Supplementary Material for

The Behavioral Economics and Politics of Global Warming

Unsettling Behaviors

by

Hersh Shefrin
Santa Clara University

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Riccardo Rebonato
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Appendices To

THE BEHAVIORAL ECONOMICS AND POLITICS OF GLOBAL WARMING

Unsettling Behaviors

Hersh Shefrin
Santa Clara University

Appendix to Section 1

I wrote this Element mainly for economists or those familiar with economic methodology. That said, the main messages of the book can be easily understood by readers without a formal background in economics. This appendix is aimed at readers who want a quick sense of the key takeaways from the Element, or would like a synopsis describing the flow of the Element, section-by-section. While these discussions feature some repetition, they can help readers see the forest for the trees.

A1.1 Key Takeaways

More than two thirds of anthropogenic cumulative emissions of carbon dioxide into the atmosphere have occurred since 1979, when the landmark Charney report was published. This feature is the result of unsettling behaviors. Despite IPCC reports, COP meetings, and debates among economists, global emissions persist at or near business-as-usual behavior, defined as the base case in economist William Nordhaus' integrated assessment model.

Neoclassical economists have argued for decades that carbon dioxide emission levels should be significantly lower than business-as-usual, in line with carbon being priced at its social cost. The most expeditious way to price carbon at its social cost is through a carbon tax. There is good reason to believe that a carbon tax would reduce carbon dioxide emissions.[1] Conversely, if the global community continues along a business-as-usual trajectory, carbon emissions will continue to grow well past mid-century, to the point where, at century-end, the atmospheric temperature will likely be more than 4°C above preindustrial levels.

Nordhaus' model, called DICE, implies that for emissions to peak by mid-century, and reach net zero by 2115, the global community will need to reduce aggregate consumption by between 0.1 percent and 0.2 percent below the business-as-usual trajectory. In concrete terms, this means that a household whose business-as-usual consumption is $100,000 per year would sacrifice between $100 and $200 annually, for the rest of the century.[2] A carbon tax trajectory that would induce this sacrifice would feature about $45 in 2025, $50 in 2030, and $90 in 2050.

[1] See Ramey, Valerie and Daniel Vine, 2010. "Oil, Automobiles, and the U.S. Economy: How Much Have Things Really Changed?" *NBER Macroeconomics Annual Volume,* 25. https://www.journals.uchicago.edu/doi/full/10.1086/657541

[2] The trajectory begins at $100 and gradually increases to $200.

As a result, by century-end, the atmospheric temperature will likely rise by 3.5°C above pre-industrial levels.

Having emissions peak at mid-century is a weak goal. A stronger goal is for emissions to reach net zero by mid-century. A modified version of Nordhaus' model implies that for this to occur, consumption reductions from business-as-usual levels would begin at about 2.5 percent by 2025 and increase to about 5 percent over the course of the century.[3] In concrete terms, this means that a household whose business-as-usual consumption is $100,000 per year would initially sacrifice $2,500 with the amount growing to $5,000 towards the end of the century. A carbon tax trajectory that would induce this sacrifice would feature about $230 in 2025, $290 in 2030, and $460 in 2050.[4] As a result, by century-end, the atmospheric temperature will likely rise by 2.3°C above pre-industrial levels.[5]

The actual price of carbon is well below Nordhaus' estimate of the social cost of carbon, let alone the value associated with achieving net zero emissions by mid-century.[6] If this state of affairs continues, emissions will likely continue along a trajectory corresponding to business-as-usual behavior.

There is strong evidence that globally, the actual price of carbon has been and continues to lie below 10 percent of the social cost associated with achieving net zero emissions by

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[3] For context, aggregate consumption in the US fell by 4 percent during the Great Recession of 2007-2009.

[4] Once the economy reaches net zero and stabilizes there, the social cost of carbon will tend to decline with cost reduction advances in abatement technology. Under Nordhaus' assumptions, net zero is not achieved until 2115, and the social cost of carbon increases over the century, reaching $271 in 2100. In the case where net zero is achieved in 2045, the social cost of carbon declines from 2050 on, falling to $358 in 2100, from its peak of $452.

[5] The global community has been focusing on limiting temperature increases to the range 1.5°C to 2°C. This range is lower than the estimates from Nordhaus' DICE framework. Nordhaus' climate assumptions are consistent with the Charney report, which provides confidence intervals, besides point estimates.

[6] As I mention below, the approach in the *Stern Review* is stronger yet. Stern's solution requires the global community to do the following. First, reduce aggregate consumption immediately by roughly 8 percent below the business-as-usual trajectory. Thereafter follow a trajectory in which the 8 percent declines over time, reaching 4 percent by mid-century and zero by the end of the century. Notably, Stern's assumptions imply a much higher saving rate than occurs with Nordhaus' assumptions. This explains the initial decrease of 8 percent. A model that maintains Nordhaus' assumptions about preferences but modifies the damage function to allow for tipping points produces a similar trajectory for the social cost of carbon as Stern's estimates, but with a lower savings trajectory. In particular, the optimal case, described above, features consumption reductions that begin at about 2.5 percent relative to the business-as-usual trajectory, and increase to about 5 percent over the course of the century. In the tipping point model, abatement costs are about 1 percent in 2020, and rise to 4 percent before mid-century.

mid-century.[7] Amazingly, a portion of the discrepancy arises because of fossil fuel subsidies, which reduce the actual price of carbon by at least a third.

The sacrifices in consumption discussed above are not the result of unemployment, but the diversion of resources to increase emissions abatement and investment. In this respect, resources diverted from consumption to combat global warming are akin to resources allocated to the military. As a fraction of total output, the cost of abatement is 0.1 percent in 2025, if consumption is reduced by 0.1 percent; but it is 1.6 percent if consumption is reduced by 2.5 percent. By way of contrast, between 2000 and 2010, when the US invaded Iraq, US military expenditures increased from just over 3 percent to just under 5 percent.[8]

The large gap between the price of carbon and its social cost is unsettling and invites the big behavioral question: What explains the global community's reluctance to moving sharply away from business-as-usual behaviors by following economists' advice about instituting a global carbon tax?

The short answer to the big behavioral question is psychological pitfalls, especially present bias. In this respect, the traditional economics literature, by and large, has focused on estimating the social cost of carbon, but not on the psychological forces which lead to the persistence of business-as-usual behavior.

A century ago, economist Irving Fisher described the challenges of exhibiting self-control by using the analogy of problem drinking, meaning excessive consumption of alcohol. The analogy is apt, because needing to reduce general consumption to address global warming is akin to someone with a drinking problem needing to reduce the amount they drink. It is not easy, and problem drinkers often resist advice to seek treatment. Addiction and dopamine are key factors. Likewise, the global community resists the call to price carbon at its social cost because doing so will lead to lower consumption as a result. Such behavior results in trusting to luck, which Fisher also discussed.

There are signs that the global community is moving away from business-as-usual behavior, by increasing investment in technology, not by pricing greenhouse gases near their

[7] In DICE, the price of carbon associated with business-as-usual behaviors lies between 6 and 10 percent of the social cost of carbon implied by the model.

[8] See https://tradingeconomics.com/united-states/military-expenditure-percent-of-gdp-wb-data.html#:~:text=Military%20expenditure%20(%25%20of%20GDP)%20in%20United%20States%20was%20reported,compiled%20from%20officially%20recognized%20sources.

respective social costs. There is reason to hope that technological advances will be beneficial. At the same time, the reluctance to use a carbon tax or equivalent cap-and-trade mechanism results in abatement being more costly than necessary, by a factor of five-to-seven.

Nudge strategies for altering behavior, which have been successful in other domains, have had no discernable net positive impact on reducing greenhouse gas emissions. The most successful nudge program, called "Save More Tomorrow" (SMT), helps people to overcome present bias and increase their personal saving rates. An important element of SMT is that saving rates follow a gentle ramp pattern. Notably, Nordhaus recommended that climate policy follow a ramp in respect to the trajectory for the social cost of carbon. The climate counterpart to SMT is GMT, "Green More Tomorrow" (GMT). However, no GMT has been instituted at the global level.

There are limits to nudges. Indeed, the only significantly successful climate nudges appear to be dark nudges, designed to encourage present bias and the maintenance of business-as-usual behaviors. As I discuss in Section 5, there was a point in the 1990s when a version of GMT might have been passed into US law. However, a dark nudging campaign initiated by the Koch brothers managed to derail the effort.

The big behavioral question has only become bigger over time. Nordhaus was excessively optimistic about the global community being able to price carbon at its social cost, about reducing the rate of greenhouse gas emissions, about the risk posed by climate tipping points, about the degree to which global temperatures would rise during the current century, and about the cost of failing to achieve net zero emissions by mid-century.

Emission rates in the US and the EU peaked around 2005, and have been declining since that time. Currently, the country with the most greenhouse gas emissions is China. Its annual rate of emissions has been growing, although for structural reasons the growth rate of its economy began to slow in 2022.[9] Between 1979 and 2021, the percentage contributions of China and the US to global carbon dioxide emissions were each about 20 percent. However, between 2005 and 2021, China's contribution rose to about27 percent while that of the US declined to about 16

[9] Lingling Wei and Stella Yifan Xie, 2023. "China's 40-Year Boom Is Over. What Comes Next?" *Wall Street Journal*, August 20. https://www.wsj.com/world/china/china-economy-debt-slowdown-recession-622a3be4?mod=WTRN_pos1&cx_testId=3&cx_testVariant=cx_164&cx_artPos=0. See also Shefrin, Hersh, 2023. "Risks Facing China Now That Its Minsky Moment Has Begun." *Forbes*. http://www.forbes.com/sites/hershshefrin/2023/09/30/risks-facing-china-now-that-its-minsky-moment-has-begun/

percent. In this respect, per dollar of economic activity, China's economy emits between 70 percent and 200 percent more carbon dioxide into the atmosphere than the US.

