the rest of the world. When countries weigh their self-interest in international bargains about emissions reductions and burden sharing, they will look at the actual gains from bargains, and the returns on these relative to other investments, rather than the gains that would come from a theoretical growth model.

3.3. *Philosophical Questions about the Time Discount Rate*

Although I find the ethical reasoning on discount rates in the *Review* largely irrelevant for the actual investments and negotiations about climate change, it is worth considering the arguments on their own merits. At the outset, we should recall the warning that Koopmans gave in his pathbreaking analysis of discounting in growth theory. He wrote, "[T]he problem of optimal growth is too complicated, or at least too unfamiliar, for one to feel comfortable in making an *entirely* a priori choice of [a time discount rate] before one knows the implications of alternative choices" (Koopmans 1965).[10] This conclusion applies with even greater force in global warming models, which have much greater complexity than the simple, deterministic, stationary, two-input models that Koopmans analyzed.

The *Review* argues that fundamental ethics require intergenerational neutrality as represented by a near-zero time discount rate. The logic behind the *Review*'s social welfare function is not as universal as it would have us believe. It stems from the British utilitarian tradition with all the controversies and baggage that accompany that philosophical stance.[11] Quite another ethical stance would be to hold that each generation should leave at least as much total societal capital (tangible, natural, human, and technological) as it inherited. This would admit a wide array of time discount rates. A third alternative would be a Rawlsian perspective that societies should maximize the economic well-being of the poorest generation. The ethical implication of this policy would be that current consumption should *increase* sharply to reflect the projected future improvements in productivity. Yet another approach would be a precautionary (minimax) principle in which societies maximize the minimum consumption along the riskiest path; this might involve stockpiling vaccines, grain, oil, and water in contemplation of possible plagues and famines. Yet further perspectives would consider ecological values in addition to

[10] Zero discounting leads to deep mathematical problems such as nonconvergence of the objective function and incompleteness of the functional.

[11] Many of the concerns in the following paragraphs are discussed in the attacks and defenses of utilitarianism in Amartya Sen and Bernard Williams (1982).

anthropocentric values. The morals of major religions—present and future—might clash with the utilitarian calculus of Ramsey growth theories.

However, none of these approaches touches on the structure of actual intertemporal decision making, in which this generation cannot decide for or tie the hands of future generations.[12] Instead, each generation is in the position of one member of a relay team, handing off the baton of capital to the next generation, and hoping that future generations behave sensibly and avoid catastrophic choices by dropping or destroying the baton. Moreover, because we live in an open-economy world of sometimes-competing and sometimes-cooperating relay teams, we must consider how the world capital market will equilibrate to the simultaneous relay races, baton-dropping, existential wars, and differing norms over space and time.

None of these alternatives is seriously considered by the *Review.* Without choosing among these alternatives, it should be clear that alternative ethical perspectives are possible. Moreover, as I suggest below, alternative perspectives provide vastly different prescriptions about desirable climate-change policies.

A final issue involves the analytical framework of the discounted utility model in growth theory. While most of the debate involves discounting, another set of issues involves the foundations of the utility function. These issues have been reviewed extensively in this *Journal* and will not be discussed at length here.[13] I will add one further note concerning the interpretation of utility at distant horizons. It seems a natural starting point to assume that people with equivalent consumption bundles should be treated as having the same level of economic welfare. Moreover, this assumption seems reasonable where it involves the same person at points of time that are not very far apart.

This approach is more difficult to interpret when it involves different generations living many years from now, and it arises with particular force when the current generation's great(n)-grandchildren consume goods and services that are largely unimagined today. These will almost certainly involve unrecognizably different health-care technologies, with supercomputers cheap enough and small enough to fit under the skin, and future generations that grow up and adapt to a world that is vastly different from that of today. It would be useful to determine how robust our prescriptions are to alternative formulations of the preference structures. These would include preferences where utility adapts to the level of consumption, or where consumption is compared to the last generation, or where large parts of the population lose interest in economic goods and turn to ascetic pursuits, or where rich nations use higher productivity to develop fiendish new weapons, or where people come to love the altered landscape of the warmer world. Perhaps we need to consider a model with uncertainty about preferences along with uncertainty about extinction, but this is largely uncharted territory in economic growth theory.