An important economic debate took place in 2007 between Nordhaus and Nicholas Stern. Many of the issues which surfaced during this debate were implicitly behavioral. Nordhaus argued that Stern's more aggressive trajectory was behaviorally infeasible, in that it required behaviors associated with saving and capital accumulation that would be unrealistically high.[10] These unrealistic behaviors stemmed from rates of return on capital that would be unrealistically low.

After 2007, real rates of return on capital remained largely unchanged, even as real interest rates fell dramatically.[11] Nordhaus' assumptions pertain to the return on capital, not the rate of interest on government debt. Nevertheless, in 2023 the Environmental Protection Agency (EPA) significantly increased its estimate of the social cost of carbon, partly because of the decline in real interest rates.

In the US, the resistance to instituting a carbon tax, let alone pricing carbon at its social cost, stems from both the right and left elements on the political spectrum. Psychological biases, especially present bias, lie at the root of my analysis of the big behavioral question. The estimate cost of such reluctance is very high, essentially raising the cost of abatement by a factor of five-to-seven.

Assumptions about technological progress and damage caused by emissions are critical to the determination of climate policy. Notably, Nordhaus assumes that the rate of technological progress will be high enough to support meaningful adaptation to significant increases in temperatures, even in the case of business-as-usual behavior. He also assumes that there will be significant improvements in abatement technology over time. As I inferred above, Nordhaus recommended that net global emissions peak in the year 2050, not fall to zero in 2050.

The global community treats net zero emissions as an appropriate goal. There is reason to believe that this goal is too modest. This is because greenhouse gas atmospheric concentrations remain too high, even if net zero emissions are achieved. Indeed, the real challenge is to become

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[10] See the World Bank site https://data.worldbank.org/indicator/NY.GNS.ICTR.ZS. Based on Nordhaus' assumptions, saving rates are approximately 25 percent. Actual savings rate have been in the vicinity of 26 percent, and reached an exceptional peak of 28 percent in 2006 and 2007. Stern's assumption lead to a savings rate that exceeds 30 percent.

[11] See Marx, Magali, Benoit Mojon and François R. Velde, 2019. "Why Have Interest Rates Fallen Far Below the Return on Capital," BIS Working Papers, No 794, 09 July 2019. https://www.bis.org/publ/work794.htm.

net negative as quickly as feasible, which requires the removal of greenhouse gases from the atmosphere.[12]

Because present bias is so powerful, hope for addressing global warming will have to come from technological advances, including advances to remove greenhouse gases from the atmosphere. Because the treatment of net negative emissions in Nordhaus' model is crude, future integrated assessment frameworks will need to focus on improving how greenhouse gas removal technologies are modeled.

The Charney report of 1979 alerted the global community that it was in the domain of losses. As a result, present bias was compounded by the aversion to accepting a sure loss, which increases the propensity to accept bets which are imprudent. Thus far, the associated bets have not paid off. The global community's willingness to accept imprudent risks has only grown. There is much to be concerned about, given the heavy reliance we are placing on technology, with the big behavioral question only getting bigger.

A1.2 Synopsis, Section-by-Section

Section 2 summarizes key messages from climate scientists, beginning in 1979 with the publication of a study known as the Charney report. Over four decades have passed since this report was published and its main messages have proved prescient. These messages generated fear in 1979 and in the decades that followed, among some, but not all. The framing of fear was an important psychological issue.

Section 3 describes the DICE model developed by Nordhaus to analyze alternative policies for addressing climate change. There are three things to note about the discussion in the section. First, the general character of the approach is described in terms of standard microeconomic theory. Second, the discussion contrasts two cases in the DICE model, one being an optimal case and the other corresponding to business-as-usual behavior, which I will call the "behavioral business-as-usual" case. Third, the section draws a sharp contrast between the messages of fear generated by mainstream climate scientists and the much less fearful messages associated with the forecasts from DICE. Notably, DICE assumes that the rate of technological progress will be high enough to support meaningful adaptation to significant increases in

[12] Nordhaus assumes that negative emissions only become possible after 2155. If anything is clear, it is the critical importance of achieving negative emissions well before that, indeed before 2050.

temperatures, even in the case of business-as-usual. In this regard, the difference between the DICE perspective and that of mainstream climate scientists is sharp enough to raise the question of bias on the part of one or the other.

Section 3 focuses on three specific concepts: "technological progress," "climate finance" and "the social cost of carbon." In respect to technological process, I place the tension mentioned in the previous paragraph within the broader context of debates between scientists and economists, especially the debate between biologist Paul Ehrlich and neoclassical economist Julian Simon. By climate finance, I mean capital budgeting decisions about projects which relate to addressing the threats posed by global warming. By social cost of carbon, I mean a measure of the social value associated with reducing atmospheric carbon dioxide emissions by one (metric) ton. Because greenhouse gas emissions are externalities, the social cost of carbon is one of the most important economic concepts for the analysis of climate policy. At the end of the section, I discuss Nordhaus' suggestion to structure a carbon club in order to price carbon at its social cost.

Section 4 discusses a major debate which took place in 2007 between William Nordhaus and Sir Nicholas Stern. Both are neoclassical economists, but with very different perspectives on what constitutes an optimal trajectory for the social cost of carbon and relatedly the degree to which resources should be allocated to abatement of carbon dioxide emissions.

Most importantly, Stern's messages are much closer in spirit to those of mainstream climate scientists than those of Nordhaus. Whereas Nordhaus contended that carbon prices and corresponding abatement rates grow slowly, along a "climate ramp," Stern argued for much more aggressive growth. Whereas Nordhaus' optimal case features net zero emissions growth around 2115, Stern's optimal case features net zero emissions before 2050, and a move to net negative emissions as soon as technically feasible.

I discuss the extent to which these differences of opinion reflect specific psychological biases, as well as capturing important features of the earlier Ehrlich-Simon debate. A major aspect of the debate between Nordhaus and Stern involved differences about the appropriate (time) discount rate. The emphasis on this discount rate, it seems to me, was too strong, and distracted from more important issues such as present bias and the relationship between emissions and damages. Although the documentation about damages in the Stern model is less precise than for the DICE model, the damage functions in the two models are very similar. Nordhaus pointed out that if he replaced the preference parameters in the DICE model to the values proposed by Stern, then DICE would generate the Stern abatement schedule and the associated trajectory for the social cost of carbon.

The approaches of Nordhaus and Stern provided brackets for plausible estimates of the social cost of carbon and corresponding climate policies. The ranges within these brackets are wide. Over time, Nordhaus has raised his estimates of the social cost of carbon, emissions, global temperatures, and damages suggesting past excessive optimism on his part. In 2022, the Environmental Protection Agency began to use an estimate of the social cost of carbon which lies in the middle portion of the range. Nevertheless, the actual trajectories remain much closer to behavioral business-as-usual than to any of the trajectories in the ranges bracketed by the approaches of Nordhaus and Stern.

This last point reflects excessive optimism on the part of Nordhaus, who over time expressed surprise that the US failed to institute policies which would lead to carbon being priced at its social cost. The revisions Nordhaus made to DICE over time also imply that he was excessively optimistic about global emission rates, associated temperature increases, and the risks from climate tipping points.

The discussion about time discounting in the Nordhaus-Stern debate brings to mind Irving Fisher, who emphasized the irrational elements of time discounting. In this respect, Fisher used the analogy of problem drinking, meaning excessive consumption of alcohol, as part of his explanation. The analogy is apt. Indeed, the need to reduce general consumption to address global warming is akin to someone with a drinking problem needing to reduce the amount they drink. Denial, cognitive dissonance, and imprudent risk taking are common to both. Reducing consumptions is not easy, and problem drinkers often resist advice to seek treatment. Likewise, the global community resists the call to price carbon at its social cost because doing so will lead to lower current consumption. Such behavior results in trusting to luck, which Fisher also discussed.

Section 5 identifies what I regard as the key psychological pitfalls which have characterized political decisions in the US about anthropogenic global warming. As I mentioned above, although political decisions might resemble the outcome of a representative social planner, that planner appears to exhibit strong behavioral features such as dynamic inconsistency of preferences, biased judgments, and incoherent probability beliefs.

The discussion in the section focuses on the role of psychology in driving US political decisions about global warming, from 1979 when the Charney report was published. The reality is that from 1979 on, the trajectory of greenhouse gas emissions has been much closer to behavioral business-as-usual than the optimal trajectory from any mainstream integrated assessment model. Not to put too fine a point on it, but *more than two thirds of anthropogenic cumulative emissions of carbon dioxide into the atmosphere have occurred since the publication of the Charney report*. Mainstream economists' recommendations have carried little weight in political choices made about addressing climate change. Psychological factors, not integrated assessment models, have carried the weight.[13]

Incentives are key to the way economists think about the world. In DICE, the interest rate provides the primary incentive for inducing consumers to save; and the price of carbon provides the primary incentive for inducing firms to engage in abatement. Of course, the two types of decision variables are not symmetric. Interest rates are principally determined by market forces. In contrast, the price of carbon is an instrument of public policy, intended to address market failures associated with externalities such as the free rider effect.

The optimal case associated with DICE captures the real-world intertemporal trajectories for saving rates and interest rates. However, not so when it comes to the trajectories for abatement rates and the price of carbon. Real world abatement rates have been much higher, and the price of carbon much lower than their theoretical counterparts in the DICE optimal case.

Section 5 focuses on the main psychological reasons for these differences, which have been manifest within political decision processes.[14] There is a big behavioral question to be addressed, namely to identify the psychology preventing cost-benefit based climate incentives from being put in place.

I pause here for a brief message to neoclassical economists. The neoclassical perspective involves a search for rationality-based explanations, and when real world outcomes are clearly not rational, to focus on problems with incentives. My position, as a behavioral economist is that

[13] Economist Robert Pindyck argues that the global community needs to accept its inability to price carbon anywhere near its social cost, and should now focus more intently on adaptation to the effects of global warming. See Pindyck, Robert, 2021. *Climate Future: Averting and Adapting to Climate Change*. New York: Oxford University Press.

[14] I would point out two behavioral issues relating to incentives. First, incentives that are appropriate under neoclassical assumptions might be inappropriate in the face of psychological pitfalls. Second, the choice of incentives is typically endogenous, and psychological pitfalls can lead to the choice of inappropriate incentives.

inappropriate incentives are a major issue for global warming.[15] That said, we cannot stop at this point. Rather, we need to explain the obstacles which have stood and continue to stand in the way of instituting appropriate incentives.

In Section 5, I discuss the hypothesis that the major obstacles can be explained as the manifestation of rational behavior in an inefficient equilibrium connected to the free rider effect. While I do agree that the free rider effect is germane, I contend that the main obstacles to instituting cost-benefit based incentives are psychologically-based, not rationally based. Indeed, explaining the associated psychology is the main theme of Section 5. Please keep in mind that most of these psychological phenomena lie outside the neoclassical framework, and cannot be shoehorned in. At the same time, there are many neoclassical elements that are vitally important; and I have no interest in throwing out the neoclassical baby with the bathwater.

During the 1980s and 1990s, mainstream climate scientists and economists argued for the institution of carbon taxes, even at low levels. The argument was that moderate abatement at that time would avoid the need for much more drastic abatement in the future. This argument, while compelling, was not compelling enough to offset psychological forces that pushed in the opposite direction.

As to global decisions and policies, consider where things currently stand.

It is true that emission rates in the US and the EU peaked many years ago, and have been declining. However, the declines have been insufficient, relative to what mainstream climate scientists contend is needed.

It is true that China has pledged to achieve peak emission rates in 2030, to achieve net zero carbon emissions in 2060, and to work with the developing world on issues of abatement. However, these pledges are insufficient, relative to what mainstream climate scientists contend is needed.

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[15] Economist Partha Dasgupta argues that inappropriate incentives relate to natural assets generally. See *The Economics of Biodiversity: The Dasgupta Review*, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/962785/The_Economics_of_Biodiversity_The_Dasgupta_Review_Full_Report.pdf?campaign_id=4&emc=edit_dk_20230916&instance_id=102896&nl=dealbook&regi_id=67959516&segment_id=144925&te=1&user_id=6e141835ff07c27db27d9269c16188b0. In addition, see a US government proposal for incorporating Dasgupta's ideas into cost-benefit analysis: https://www.whitehouse.gov/wp-content/uploads/2023/08/DraftESGuidance.pdf?campaign_id=4&emc=edit_dk_20230916&instance_id=102896&nl=dealbook&regi_id=67959516&segment_id=144925&te=1&user_id=6e141835ff07c27db27d9269c16188b0

It is true that both compliance and voluntary carbon market are expanding. These are effectively institutions for dealing with emission externalities along the lines proposed by the Economics Nobel laureate Ronald Coase. However, prices in these markets are much lower than levels associated with estimates of the social cost of carbon. This is especially true of voluntary markets, which share the same feature as some nudge programs. In particular, both are associated with climate goals that are excessively low, but induce those involved to feel they have done enough.[16]

It is true that in 2021, 42 years after the release of the Charney report, the US passed a series of climate provisions as part of the Infrastructure Investment and Jobs Act. This was followed by passage in 2022 of the Inflation Reduction Act, which included additional major climate provisions.[17] However, neither piece of legislation featured a tax on greenhouse gas emissions.

It is true that US legislation included a provision to penalize excessive methane emissions, and that methane is a much more potent greenhouse gas than carbon dioxide. However, there is a worldwide methane emergency, and hints that we might be near a methane tipping point which will be irreversible in the near term. While methane persists for a much shorter period than carbon dioxide, the tipping point concern is that it will be impossible to prevent melting tundra from releasing a large continuous flow of methane into the atmosphere.

It is true that ESG investing -- which focuses on issues related to the environment, social values, and governance -- has been growing dramatically. However, the evidence suggests that ESG investors have little willingness for sacrificing total returns for environmental and social benefits. In addition, ESG investors are vulnerable to greenwashing, leading them to overestimate the environmental improvements associated with their investments.[18] On a related point, ESG investors might fail to understand that their actions might increase the cost of capital for emission intensive firms, and in doing so actually induce higher total emissions, not lower total emissions.

It is true that large financial institutions, such as BlackRock -- the largest private

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[16] Cognitive dissonance is an issue here. See Aronson, Elliot, 1969. "The Theory of Cognitive Dissonance: A Current Perspective," *Advances in Experimental Social Psychology*, Vol. 4, 1-34.

[17] See http://www.forbes.com/sites/hershshefrin/2023/04/21/on-earth-day-2023-smart-ira-climate-investments-offer-hope/.

[18] See Kenneth P. Pucker and Andrew King, 2022. "ESG Investing Isn't Designed to Save the Planet," *Harvard Business Review*, August 1, 2022. https://hbr.org/2022/08/esg-investing-isnt-designed-to-save-the-planet.

investment firm in the world -- are seeking to use their proxy power to induce private sector behavior to be less myopic about the long-run impact of their emissions. However, these financial institutions are running into strong opposition from energy producing parties whose interests will be threatened.[19]

It is true that there are nudge techniques for inducing people to choose behaviors which are climate friendly.[20] However, most of these techniques are minor, and some can lead people to choose behaviors that fall well short of what is necessary.[21]

The point is that all of these measures collectively will be insufficient, as the global emissions trajectory will still be closer to behavioral business-as-usual than to any of the optimal trajectories produced by integrated assessment models. Still, economists can hope.

There is something else that I need to say. It is true that the global community is now focused on behaviors that limit temperature increases to 1.5°C or 2°C, more so than it has to date. However, greenhouse gas concentrations associated with these goals are still dramatically larger than humans have ever experienced, with very large attendant risks. There is a great need to shift the goals to the restoration of greenhouse gas concentrations to levels near those which prevailed at the dawn of the industrial age. This will mean removing about a trillion tons of carbon dioxide from the atmosphere, and neutralizing a large amount of methane as well. This is a tall order; and the magnitude of the challenge is unsettling.

Section 6 is about hope, the hope of restoring greenhouse gas concentrations to pre-industrial levels. Hope features an emphasis on favorable outcomes in situations involving risk. Hope is needed because global warming threats are real and significant; and let me say something about the threats before getting to the hope.

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[19] See Goldstein, Matthew and Maureen Farrell, 2022. "BlackRock's Pitch for Socially Conscious Investing Antagonizes All Sides," *The New York Times*. https://www.nytimes.com/2022/12/23/business/blackrock-esg-investing.html.

[20] Thaler, Richard H. and Cass R. Sunstein, 2021. *Nudge: The Final Edition*. New York: Penguin Books. Thaler and Sunstein devote a chapter to climate change, which they titled "Saving the Planet." The chapter in this edition is an expanded version of the first edition which was published in 2008, and contains a lucid discussion of key behavioral ideas. In particular, the 2021 version highlights a set of behavioral phenomena beginning with present bias. Thaler and Sunstein's discussion of present bias is in line with my discussion of self-control in Shefrin, Hersh, 2013. "Behavioral Economics and Business," in *The Purpose of Business: Contemporary Perspectives from Different Walks of Life*. Edited by Albert Erisman and David Gautschi. New York: Springer (Palgrave-MacMillan). Thaler and Sunstein emphasize the importance of incentives in the structure of nudges.

[21] See Hagmann, David, Emily H Ho, and George Loewenstein, "Nudging Out Support for a Carbon Tax," *Nature Climate Change*, Vol 484(9), 484-489. See also Sunstein, Cass R. and Lucia A. Reisch, 2014. "Automatically Green: Behavioral Economics and Environmental Protection," *Harv. Envtl. L. Rev.* 38, 127-158.

Given the strength of present bias, there are reasons to suggest that the main source of hope will relate to new technologies associated with alternative energy sources and the removal of greenhouse gases from the atmosphere. What we need to hope for is the achievement of net negative emissions at reasonable cost that will dramatically reduce greenhouse gas concentrations in the atmosphere. There is a glimmer of hope in respect to the development of such technologies at costs that are sufficiently low. Belatedly, in 2021 and 2022, the US passed two major pieces of legislation effort to invest in these technologies.

There is progress in the development of major new technologies such as fusion. There is progress in the development of scalable technologies that will remove large amounts of greenhouse gases from the atmosphere. That said, there is also the threat that psychological pitfalls will interfere with the development and operationalization of these technologies.

The hope is that the global community will focus sufficiently on identifying and mitigating the effects of psychological pitfalls to restore greenhouse gas concentrations to levels somewhere near the levels that prevailed at the outset of the industrial revolution, before these gases do irreparable damage. Doing so lies within the realm of possibility; but, it will take a combination of great effort and good luck to make it happen.