3.4. *Real Interest Rates under Alternative Calibrations of the Ramsey Equation*

While time discount rates get most of the headlines, the real return on capital is the variable that drives efficient current emissions reductions. It is the real return on capital that enters into the equality between the marginal consumption cost of emissions reductions today and the discounted marginal consumption benefit of reduced climate damages in the future.

However, in the optimal growth framework, the real return is an endogenous variable that is determined by the Ramsey equation discussed above. In equilibrium, the real interest rate depends not only on the time discount rate but also upon a second

[12] Such is the spirit of the study of E. S. Phelps and R. A. Pollak (1968).

[13] See Shane Frederick, George Loewenstein, and Ted O'Donoghue (2002).

ethical parameter, the consumption elasticity. A realistic analysis would also need to account for distortions from the tax system, for uncertainties, and for risk premiums on investments, but these complications will be ignored in the present context.[14]

The *Review* assumes that the consumption elasticity is $\alpha = 1$, which yields the logarithmic utility function. The elasticity parameter is casually discussed, with no justification in the original report.[15] With its assumed long-run growth of per capita output of 1.3 percent per year and the time discount rate of 0.1 percent per year, this leads to an equilibrium real interest rate of 1.4 percent per year. This rate is apparently used in a partial-equilibrium framework without any reference to either actual rates of return or to the possibility that the economy might not have reached the long-run equilibrium.

Even though the real interest rate is crucial to balancing present and future, there is no apparent reference to any of this in the *Review*. However, in calibrating a growth model, the time discount rate and the consumption elasticity cannot be chosen independently if the model is designed to match observable real interest rates and savings rates. To match a real interest rate of, say, 4 percent and a growth in per capita consumption of 1.3 percent per year requires some combination of high time discounting and high consumption elasticity. For example, using the *Review*'s economic growth, a zero time discount rate requires a consumption elasticity of 3 to produce a 4 percent rate of return. If we adopt the Stern consumption elasticity of 1, then we need a time discount rate of 2.7 percent per year to match observed rates of return.

The experiments for the DICE-2007 model discussed later in this review are slightly different from these equilibrium calculations because of population growth and nonconstant consumption growth, but we can use the equilibrium calculations to give the flavor of the results. In the baseline empirical model, I adopt a time discount rate of 1.5 percent per year with a consumption elasticity of 2. These yield an equilibrium real interest rate of 5.5 percent per year with the consumption growth that is projected over the next century by the DICE-2007 model. It turns out that the calibration of the utility function makes an enormous difference to the results in global-warming models, as I show in the modeling section below.

The *Review*'s approach also has an important implication for consumption and saving.[16] If the *Review*'s philosophy were adopted, it would produce much higher overall saving as compared with today. To a first approximation, the *Review*'s assumptions about time discounting and the consumption elasticity would lead to a doubling of the optimal global net savings rate. While this might be worth contemplating, it hardly seems ethically compelling. Global per capita consumption today is around $10,000. According to the *Review*'s assumptions, this will grow at 1.3 percent per year, to around $130,000 in two centuries. Using these numbers, how persuasive is the ethical stance that we have a duty to reduce current consumption by a substantial amount to improve the welfare of the rich future generations?

3.5 *A Fiscal-Policy Experiment*

We can put the Ramsey analysis in an intuitive manner by considering a fiscal

[14] The interpretation of the divergence between the rate of return on capital and the risk-free rate raises an issue in this context. If we assume that this gap is determined in markets as a systematic premium on risky assets, then we would need to investigate the risk characteristics of investments in climate change. The discussion here assumes that climatic investments share the risk properties of other capital investments. If they were shown to have more or less systematic risk, then the risk premium on climatic investments would need to be appropriately adjusted.

[15] The discussion of the consumption elasticity is contained in the appendix to chapter 2. Note as well that since the consumption elasticity is a parameter that reflects social choices about consumption inequality across generations, it cannot be automatically derived from individual preferences or risk aversion.

[16] This point was emphasized by Dasgupta (2007).

experiment that asks whether a particular abatement policy improves the consumption possibilities of future generations. Begin with the path of consumption that corresponds to the current state of affairs—one in which there are essentially no policies to reduce greenhouse gas emissions. Call this path the "baseline" trajectory.