There is risk attached to new technologies. However, DICE is a certainty framework. In Section 6, I discuss improvements to the DICE framework which relate to the incorporation of risk. This is an important advance, as new technologies are inherently risky, as are climate damages and other economic outcomes. Notably, the new integrated assessment models generate much higher values for the social cost of carbon than their certainty counterparts, plausibly by a factor of four. Moreover, there is evidence that carbon is actually priced in the range of 6 percent to 10 percent of its social cost.

The big behavioral question is becoming bigger over time. This means that the global community will have to hope that actual technological progress on alternative energy and greenhouse gas removal will be greater than previously thought. Moreover, the reluctance to use a carbon tax or equivalent cap-and-trade mechanism results in abatement being more costly than necessary, by a factor of five-to-seven.

Psychological biases, especially present bias, lie at the root of my analysis of the big behavioral question. In particular, these biases explain the reluctance to use taxes to price greenhouse gases in line with their respective social costs. This reluctance results in abatement being more costly than necessary, plausibly by a factor of five-to-seven. The cost of reluctance is a behavioral cost, and it is large.

Hope based on technology is fine, but there is a risk that it will be insufficient; and this is unsettling. The global community needs to face up to the big behavioral question and to the magnitude of the costs associated with psychological biases that obstruct the implementation of good climate policies.

Appendix to Section 2

Section 2 concentrates on the perspective of mainstream climate scientists, beginning in 1979. Two psychological issues arising in the section are fear and framing. This appendix includes some additional remarks about both issues, which arise in a book by author Jeff Goodell entitled *The Heat Will Kill You First: Life and Death on a Scorched Planet*.[22]

A reviewer of the book, Jennifer Szalai, titled her review "Extreme Heat Is Here to Stay. Why Are We Not More Afraid?" The question is central, and a major theme of this book. Notably, while Szalai's review does not provide an answer to the question, mine centers on psychological biases, with present bias topping the list.

The major framing issue mentioned in Section 2 involves the use of the phrase "climate change" in place of "global warming," because the former is less threatening than the latter. Interestingly, Goodell suggests that even the term "global warming" is insufficient for describing the magnitude of the threat from human caused emissions of greenhouse gases into the atmosphere. In his view, the phrase global warming is "gentle and soothing."

Think about how the title of Goodell's book frames the dangers. Words like "heat," "kill," "death," and "scorched" are intended to induce emotions with strong negative affect. In other words, these words are intended to induce strong feelings of fear. Goodell suggests that even the word "hot" has too many pleasant associations, such as good beach weather.

Framing is certainly part of the issue. However, framing is not pivotal. Twenty years after the Luntz report discussed in the section, very high temperatures were being experienced directly in the American Southwest, with general agreement that the main reason was global warming.

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[22] Goodell, Jeff, 2023. *The Heat Will Kill You First: Life and Death on a Scorched Planet*. New York: Little Brown and Company.

Yet, population growth in the Southwest continued to grow, especially in Arizona.[23] The state began to explore the possibility of funding a desalination plant in Mexico as a source of fresh water.[24]

Appendix to Section 3

A3.1 The DICE Equations Describing the Climate

In this subsection, I explain how the DICE-2016 model describes the state of Earth's climate at the end of 2015, and makes predictions about the period 2016-2020.

The model structure involves the following three components:

1. carbon concentration in the atmosphere and oceans;
2. radiative forcing underlying global warming; and
3. determinants of temperature in the atmosphere and deep oceans.

A3.1.1 Carbon Concentration

DICE-2016 focuses on how carbon dioxide is distributed across three venues, namely the atmosphere, biosphere and upper oceans, and the deep ocean. In doing so, I will use numbers as part of the explanation. The numbers are important for understanding the magnitude of the climate crisis.

At the end of 2015, the atmospheric concentration of carbon dioxide (ppm) was approximately 400, which corresponds to a total amount of 851 GT of carbon (gigatons, meaning 851 billion metric tons). The concentration in the biosphere and upper oceans was 460 GT of carbon and the concentration in the deep oceans was 1,740 GT of carbon.

Notice that most of Earth's carbon resides in the ocean; and most of what resides in the ocean is in the form of calcium carbonate, the limestone making up coral reefs.

DICE-2016 denotes the three total carbon concentrations at date *t* respectively by the symbols $M_{AT}(t)$, $M_{UP}(t)$, and $M_{LO}(t)$; and the figures mentioned in the previous paragraph pertain to the end of year t=2015. The model features a carbon cycle in which carbon moves through the

[23] See Nugen, Ciara, 2023. "Arizona Faces an Existential Dilemma: Import Water or End Its Housing Boom," *Time Magazine*. https://time.com/6248517/arizona-growing-population-drought-housing/.
[24] See Flavelle, Christopher, 2023. "Arizona, Low on Water, Weighs Taking It From the Sea. In Mexico." *New York Times*. https://www.nytimes.com/2023/06/10/climate/arizona-desalination-water-climate.html.

three layers. Notably, carbon dioxide emissions are assumed to enter the ecological system through the atmosphere. In addition to emissions, carbon dioxide is also released into the atmosphere from the upper oceans, although this second release is offset by carbon dioxide withdrawals from the atmosphere which flow into the upper oceans.

DICE-2016 models the net carbon dioxide flows to the atmosphere at date *t* using the equation

$$M_{AT}(t) = E(t-1) + \varphi_{11}M_{AT}(t-1) + \varphi_{21}M_{UP}(t-1)$$

During the five-year period 2011-2015, total carbon dioxide emissions per year averaged 38.345 GT (gigatons, meaning 38.345 billion metric tons). Of this amount, 35.745 GT (or 93.2 percent) were industrial emissions from the global economy. Total emissions of carbon for the five year period ending in 2015 are denoted *E(2015).* Note: *E(2015)* is computed by multiplying total carbon dioxide emissions per year by 5, and dividing the product by 3.666: the carbon content of 3.666 GT of carbon dioxide is 1 GT.

The parameters in the equation for $M_{AT}(t)$ are $\varphi_{11} = 0.88$ and $\varphi_{21} = 0.196$. That is to say, 88 percent of the carbon dioxide in the atmosphere remains in the atmosphere, with the remaining 12 percent entering the upper oceans. On the flip side, 19.6 percent of the carbon dioxide in the upper oceans enters the atmosphere.

At the end of 2015, DICE-2016 predicted the concentration $M_{AT}(2020)$ of atmospheric carbon dioxide to be 891.338 GT of carbon. The forecast equation is:

$$M_{AT}(2020) = 38.345 + 0.88\times851 + 0.196\times460 = 891.338$$

The other two equations in the carbon cycle, for carbon dioxide concentrations in the lower and upper oceans are as follows:

$$M_{UP}(t) = \varphi_{12}M_{AT}(t-1) + \varphi_{22}M_{UP}(t-1) + \varphi_{32}M_{LO}(t-1)$$

$$M_{LO}(t) = \varphi_{23}M_{UP}(t-1) + \varphi_{33}M_{LO}(t-1)$$

With the numerical parameter assumptions in DICE-2016, these equations become:

$$M_{UP}(t) = 0.12M_{AT}(t-1) + 0.797M_{UP}(t-1) + 0.001465M_{LO}(t-1)$$

$$M_{LO}(t) = 0.007M_{UP}(t-1) + 0.998535M_{LO}(t-1)$$

As is evident from the magnitude of the coefficients in the equation for $M_{LO}(t)$, the deep oceans are a major carbon sink in that they retain most of the carbon sequestered there. However, the deep oceans also accept only a small proportion of carbon in the upper oceans.

A3.1.2 Radiative Forcing

Turning next to climate sensitivity, DICE-2016 models this concept by means of the equation

$$F(t) = \eta\{log_2[M_{AT}(t) / M_{AT}(1750)]\} + F_{EX}(t)$$

Here the symbol F denotes the notion of radiative forcing, meaning the amount of global warming energy. $F_{EX}(t)$ represents the amount of thermal radiation that prevailed at the outset of the industrial age in 1750, before humans began to burn large amounts of fossil fuels. The variable η denotes the expected additional amount of thermal energy produced from a doubling of atmospheric carbon dioxide. In DICE-2016, η takes the value 3.681 watts per square meter. Finally $log_2[M_{AT}(t) / M_{AT}(1750)]$ is the number of doublings of atmospheric carbon dioxide since the beginning of the industrial age. Here $M_{AT}(1750)$ takes the value 588 GT of carbon.

A3.1.3 Determinants of Temperature

Consider the DICE-2016 counterpart to the Hansen (1981) global warming equation $T_s = T_e + \Gamma H$ described in Section 2. In DICE-2016, the counterpart corresponds to the climate equilibrium solution[25] of a set of equations. The lead equation in the set pertains to the atmospheric temperature, and is written as follows:

$$T_{AT}(t) = T_{AT}(t\text{-}1) + \xi_1\{F(t) – \xi_2 T_{AT}(t\text{-}1) – \xi_3[T_{AT}(t\text{-}1) – T_{LO}(t\text{-}1)]\}$$

Here $T_{AT}(t)$ represents the change in global temperature since the beginning of the industrial age, and the difference $T_{AT}(t)$ - $T_{AT}(t\text{-}1)$ represents the atmospheric temperature change from one five-year period to the next. Notably, this last equation describes the transition from one climate equilibrium to another.

I draw readers' attention to the impact of radiative forcing variable $F(t)$ in the preceding equation. The equation for atmospheric temperature $T_{AT}(t)$ stipulates that temperature adjusts to the difference between the energy associated with the radiative forcing $F(t)$ and the weighted average of energies associated respectively with the existing atmospheric temperature and the temperature gradient between atmosphere and deep oceans.

In DICE-2016, $T_{AT}(2015)$ is taken to be 0.85°C, with the predicted value $T_{AT}(2020)$ being 1.02°C, the change being 0.17°C. The value of $T_{LO}(2015)$ in DICE-2016 is taken to be 0.007°C.

[25] The climate equilibrium solution features stable temperatures for the atmosphere, upper ocean, and lower ocean.

Both the Charney report and Hansen (1981) were clear to say that the relationship between atmospheric carbon concentration and atmospheric temperature is complex. This is because temperature changes lag changes in carbon concentration in a way that depends on several climatic variables.

With this in mind, consider the DICE-2016 equation for $T_{AT}(t)$. Notice that ξ_1 denotes the speed of atmospheric temperature/energy adjustment parameter to radiative forcing, and ξ_3 denotes the coefficient of heat loss from atmosphere to oceans. The coefficient ξ_2 is a ratio, with the numerator being the forcings at carbon dioxide doubling (in units of watts per square meter) and the denominator being the equilibrium temperature increase for CO2 doubling.[26]

Here is the equation for the temperature increase from period $t-1$ to period t, with numerical values for the coefficients:

$$T_{AT}(t) - T_{AT}(t-1) = 0.101\{F(t) – 1.187T_{AT}(t-1) – 0.088[T_{AT}(t-1) – T_{LO}(t-1)]\}$$

The corresponding temperature equation for the deep oceans is:

$$T_{LO}(t) - T_{LO}(t-1) = \xi_4[T_{AT}(t-1) – T_{LO}(t-1)]$$

with ξ_4 denoting the coefficient of heat gain by the deep oceans, which DICE-2016 assumes to be 0.025.

Physical equilibrium involves zero temperature changes. By imposing this condition on the last two equations, we obtain the equilibrium condition:

$$T_{AT} = F / [\xi_2 – (\xi_3(1-\xi_4)/\xi_4)]$$

where, as above, F is determined as a linear equation in the degree of doubling of atmospheric carbon dioxide concentration. This last equation, for T_{AT}, corresponds to Hansen's equation $T_s = T_e + \Gamma H$.

A3.2 The DICE Equations Describing the Global Economy

A3.2.1 Capital Investment

The way that the production sector moves along the production possibility frontier, say with an increase in the output of date $t+1$ consumption and corresponding reduction in the output of date t consumption, is through capital investment.

[26] The value of coefficient ξ_2 = 3.681/3.100 = 1.187.

By using resources at date t to produce more capital instead of more consumption goods, the production sector has available to it more productive capacity at date $t+1$ than it would have otherwise. In a competitive economy, whether it makes sense for the production sector to move along the production possibility frontier in this way, depends on whether the move will increase the profitability of the production sector. A move that increases the profits of the production sector corresponds to a positive net present value project, because the value of the incremental date $t+1$ consumption exceeds the value of the foregone date t consumption that instead went into the increased production of capital goods.

The following equations describe the nature of the tradeoff:

$$Q(t) = C(t) + I(t)$$

$$K(t) = I(t-1) + (1-\delta_k)K(t-1)$$

The first equation stipulates that net global output $Q(t)$ comprises global consumption $C(t)$ and global investment $I(t)$ in new capital goods. Net output is produced using as inputs labor $L(t)$ and capital $K(t)$.

The second equation stipulates that the global capital stock at date t consists of new additions to from investment $I(t)$ and the legacy capital stock from date $t-1$, after depreciation where δ_k is the rate of depreciation. In DICE-2016, δ_k takes the value 10 percent.

Notice that a shift in composition at date t from $C(t)$ to $I(t)$ reduces $C(t)$ but increases $K(t+1)$ and therefore increases $C(t+1)$. The economy has moved in the northwest direction up the production possibility frontier (displayed in Figure 9).

A3.2.2 Gross Production, Net Production, Emissions, and Global Warming

Consider the following equations from DICE-2016 which describe production in the global economy. The first equation pertains to gross production $Q_G(t)$ associated with global output at date t.

$$Q_G(t) = A(t)K(t)^{\gamma}L(t)^{1-\gamma}$$

The equation for $Q_G(t)$ has a standard Cobb-Douglas form, in which gross production is the output from a process that uses two inputs at date t, capital good services $K(t)$ and labor time services $L(t)$.[27]

Gross production at date $t+1$, $Q_G(t+1)$, is given by

$$Q_G(t+1) = A(t+1)K(t+1)^{\gamma}L(t+1)^{1-\gamma}$$

As was mentioned above, one way to increase gross production $Q_G(t+1)$ is to invest at date t in order to increase the value of capital goods $K(t+1)$ at date $t+1$.

As I mentioned earlier when discussing the climate component of DICE-2016, the level of carbon dioxide emissions, $E_{Ind}(t)$, from the production sector impact the climate by contributing to atmospheric carbon concentration M_{AT} from date forward.

Given this knowledge, decision makers in the production sector might choose to engage in abatement activities, in order to reduce the level of $E_{Ind}(t)$. Abatement includes activities such as renewable energy production, increasing the use of electric vehicles in transportation, and carbon capture and sequestration. If no abatement is undertaken, DICE-2016 assumes that emissions are proportional to gross output, with the factor of proportionality being $\sigma(t)$. That is,

$$E_{Ind}(t) = \sigma(t)\, Q_G(t)$$

Let $\mu(t)$ denote the degree of abatement activity at date t, measured as a proportion of gross output. Even though abatement encompasses many activities, for sake of simplicity think of abatement as carbon capture and sequestration.[28] Doing so allows us to interpret the variable $\mu(t)$ as the fraction of output being subject to 100 percent carbon capture and sequestration. In this case, industrial emissions will decrease from the zero-abatement amount of $\sigma(t)\, Q_G(t)$ to

$$E_{Ind}(t) = \sigma(t)[(1-\mu(t)]\, Q_G(t)$$

That is, DICE-2016 assumes that abatement at level $\mu(t)$ will reduce emissions by $\sigma(t)\mu(t)Q_G(t)$, but at a cost per unit gross output of

$$\Lambda(t) = \theta_1(t)\mu(t)^{\theta 2}$$

In other words, the benefit of abatement is a reduction of emissions $E_{Ind}(t)$ by $\sigma(t)\mu(t)Q_G(t)$, with a corresponding cost (in units of gross output) of $\Lambda(t)\, Q_G(t)$.[29]

[27] DICE-2016 assumes that labor is measured by population which grows over time according to the projections made by the United Nations. These projections show population growth leveling off over the course of the current century.

[28] I often use the term "carbon capture" as shorthand for "carbon capture and sequestration."

[29] The last term equals $\theta_1(t)\mu(t)^{\theta 2}\, Q_G(t)$).

Of course, emissions and output are in different units, and therefore we need a way to assign a "dollar" value to the cost of emissions. To do this, Nordhaus uses a "damage function" which specifies the detrimental effect of high atmospheric temperature T_{AT} on output. The damage function for date *t* takes the form $1/[1+\Omega(t)]$ and is interpreted to mean that output, net of the cost of mitigation, is reduced further by the fraction $1/[1+\Omega(t)]$. In DICE-2016, the function $\Omega(t)$ is assumed to be quadratic in atmospheric temperature. That is,

$$\Omega(t) = \psi_1 T_{AT}(t) + \psi_2 [T_{AT}(t)]^2$$

In summary, DICE-2016 specifies that net output $Q(t)$, meaning net of abatement costs and the damage from global warming is given by the equation:

$$Q(t) = [1 - \Lambda(t)]A(t)K(t)^{\gamma}L(t)^{1-\gamma}/[1+\Omega(t)]$$

A3.2.3 Values of $Q_G(t)$ and $Q(t)$ for 2015 and 2020

The text describes tradeoffs associated with two periods, one ending in 2020 and the other ending in 2025. The backdrop for this description involves values for gross and net output for the periods ending in 2015 and 2020. At the end of 2015, atmospheric carbon concentration was about 400 ppm, which the DICE-2016 model forecast would rise to about 418 ppm at the end of 2020.

Average gross output per annum (Q_G), meaning output gross of abatement cost and climate damage was $105.177 ($trill) for the period ending in 2015, which the DICE-2016 model forecast would rise to about $125.347 ($trill) for the period ending in 2020.

The input values for 2015 were $223.000 ($trill) of capital and 7,403 million person-years of labor. DICE-2016 forecast that the input values in 2020 would be $267.942 ($trill) of capital and 7,853 million person-years of labor. The equation determining Q_G is:

$$Q_G(t) = A(t)K(t)^{\gamma}L(t)^{1-\gamma} = 5.53 \times 267.942^{0.3} \times 7.853^{0.7} = 125.35$$

The value of net output $Q(2020)$ is computed by taking the $267.942, multiplying by one minus the damage ratio, which for 2020 was 0.002438, and then subtracting the abatement cost ($0.001 trillion). The end result is net output for 2020 being predicted to be $125.04 ($trill). The difference between gross and net output, $0.31 trillion, is due to global warming.

A3.2.4 The Consumer Sector

At date t, the consumer population consists of $L(t)$ people, all of whom are assumed to belong to the workforce. The assumption in DICE-2016 is that at each date t, total consumption is spread uniformly across the population. As a result, per capita consumption c_t is given by[30]

$$c_t = C(t)/L(t)$$

According to the model, consumption level c_t leads to per capita utility $u(c_t)$ which is given by the function

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

An important issue in DICE-2016 is the degree to which consumers are willing to make sacrifices for their future selves and for their successors. Keep in mind that consumers make sacrifices by being willing to substitute current consumption, say at date t, for future consumption at dates after t. They can do so in two ways, first by diverting output from consumer goods to capital goods, and second by investing in carbon dioxide abatement.