Then, adopt a set of abatement strategies that correspond to the optimum in the Ramsey growth model. However, along with this optimal abatement strategy, we undertake fiscal tax and transfer policies to maintain the baseline consumption levels for the present (say for fifty years). The optimum might have slightly lower consumption in the early years, so the fiscal-policy experiment would involve both abatement and fiscal deficits and debt accumulation for some time, followed by fiscal surpluses and debt repayment later. Call this the "optimal-plus-deficit" strategy. In essence, this alternative keeps consumption the same for the present but rearranges societal investments away from conventional capital (structures, equipment, education, and the like) to investments in abatement of greenhouse gas emissions (in "climate capital," so to speak).

Assuming that the investments and fiscal policies are efficiently designed, so that capital continues to earn its marginal product as measured by the market real return, the optimal-plus-deficit strategy will increase the consumption possibilities of all future generations (those coming after fifty years). In other words, the optimal abatement policies (compared with no abatement) by construction must be Pareto-improving. Under the optimal policies, the optimal investments in climate capital must raise future output by more than enough to repay the debt.

What about the very tight emissions reductions policies proposed in the *Review*? Consider undertaking the *Review*'s emissions-control strategy and using fiscal policies to keep consumption unchanged for fifty years—that is the "*Review*-plus-deficit" strategy. It is certain that (using returns on capital that match estimated market returns) the *Review*'s strategy would leave future generations with less consumption than the optimum-plus-deficit. Indeed, by my calculations, the *Review*'s strategy would leave the future absolutely worse off—it would be Pareto-deteriorating. The reason why the *Review*'s approach is inefficient is that it invests too much in low-yield abatement strategies too early. After fifty years, conventional capital is much reduced, while "climate capital" is only slightly increased. The efficient strategy has more investment in conventional capital at the beginning and can use those additional resources to invest heavily in climate capital later on.

3.6 *Measuring Impacts with Near-Zero Discounting*

These analytical points are useful for understanding the *Review*'s estimates of the damages from climate change. The *Review* concludes, "Putting these . . . factors together would probably increase the cost of climate change to the equivalent of a 20% cut in per-capita consumption, now and forever." This frightening statement suggests that the globe is perilously close to driving off a climatic cliff in the very near future. Faced with such a grave prospect, any sensible person would surely reconsider current policies.

A close look reveals that the statement is quite misleading because it employs an unusual definition of consumption losses. When the *Review* says that there are substantial losses "now," it does not mean "today." The measure of consumption used is the "balanced growth equivalents" of consumption, which is essentially a proportional income annuity. With zero discounting, this is the certainty equivalent of the average annual consumption loss over the indefinite future.

In fact, the *Review*'s estimate of the output loss now, as in "today," is essentially zero. Moreover, the projected impacts from climate change are far into the future. Take as an example the high-climate scenario with catastrophic and nonmarket impacts. For this case, the mean losses are 0.4 percent of world output in 2060, 2.9 percent in 2100, and 13.8 percent in 2200 (figure 6.5d, pp. 177–78). This is calculated as a loss in "current per capita consumption" of 14.4 percent shown in table 6.1. With even further gloomy adjustments, it becomes the "high+" case of "20% cut in per-capita consumption, now and forever."

How do damages, which average around 1 percent of output over the next century, become a 14.4 percent reduction in consumption now and forever? The answer is that, with near-zero discounting, the low damages in the next two centuries get overwhelmed by the long-term average over the many centuries that follow. In fact, using the *Review*'s methodology, more than half of the estimated damages "now and forever" occur after the year 2800. The damage puzzle is resolved. The large damages from global warming reflect large and speculative damages in the far-distant future magnified into a large current value by a near-zero time discount rate.

3.7 *A Wrinkle Experiment*

The effect of low discounting can be illustrated with a "wrinkle experiment." Suppose that scientists discover a wrinkle in the climate system that will cause damages equal to 0.1 percent of net consumption starting in 2200 and continuing at that rate forever after. How large a one-time investment would be justified *today* to remove the wrinkle that starts only after *two centuries*? Using the methodology of the *Review,* the answer is that we should pay up to 56 percent of one year's world consumption today to remove the wrinkle (box 6.3, pp. 183–85). In other words, it is worth a one-time consumption hit of approximately \$30,000 billion today to fix a tiny problem that begins in 2200.[17]

It is illuminating to put this point in terms of average consumption levels. Using the *Review*'s growth projections, the *Review* would justify reducing per capita consumption for one year today from \$10,000 to \$4,400 in order to prevent a reduction of consumption from \$130,000 to \$129,870 starting two centuries hence and continuing at that rate forever after.

The bizarre result arises because the value of the future consumption stream is so high with near-zero time discounting that we would trade off a large fraction of today's income to increase a far-future income stream by a very tiny fraction. This is yet another reminder of Koopmans's warning quoted above to proceed cautiously to accept theoretical assumptions about discounting before examining their full consequences.

3.8 *Hair Triggers and Uncertainty*

A related feature of the *Review*'s near-zero time discount rate is that it puts present decisions on a hair-trigger in response to far-future contingencies. Under conventional discounting, contingencies many centuries ahead have a tiny weight in today's decisions. Decisions focus on the near future. With the *Review*'s discounting procedure, by contrast, present decisions become extremely sensitive to uncertain events in the distant future.

[17] A simplified derivation of this result is as follows. For this derivation, assume that the rate of growth of consumption is constant at g, that population is constant, that initial consumption is $C(0)$, and that the Ramsey equation holds with the *Review*'s parameters. In this case, the growth corrected discount rate is $\theta = r - g = 0.001$ per year. The wrinkle assumes that there are damages equal to a constant fraction $\lambda = 0.001$ of consumption starting two hundred years in the future. Using linear utility, the present value of the damages from the wrinkle is

$$\int_{200}^{\infty} \lambda C(t) e^{-\theta t} dt = \lambda C(0) e^{-\theta 200} / \theta =$$
$$\lambda C(0) 0.818 / .001 = 0.818 C(0).$$

For linear utility, the wrinkle has present value of 81.8 percent of one year's current consumption. The number in the text is slightly lower because of curvature of the utility function.

We saw above how an infinitesimal impact on the post-2200 income stream could justify a large consumption sacrifice today. We can use the same example to illustrate how far-future uncertainties are magnified by low discount rates. Suppose that the climatic wrinkle is not a sure thing; rather, there is a 10 percent probability of a wrinkle that would reduce the post-2200 income stream by 0.1 percent. What insurance premium would be justified today to reduce that probability to zero? With conventional discount rates, and one might say with common sense, we would ignore any tiny low-probability wrinkle two centuries ahead.

With the *Review*'s near-zero discount rate, offsetting the low-probability wrinkle would be enormously valuable. We would pay an insurance premium today of as much as 8 percent of one year's consumption (about $4 trillion) to remove the year-2200 contingency. If the contingency were thought to occur in 2400 rather than 2200, the insurance premium would still be 6.5 percent of one year's income. Because the future is so greatly magnified by a near-zero time discount rate, policies would be virtually identical for different threshold dates. Moreover, a small refinement in the probability estimate would trigger a large change in the dollar premium. If someone discovered that the probability was 15 percent rather than 10 percent, the insurance premium would rise by almost $2 trillion.

While this feature of low discounting might appear benign in climate-change policy, we could imagine other areas where the implications could themselves be dangerous. Imagine the preventive war strategies that might be devised with low time discount rates. Countries might start wars today because of the possibility of nuclear proliferation a century ahead; or because of a potential adverse shift in the balance of power two centuries ahead; or because of speculative futuristic technologies three centuries ahead. It is not clear how long the globe could long survive the calculations and machinations of zero-discount-rate military strategists. This is yet a final example of a surprising implication of a low discount rate.

4. *Modeling Alternative Discount Strategies in the DICE-2007 Model*

The analytical points discussed in earlier sections can usefully be illustrated using an empirical model of the economics of global warming. It is virtually impossible for those outside the modeling group to understand the detailed results of the *Review*. It would involve studying the economics and geophysics in several chapters, taking apart a complex analysis (the PAGE model), and examining the derivation and implications of each of the economic and scientific judgments. Understanding the analysis is made even more difficult because the detailed calculations behind the *Review* have not been made available.