One determinant of the degree to which consumers are willing to make intertemporal sacrifices is the "elasticity of intertemporal substitution" (EIS). The EIS can be expressed as the elasticity of consumption growth with respect to marginal utility growth:

$$dln(c_{t+1} / c_t) \; / \; dln\,(u'(c_{t+1}) / u'(c_t))$$

As I discuss in Sections 5 and 7, the EIS is also the percent change in consumption growth with respect to the interest rate r:[31]

$$dln(c_{t+1} / c_t) \; / \; dr$$

The power function utility function specified above features a constant elasticity of intertemporal substitution, which is equal to $1/\alpha$. In DICE-2016, $\alpha = 1.45$.

When $\alpha = 0$, the utility function is linear, and the elasticity of intertemporal substitution is infinite. This means that the consumer is comfortable with very unbalanced consumption levels over time, being quite willing to substitute consumption at one date for consumption at another date. However, as α increases and approaches 1 from below, which means that the utility function becomes closer to being logarithmic ($u(c_t) \sim ln(c_t)$), the elasticity of intertemporal

[30] In some equations, I write c_t in place of $c(t)$ for ease of notation.

[31] The logarithm of the gross rate of consumption growth is approximately the net rate, which is how to interpret the EIS.

substitution itself approaches *1*. In this case, the consumer is much more reluctant to experience unbalanced consumption over time.

A3.2.5 The Optimal Case

Imagine a utilitarian social planner who assesses the overall welfare impact from actions taken by earlier generations which impact their future selves and the welfare of later generations. To undertake this evaluation, the social planner aggregates the welfare (or utilities) of all consumers over time by using a social welfare function of the form

$$W = \sum_t R(t)\, u(c_t)\, L(t)$$

In the social welfare function, $R(t)$ is a time discount factor

$$R(t) = (1+\rho)^{-t}$$

with ρ being the time discount rate. A common assumption in neoclassical economics is that $\rho>0$. This inequality captures the idea that consumers are impatient. Specifically, all else being the same, consumers attach greater weight to consumption that arrives earlier in time rather than later in time. In DICE-2016, ρ takes the value 1.5 percent.

As I mentioned earlier, Nordhaus focuses on two cases for DICE-2016. The first is one I describe as "behavioral" because it involves underreaction to the threat posed by global warming. The second case, which Nordhaus calls the "optimal case," involves maximizing social welfare W by choosing two sets of policies, one for carbon dioxide abatement and the other for savings and investment.

A3.2.6 The Social Cost of Carbon

In DICE-2016, the social cost of carbon formerly corresponds to the partial derivative

$$-\partial \Lambda(t) Q_G(t) \,/\, \partial E_{Ind}(t)$$

where Q_G denotes output gross of abatement cost, global warming damage $\Lambda(t)$ is the fraction of output devoted to abating emissions, and E_{Ind} is the level of industrial emissions.[32] The sign in the last expression is negative because the cost is associated with lowering emissions, not raising

[32] Readers might want to refer back to Section 3 to remind themselves of the notation in DICE.

emissions. The foregoing partial derivative measures the amount of gross output foregone which is required to reduce emissions by a marginal unit (i.e., ton).

DICE-2016 employs the following expression for the social cost of carbon $-\partial Q_G(t)/\partial E_{Ind}(t)$:

$$-\partial Q_G(t)/\partial E_{Ind}(t) = -[\theta_1(t)\ \theta_2(t)\ \mu(t)^{\theta 2\ -1}]\ /\ \sigma(t)$$

where $\mu(t)$ can be interpreted as the fraction of gross output that is the subject to 100 percent- abatement.[33] The parameters in this last expression come from the following two equations:

$$\Lambda(t) = \theta_1(t)\mu(t)^{\theta 2}$$

$$E_{Ind}(t) = \sigma(t)[(1 - \mu(t)]\ Q_G(t)$$

Recall that $\Lambda(t)$ measures the fraction of gross output at date t which is foregone in order to achieve complete abatement of $\mu(t)$ of gross output.[34]

A3.2.7 Derivation of DICE-2016 Equation for Social Cost of Carbon

I find Nordhaus' discussion of the equation for the social cost of carbon to be a bit vague. For this reason, I discuss the derivation of Nordhaus' expression for the social cost of carbon.

Recall from Section 3 that the equation for output, net of abatement cost and global warming damage is given by

$$Q(t) = [1 - \Lambda(t)]A(t)K(t)^{\gamma}L(t)^{1-\gamma} / [1+\Omega(t)]$$

The equation for output net of abatement cost, but before damage from global warming is given by

$$[1 - \Lambda(t)]A(t)K(t)^{\gamma}L(t)^{1-\gamma}$$

Notably, the portion

$$\Lambda(t)A(t)K(t)^{\gamma}L(t)^{1-\gamma}$$

describes the before-damage cost of abatement at date t, and this last expression is simply

[33] In the model, a portion µ of gross output is assumed to be set aside for complete carbon dioxide removal, with the remainder of output not undergoing any abatement.

[34] The DICE-2016 parameter values for 2015 are $\vartheta_1(t)= 72.25$, $\vartheta_2(t)=2.6$ and $\sigma(t) =0.35$.

$$\Lambda(t)Q_G(t)$$

where $Q_G(t)= A(t)K(t)^{\gamma}L(t)^{1-\gamma}$. In DICE-2016, reducing industrial emissions requires an increase in abatement activity μ, with the relationship between emissions and abatement activity expressed as:

$$E_{Ind}(t) = \sigma(t)[(1- \mu(t)]\ Q_G(t)$$

The associated cost Λ, as a fraction of output is given by

$$\Lambda(t) = \theta_1(t)\mu(t)^{\theta 2}$$

where $\mu(t)$ denotes the rate of abatement, otherwise known as the "emissions control rate." With these two equations in mind, consider the (negative) of the marginal cost of abatement

$$\partial\Lambda(t)Q_G(t)\ /\ \partial E_{Ind}(t)$$

which by the chain rule is given by:

$$[\partial\Lambda(t)Q_G(t)\,/\,\partial\mu]\quad[\partial\mu\,/\,\partial E_{Ind}(t))]$$

$$= Q_G(t)[\ \theta_1(t)\ \theta_2(t)\ \mu(t)^{\theta 2\ -1}]\ [\partial\mu\,/\,\partial E_{Ind}(t))]$$

The equation relating emissions and abatement activity implies that

$$\mu(t) = 1 -[E_{Ind}(t)\,/\,\sigma(t)\ Q_G(t)]$$

and therefore

$$\partial\mu\,/\,\partial E_{Ind}(t)) = -\ 1\,/\,[\ \sigma(t)\ Q_G(t)]$$

Hence, by substitution, the social cost of carbon is given by

$$-\partial\Lambda(t)Q_G(t)\ /\ \partial E_{Ind}(t) = Q_G(t)[\ \theta_1(t)\ \theta_2(t)\ \mu(t)^{\theta 2\ -1}]\ [1\,/\,\sigma(t)\ Q_G(t)]$$

$$= [\theta_1(t)\ \theta_2(t)\ \mu(t)^{\theta 2\ -1}]\ /\ \sigma(t)$$

which is Nordhaus' expression for the social cost of carbon. Notably, in operationalizing this expression, DICE-2016 assumes that $\theta_1(t)$ and $\theta_2(t)$ are related through the expression

$$\theta_1(t) = \sigma(t)\ p_B\ /\ \theta_2(t)$$

where p_B is the value of a backstop technology. The backstop technology variable is defined as[35]

$$p_B = -\partial\Lambda(t)Q_G(t)\ /\ \partial E_{Ind}(t) \text{ when } \mu(t) = 1$$

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[35] See Nordhaus, William with Paul Sztorc, 2013. *DICE 2013R: Introduction and User's Manual Second edition October 2013*, downloaded from Nordhaus' website. The manual states: "In the full regional model, the backstop technology replaces 100 percent of carbon emissions at a cost of between $230 and $540 per ton of CO2 depending upon the region in 2005 prices. For the global DICE-2013R model, the 2010 cost of the backstop technology is $344 per ton CO2 at 100 percent removal. The cost of the backstop technology is assumed to decline at 0.5 percent per year. The backstop technology is introduced into the model by setting the time path of the parameters in the abatement-cost equation (6) so that the marginal cost of abatement at a control rate of 100 percent is equal to the backstop price for a given year." In DICE-2016, the backstop price in 2015 is $550, and decreases at the rate of 2.5 percent every (five year) period.

and therefore

$$E_{Ind}(t) = \sigma(t)[(1- \mu(t)]\ Q_G(t) = 0$$

Note that when $\mu(t) = 1$, the economy achieves the point of "net zero" emissions. At this point, the following equality holds:

$$p_B = [\theta_1(t)\ \theta_2(t)\ \mu(t)^{\theta 2\ -1}]\ /\ \sigma(t) = [\theta_1(t)\ \theta_2(t)]\ /\ \sigma(t)$$

Solving this last expression for $\theta_1(t)$ yields

$$\theta_1(t) = \sigma(t)\ p_B\ /\ \theta_2(t)$$

and therefore,

$$-\partial \Lambda(t) Q_G(t)\ /\ \partial E_{Ind}(t) = [\theta_1(t)\ \theta_2(t)\ \mu(t)^{\theta 2\ -1}]\ /\ \sigma(t) = p_B\ \ \mu(t)^{\theta 2\ -1}$$

DICE-2016 computes the social cost of carbon for each date t as part of the optimal solution, and then infers $\mu(t)$ by solving the preceding equation and using the using the minimum of its solution or 1. In this regard, the value of p_B is set as a parameter.