The alternative approach followed here is to use a small and well-documented model of the economics of climate change to estimate the optimal policy, and then to make parameter adjustments to parallel assumptions made in the *Review.* For this purpose, I use the DICE model, which is an acronym for a Dynamic Integrated model of Climate and the Economy. This model, developed in the early 1990s, uses a simple dynamic representation of the scientific and economic links among population, technological change, greenhouse gas emissions, concentrations, climate change, and damages.[18]

The analytical structure of the DICE model is identical to that in the *Review.* DICE calculates the paths of capital investment and greenhouse gas reductions that maximize a social welfare function, where the social welfare function is the discounted sum of population-weighted utilities of per

[18] Results and documentation of the DICE model are provided in William Nordhaus (1992), Nordhaus (1994), Nordhaus and Zili Yang (1996), Nordhaus and Joseph Boyer (2000), Nordhaus (2001), and DICE model web site (2007).

capita consumption. For this analysis, I have used the DICE-2007.delta.v7 model. This is a completely revised version of the earlier DICE and RICE models incorporating the latest available data, economics, and science.[19] The model uses a time discount rate of 1.5 percent per year along with a consumption elasticity of 2. These parameters were chosen to be consistent with market interest rates and savings rates.

I then make three runs, which are explained as we proceed: run 1—*optimal climate change policy in the DICE-2007 model*; run 2—*optimal climate change using the Stern Review zero discount rate*; and run 3—*optimal climate change with zero discount rate and recalibrated consumption elasticity*.

Run 1 calculates the *optimal climate change policy in DICE-2007.* This run takes the DICE-2007 model and calculates the optimal trajectory of climate change policies as described above. Some discussion of the terminology is needed here. The "social cost of carbon" is the marginal damage caused by an additional ton of carbon emissions. In a dynamic framework, it is the discounted value of the change in the utility of consumption denominated in terms of current consumption. The "optimal carbon price," or "optimal carbon tax," is the price (or carbon tax) on carbon emissions that balances the incremental costs of reducing carbon emissions with the incremental benefits of reducing climate damages. In an uncontrolled regime, the social cost of carbon will exceed the (zero) carbon price. In an optimal regime, the carbon tax will equal the social cost of carbon. The "emissions reduction rate" is relative to a no-controls baseline.

Run 1 calculates the optimal carbon price in 2015 to be $35 per ton C, rising over time to $85 in 2050 and to $206 in 2100 (all data are in 2005 U.S. dollars). The social cost of carbon without emissions restraints in 2015 is also $35 per ton C.[20] The optimal rate of emissions reduction is 14 percent in 2015, 25 percent in 2050, and 43 percent in 2100.[21] This optimized path leads to a projected global temperature increase from 1900 to 2100 of around 2.3 degrees C. While the findings of such mainstream economic assessments may not satisfy the most ardent environmentalists, they would go far beyond the meager policies currently in place.

The results of the standard DICE model just discussed are completely different from those in the *Review.* The *Review* estimates that the current social cost of carbon in the uncontrolled regime is $350 per ton C in 2005 prices ($85 per ton of carbon dioxide and in 2000 prices) (p. 344). This number is ten times the DICE model result. Based on calculations made in earlier publications (see footnote 18), it seems likely that the major reason for the *Review*'s sharp emissions reductions and high social cost of carbon is the low time discount rate. I therefore calculated run 2, *optimal climate change using the Stern Review zero discount rate.* The assumptions are the same as run 1 except that the time discount rate is changed to 0.1 percent per year and the consumption elasticity is changed to 1. This dramatically changes the trajectory of climate-change policy. The 2015 optimal carbon price in the DICE model rises from $35 in run 1 to $360 per ton C in run 2. Efficient emissions reductions in run 2 are much larger—with emissions reductions of 53 percent in 2015—because future damages are in effect treated as occurring today. So run 2 confirms the intuition that a low real return on capital leads to a very high initial carbon price and

[19] Documentation of the changes in the DICE-2007 model and the GAMS computer program for the DICE-2007 model are provided at DICE model web site (2007).

[20] The year "2015" refers to the ten-year period covering 2010–19. This is assumed to be the first period in which full implementation can take place.

[21] The future numbers are the solutions to the model based on current information and provide estimates of optimal future policies under current estimates of parameters. They are not decisions that are taken today. They should be revised over time as new scientific and economic information becomes available.

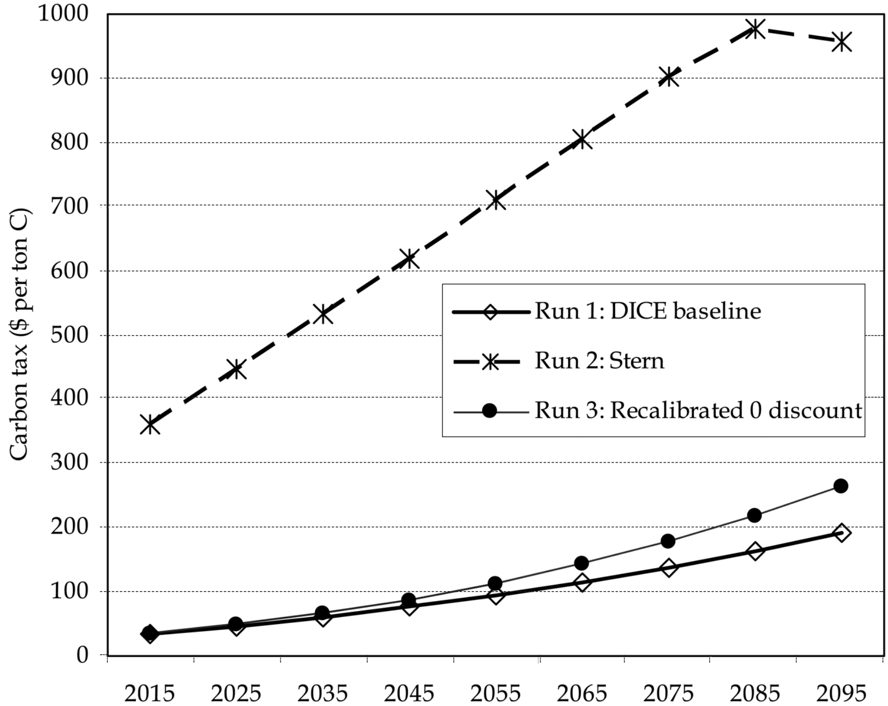

Figure 1. Optimal Carbon Tax in Alternative Runs

Note: This shows the calculated optimal carbon tax, or price that equilibrates the marginal cost of damages with the marginal cost of emissions, in the different runs. These numbers are slightly below the estimated social cost of carbon for the uncontrolled runs. Figures are 2005 U.S. international prices per ton carbon. To get prices per ton of carbon dioxide, the number should be divided by 3.67. The period is the decade centered on the year shown.

very sharp initial emissions reductions. The climate-policy ramp flattens out.

One of the problems with run 2 is that it generates real returns that are too low and savings rates that too high as compared with actual market data. We correct this with run 3, *optimal climate change with zero discount rate and recalibrated consumption elasticity.* This run draws on the Ramsey equation; it keeps the near-zero time discount rate and calibrates the consumption elasticity to match observable variables. This calibration yields parameters of $\rho = 0.1$ percent per year and $\alpha = 3$. The calibration produces a real return on capital for the first eight periods of 5.6 percent per year for run 3 as compared with an average for run 1 of 5.5 percent per year. Run 2 (the *Review* run) has a real return of 2.0 percent per year over the period.

Run 3 looks very similar to run 1, the standard DICE-2007 model optimal policy. The optimal carbon price for run 3 in 2015 is $36, which is slightly above run 1's $35 per ton C. The recalibrated run looks nothing like run 2, which reflects the *Review*'s assumptions. How can it be that run 3, with a near-zero time discount rate, looks so much like run 1? The reason is that run 3 is calibrated to that ensure it produces the market return to capital. This calibration removes, for the near term at least, the cost–benefit dilemmas as well as the savings and uncertainty problems discussed above.

Figures 1 and 2 show the time paths of interest rates and optimal carbon taxes under the three runs examined here. These figures illustrate the point that it is not the time discount rate itself which determines