Denote p_c as the social cost of carbon, the last expression becomes:

$$p_c = p_B\ \ \mu(t)^{\theta 2\ -1}$$

which implies that $\mu(t)$ is the smaller of 1 and

$$\mu(t) =[p_B\ /\ p_c]^{1/\ \theta 2\ -1}$$

at least until year 2150. Thereafter, DICE-2016 resets the maximum value of $\mu(t)$ to 1.2, allowing for net carbon emissions to become negative, not just (net) zero. In this case, DICE-2016 assumes that unit abatement cost is capped at the backstop price.

Notice from Figure 12 that the emissions control rate $\mu(t)$ reaches 100 percent in 2090, meaning the economy achieves net zero emissions, and jumps to 120 percent in 2160.

Readers should be aware that capping the value of $\mu(t)$ typically interrupts the equality between the marginal benefit of abatement and the marginal cost. At the cap, marginal benefit will typically exceed marginal cost.

There is a technical issue to raise about computing the social cost of carbon. The issue pertains to the base on which abatement cost is measured. Nordhaus uses gross output Q_G which is output before global warming damage. However, at any date, it is only "damaged output" which is available for consumption or for new capital or for abatement activity. If this is the case, then the base for computing the social cost of carbon should be damaged output,

$$Q_G(t)\ /\ [1+\Omega(t)]$$

In DICE, the marginal cost of abatement is defined as the negative of

$\partial \Lambda(t)Q_G(t) \ / \partial E_{Ind}(t)$

where $\Lambda(t)Q_G(t)$ is the cost expressed in terms of pre-damaged output, not post-damaged output $\Lambda(t)Q_G(t) / [1+\Omega(t)]$. Of course, if the damage factor $\Omega(t)$ is relatively small, then the adjustment factor will also be small.

Finally, I reiterate a point I made in the previous subsection pertaining to the equations which relate industrial emissions $E_{Ind}(t)$, abatement activity $\mu(t)$, and abatement unit cost $\Lambda(t)$. DICE-2016 provides for an abatement technology which, while time-varying, is otherwise independent of investment activity.

A3.2.8 Competitive Equilibrium Subtleties

The first fundamental theorem of welfare economics stipulates conditions under which a competitive equilibrium is Pareto-efficient.

The second fundamental theorem of welfare economics stipulates conditions under which any Pareto-efficient allocation can be achieved as a competitive equilibrium. The conditions for the second fundamental theorem require the possibility of lump sum transfers among consumers.

Given that the DICE optimal case features a Pareto-efficient allocation, and Nordhaus' framework is for a mixed public-private sector economy, not a centrally planned economy, it is vital to understand the character of competitive equilibrium in a DICE setting. In this subsection, I discuss the character of competitive equilibrium in a DICE-setting, noting some important but subtle issues.

I mentioned in the body of Section 4 that it is important to think of a consumer as a family household, whose dynamic planning reflects expectations about their future selves and their offspring. This feature, along with exponential discounting, is important in order that consumer preference maps be consistent with those of the social planner.

In a DICE setting, the social planner establishes the price of carbon. Firms choose respond to market prices to maximize firm value (in the sense of net present value NPV). In each period, firms actually make several types of decisions. Given factor prices for labor and capital, they decide how much to produce. Given the return on capital, they choose projects whereby they acquire new capital: meaning they invest. Given the price of carbon, they choose the proportions of a mix between clean output (with zero emissions) and dirty output (with positive emissions).

By dirty output, I mean output whose production involves emissions. In respect to the last point, firms first produce 100 percent dirty output, using labor and capital. They then decide how much of this dirty output to convert to capital, and how much dirty output to divert to clean output (which is emission-free).

There are subtleties in this setup because the production technology is constant returns to scale. In a traditional setting, the market value of the labor and capital is equal to the value of output, in this case the initial dirty output. However, converting dirty output to clean output through abatement is costly, and so the amount of clean output produced from a unit of dirty output is less than unity. In equilibrium, the factors of production can only be compensated with output, and so the standard factor prices will need to reduced/taxed to deal with abatement cost. Otherwise, the owners of labor and capital will have more income to spend than there is output to purchase.

In one sense, clean output and dirty output can be regarded as different commodities, such as food and clothing. Multi-product firms simply choose a commodity production mix to maximize profit. The act of abatement corresponds to a movement along a production possibility frontier in which clean output is transformed into dirty output. The relative prices of the two commodities is determined by the price of carbon.

Consider how the above discussion is reflected in DICE. In the appendix to Section 3, I describe how emissions are modeled in the formal DICE framework. Specifically, DICE-2016 assumes that emissions are proportional to gross output, with the factor of proportionality being $\sigma(t)$. That is,

$$E_{Ind}(t) = \sigma(t)\, Q_G(t)$$

The symbol $\mu(t)$ denotes the degree of abatement activity in period t, measured as a proportion of gross output. Even though abatement encompasses many activities, for sake of simplicity think of abatement as carbon capture and sequestration. Doing so allows us to interpret the variable $\mu(t)$ as the fraction of output being subject to 100 percent carbon capture and sequestration, and it is this fraction which corresponds to clean output.

Applying abatement level $\mu(t)$ leads industrial emissions to decrease from the zero-abatement amount of $\sigma(t)\, Q_G(t)$ to

$$E_{Ind}(t) = \sigma(t)[(1-\mu(t)]\, Q_G(t)$$

In other words, the choice of abatement at level $\mu(t)$ will reduce emissions by $\sigma(t)\mu(t)Q_G(t)$, and this will require a cost per unit gross output of

$$\Lambda(t) = \theta_1(t)\mu(t)^{\theta 2}$$

which implies that total abatement cost in period t will be will be $\Lambda(t)\ Q_G(t)$ (in units of gross output).

Recall that DICE-2016 specifies that net output $Q(t)$, meaning net of abatement costs and the damage from global warming is given by the equation:

$$Q(t) = [1 - \Lambda(t)]A(t)K(t)^{\gamma}L(t)^{1-\gamma}/[1+\Omega(t)]$$

Keep in mind that the total cost of abatement is first determined in units of gross output, namely $\Lambda(t)\ Q_G(t)$. This means that gross output is used to reduce emissions, not output net of damages.[36] Once abatement has taken place, and therefore abatement costs incurred, the damage function is applied to compute net output, which is available for consumption and investment.

Consumers will pay for consumption in terms of gross output, but what enters their consumption functions will be net output. They are paying for undamaged output but receiving and consuming damaged output.

This is important, as factor prices are denominated in terms of gross output. With constant returns to scale production technology, the total value of the factor inputs at date t, measured using equilibrium factor prices, will be exactly $Q(t)$.

Likewise, firms engaging in investment will produce new capital from net output, not gross output. Damages will impact capital accumulation just as they impact consumption utility.

In DICE, it is firms that choose abatement levels but consumers who incur the costs of foregone output. Because consumers as the owners of labor and capital receive income equal to $Q(t)$ (units of output), consumers will need to pay a total tax at date t equal to the abatement cost, this being the product of the price of carbon p_c and $E_{Ind}(t) = \sigma(t)[(1- \mu(t)]\ Q_G(t)$.

Because consumers receive the same utility from clean output as dirty output, the equilibrium prices for clean and dirty inputs will need to be equal.

Because clean output is costlier to produce than dirty output, in equilibrium firms will need price subsidies (for clean output) in order to be willing to produce any clean output. The associated price subsidy will be determined by the price of carbon. Such subsidies will be financed from the taxes levied on consumers.

[36] My preference would be to use output net of damages, not gross output, as the input for abatement.

If $\mu(t)>1$, then the amount produced of dirty output will be negative, meaning that atmospheric carbon concentration declines. What enters consumers' utility functions is total damaged output, not dirty or clean output, and therefore negative dirty output presents no modeling problem for consumers. For the production sector, production of negative amounts of dirty output along the production possibility frontier does not create modeling issues. First order profit maximization conditions still apply, as they do when the production possibility frontier is wholly contained in the nonnegative quadrant.

The "subsidy frame" is the most straightforward way to describe a competitive equilibrium associated with a DICE model that has been optimized for savings.

Of course, the argument also applies when the model is optimized for carbon prices as well. In this regard, recall that what differentiates the behavioral business-as-usual case differs from the optimal case is the cost of carbon. Notably, the above argument takes the cost of carbon as given, but does not require it to be optimal. Therefore, the same qualifying remarks apply to the behavioral business-as-usual case as to the optimal case.

The "subsidy frame" can be recast as a "tax frame," with a tax on emissions. In the tax frame, a firm that produces only dirty output will be taxed at the price of carbon on each unit of gross output. However, such a firm might increase its revenue by shifting to clean output, and to do so would reduce the magnitude of the tax. However, the baseline of 100 percent dirty output involves an initial tax on the firm equal to the product of the tax rate per unit output and total amount of gross output. This product is given by $p_c \sigma(t) Q_G(t)$.

All else being the same, such a tax would lead the production sector to have negative economic profits, after-tax. Negative economic profits translate into negative market values.

In a competitive economy, firms cannot have negative (net present) values if they are to be going concerns. Therefore, some type of public sector subsidy will still be required in the tax frame to offset the taxes firms pay to produce clean output. Therefore, consumers will still need to be taxed in order to cover the subsidy, but in the tax frame, the subsidy is lump sum rather than a distortionary price on clean output.

A3.3 C-DICE: Carbon Club Solution to Global Warming Free Rider Problem

This subsection uses C-DICE to develop the relationship between the behavioral business-as-usual values for abatement and carbon tax respectively and their optimal counterparts.