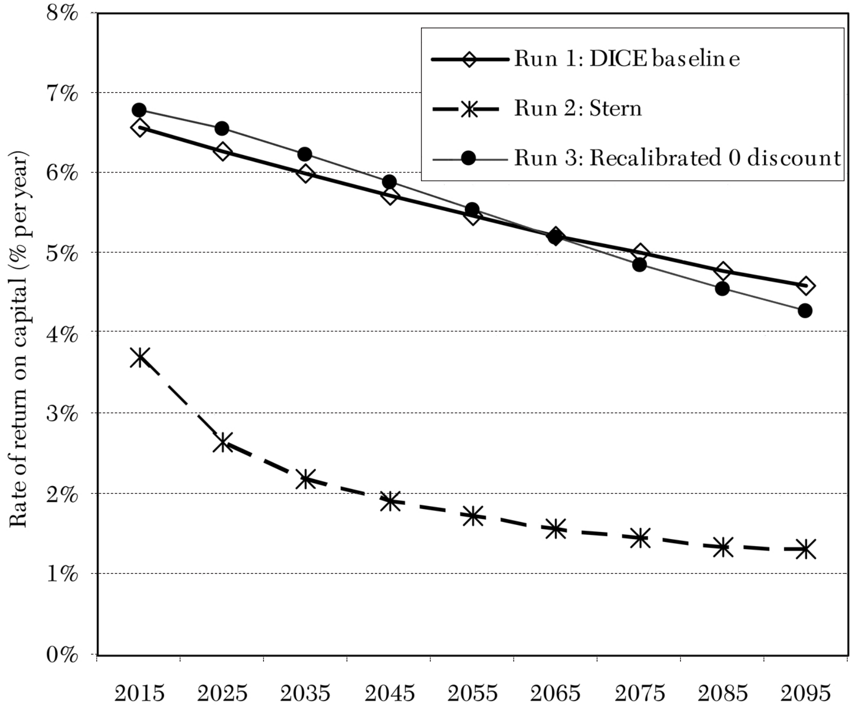

Figure 2. Rate of Return on Capital in Alternative Runs

Note: This shows the marginal product of capital in the different runs. Conceptually, the return is the discount rate on consumption from one period to the next. Note that there is no inflation, risk, or taxes in the model. The figure is the estimated geometric average real return from the date shown to the next date.

that high carbon tax in the *Review* runs, but the combination of the time discount rate and consumption elasticity as they work through the rate of return on capital.

These experiments highlight that the central difference between the *Review* and many other economic models lies in the implicit real return on capital embedded in the model. The *Review*'s calibration gives too low a rate of return and too high a savings rate compared to actual macroeconomic data. If the model is designed to fit current market data, then the modeler has one but not two degrees of freedom in choosing the time discount rate and the consumption elasticity. The *Review* seems to have become lost in the discounting trees and failed to see the capital market forest by overlooking the constraints on the two normative parameters.

Since this analysis was first undertaken, similar results have been found by other modelers. A particularly enlightening set of runs was made by Chris Hope, who is the designer of the PAGE model that was used for some economic modeling runs in the *Stern Review.* Hope attempted to replicate the *Review*'s results in his own model. He found that, using his assumed assumptions and discount rates, the mean social cost of carbon was \$43 per ton C. Simply substituting the 0.1 percent per year discount rate into the PAGE model raises the mean social cost of carbon from \$43 per ton C to \$364 per ton C, which is close to the ratio found here (Hope 2006). A study by Mityakov (2007), using yet another calibrated model of the economics of global warming, finds that the *Review*'s discounting assumptions raise the present value of damages by a factor of 8 to 16 depending upon the baseline discount rate.

What should the prudent reader conclude from all this? There are many perspectives through which to view the future costs and benefits of policies to slow global warming. These perspectives differ in terms of normative assumptions, national interests, estimated behavioral structures, scientific data and modeling, risk aversion, and the prospects of future learning. No sensible policymaker would base the globe's future on a single model, a single set of computer runs, or a single national or ethical perspective. Sensible decision making requires a robust set of alternative scenarios and sensitivity analyses to determine whether some rabbit has in the dead of night jumped into the hat and is responsible for unusual results. One of the major flaws in the *Review* is the absence of just these robustness analyses.

5. *Summary Verdict*

How much and how fast should the globe reduce greenhouse gas emissions? How should nations balance the costs of the reductions against the damages and dangers of climate change? The *Stern Review* answers these questions clearly and unambiguously: we need urgent, sharp, and immediate reductions in greenhouse gas emissions.

I am reminded here of President Harry Truman's complaint that his economists would always say, on the one hand this and on the other hand that. He wanted a one-handed economist. The *Stern Review* is a President's or a Prime Minister's dream come true. It provides decisive answers instead of the dreaded conjectures, contingencies, and qualifications.

However, a closer look reveals that there is indeed another hand to these answers. The *Review*'s radical revision of the economics of climate change does not arise from any new economics, science, or modeling. Rather, it depends decisively on the assumption of a near-zero time discount rate combined with a specific utility function. The *Review*'s unambiguous conclusions about the need for extreme immediate action will not survive the substitution of assumptions that are more consistent with today's marketplace real interest rates and savings rates. Hence, the central questions about global-warming policy—how much, how fast, and how costly—remain open. The *Review* informs but does not answer these fundamental questions.

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