The equations defining C-DICE are for a set of countries indexed $i=1,\ldots I$, and describe a static model. The first equation is for consumption c_i for country i.

$$c_i = Q_{G,i} - \Lambda_i Q_{G,i} - D_i$$

where for country i, $Q_{G,i}$ is gross output, Λ_i is the cost of abatement per unit gross output, and D_i is damage from emissions. For country i, emissions are denoted by E_i, and abatement activity is denoted by μ_i, with the relationship between the two being variables being:

$$E_i = \sigma(1- \mu_i)Q_{G,i}$$

Let φ_i denote the relative size of country i. with the global value of variables for consumption, emissions, abatement cost, and damages being the sum of the individual country variables. Global values are denoted by the subscript W. For example, global consumption is denoted c_W and individual consumption c_i is given by

$$c_i = \varphi_i c_W$$

Damages D_i for country i are given by the equation

$$D_i = \gamma \varphi_i E_W$$

The equation for total abatement cost is given by:

$$\Lambda_i Q_{G,i} = \theta_1 \mu(t)^{\theta 2} Q_{G,i}$$

For C-DICE, Nordhaus assumes that $\theta_2 = 2$ meaning that abatement costs are quadratic in μ.

In a noncooperative Nash equilibrium, each country i chooses abatement level μ_i to maximize consumption c_i. The resulting first order condition for this maximum implies that the maximizing value of μ_i is:

$$\mu_i = \gamma \varphi_i \sigma / 2\theta_1$$

The price (meaning marginal cost) of carbon τ_i for country i is given by $\partial c_i/\partial E_i$, which implies that

$$\tau_i = \varphi_i \gamma$$

Think of τ_i as a tax rate. The last two equations together imply that

$$\mu_i = \gamma \tau_i / 2\theta_1$$

For the Nash equilibrium, the aggregate world-values for abatement rate μ_N and carbon price τ_N are given respectively by

$$\mu_N = \Sigma\, \varphi_i\, \mu_i$$

and

$$\tau_N = \Sigma\, \varphi_i\, \tau_i$$

To use this model to analyze the impact of coalitions, simply treat a coalition of countries as a single country whose size is the sum of the coalition members' individual sizes φ_i. For the grand coalition, corresponding to $\varphi_i = 1$, the respective values for abatement and carbon price are:

$$\mu = \gamma\, \sigma / 2\theta_1$$

and

$$\tau = \gamma$$

By substituting the Nash equilibrium values for μ_i and τ_i into the expressions for μ_N and τ_N, obtain

$$\mu_N/\mu = \tau_N/\tau = \Sigma\, \varphi_i^2$$

The last term, $\Sigma\, \varphi_i^2$, is the Herfindahl index, which is a measure of the size distribution. The lower the index, the more similar are the countries to each other.

The last equation is key, in that it links the Nash equilibrium values of μ_N and τ_N, corresponding to behavioral business-as-usual, to their respective optimal values. Nordhaus indicates that value of the Herfindahl index for country GDP is about 0.12. This leads him to conclude that Nash levels for abatement and carbon price are about 12 percent of their respective optimal values.

In C-DICE, the optimal solution μ_i depends only on own emissions, not on the emissions of others countries. This implies that if the grand coalition forms, each country will be predisposed to leave, reduce its abatement level, and free ride on the others. The net value of doing so, in the absence of exogenous penalties, will be the difference between the incremental saving in abatement cost and increase in damages. This expression is given by:

$$\varphi_i Q_{G,i}[\gamma\sigma(\mu - \mu_i) - \theta_1(\mu^2 - \mu_i^2)]$$

For a tariff policy to induce a stable grand coalition, the cost of the tariff to country *i*, for not being part of the grand coalition, must be at least this value.

Tariffs impose a deadweight cost to international trade. For a stable tariff policy to be welfare improving, the aggregate deadweight cost must be less than the value generated by moving from the Nash equilibrium to the grand coalition. The value of the latter is:

$$Q_{G,i}[\gamma\sigma(\mu - \mu_N) - \theta_1(\mu^2 - \mu_N^2)]$$

Nordhaus reports that the magnitude of the externality imposed by China on the rest of the world is approximately $30 billion per year, whereas the net exit cost of leaving the grand coalition is approximately $8 billion. For the US, the analogous values are $16 billion and $10 billion respectively. In respect to the aggregate, Nordhaus contends that the sum of the transnational externalities is $124 billion, while the sum of the net exit costs is $102 billion.

Because countries' trade patterns are unlikely to be perfectly correlated with their emissions, Nordhaus notes that climate policy might well require lump sum transfers alongside tariffs.

A3.4 Additional Commentary by Nordhaus About the Kyoto Protocol

Nordhaus states the following:

> Quantitative targets in the form of tradable emissions limits have failed in the case of the Kyoto Protocol, have shown excessive price volatility, lose precious governmental revenues, and have not lived up to their promise of equalizing prices in different regions. Moreover, as emphasized by Weitzman (2014), prices serve as a simpler instrument for international negotiations because they have a single dimension, whereas emissions reductions have the dimensionality of the number of regions. To the extent that carbon-price targets lead to carbon taxes, the administrative aspects of taxes are better understood around the world than marketable emissions allowances, and they are less prone to corruption.

Appendix to Section 4

A4.1 Ethics and Sacrifice

In Section 4, I point out that the *Review* argues that there is no ethically justifiable reason to favor the prior cohort over its successor, and suggests a rate of near zero instead. Specifically, the *Review* uses an annual rate ρ of 0.01 percent. In this regard, the *Review* takes the position that time discounting at a positive rate constitutes a flaw in human nature.

Below is an excerpt from the *Review* on this point:

> The discussion of the issue of pure time preference has a long and distinguished history in economics, particularly among those economists with a strong interest and involvement in philosophy. It has produced some powerful assertions. Ramsey (1928, p.543) described pure time discounting as 'ethically indefensible and [arising] merely from the weakness of the imagination'. Pigou (1932, pp 24-25) referred to it as implying that 'our telescopic faculty is defective'. Harrod (1948, pp 37-40) described it as a 'human infirmity' and 'a polite expression for rapacity and the conquest of reason by passion'. Solow (1974, p.9) said 'we ought to act as if the social rate of time preference were zero (though we would simultaneously discount future consumption if we expected the future to be richer than the present)'. Anand and Sen (2000) take a similar view, as does Cline (1992) in his analysis of the economics of global warming.[37] (p. 31)

Consider what these remarks mean in practical terms for consumption per capita by comparing two sets of assumptions for DICE-2106, Nordhaus' assumptions and Stern's assumptions. Under Nordhaus' assumptions, the optimal case entails consumption per capital declining by about 0.1% in 2015 and 2020 relative to behavioral business-as-usual, and remaining below 0.2 percent for the rest of the century. Under Stern's assumptions, the declines are much larger, 8% and 6% respectively. Thereafter, until mid-century, the degree of sacrifice remains stable under Nordhaus' assumptions, but declines under Stern's assumptions. Around 2080, the degree of sacrifice falls to zero under both assumptions. After that, both optimal cases feature higher consumption than under behavioral business-as-usual; however, Stern's assumptions provide higher consumption than Nordhaus' assumptions.

[37] The references in this quoted passage are to:
Anand, S and A.K. Sen (2000): 'Human development and economic sustainability', *World Development*, 28(12): 2029-2049
Cline, W.R. (1992): 'The Economics of Global Warming', Washington D.C.: Institute for International Economics.
Harrod, R.F. (1948): 'Towards a Dynamic Economics', London: Macmillan.
Pigou, A. C. (1912): 'Wealth and Welfare', London: Macmillan.
Pigou, A. C. (1932): 'The Economics of Welfare', (4th ed), London: Macmillan.
Ramsey, F.P. (1928): 'A Mathematical Theory of Saving', *Economics Journal*, 38 (December): 543-559

To place these magnitudes in context, consider that during the Great Recession of 2007 to 2009, consumption in the US declined by approximately 4 percent. During the pandemic, US consumption declined by 2.7 percent.[38] During a typical US recession, gross domestic product (GDP) has declined by approximately 2 percent, but consumption has declined by less than 2 percent.[39]

A4.2 Intuition Underlying the Ramsey Equation

For Nordhaus, the institutional setting for making decisions about climate finance is absolutely critical; and as a result, it is important to understand exactly how interest rates are formally determined in his model. Nordhaus (2007) explains his use of the classic Ramsey equation for this purpose.

There are three variables in the DICE framework which determine the rate of interest. They are the time discount rate, the EIS, and the growth rate in per capita consumption.

The three variables impact the interest rate through the relative demand and supply of future consumption relative to current consumption. Intuitively, the impacts of these variables are follows: Increasing the time discount rate raises the relative demand for current consumption, and therefore the price of current consumption which is the (gross) interest rate. Decreasing the EIS raises the relative demand for current consumption. Increasing the growth rate of per capita consumption decreases the supply of current consumption relative to future consumption, meaning the supply of current consumption relative to future consumption.

The Ramsey equation, which Nordhaus describes below, captures the intuition just described. In addition, the Ramsey equation indicates that the effects of the inverse-EIS (α) and growth rate enter only through their interaction, as a product. A higher growth rate accentuates

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[38] Pistaferri Luigi and Itay Saporta Eksten, 2011. “Consumption and the Great Recession: An Analysis of Trends, Perceptions, and Distributional Effects. An Update Using Revised NIPA Data.” Working paper: Stanford University. https://web.stanford.edu/~pista/cons_recess_August_2011.pdf
Bureau of Labor Statistics Report, 2021. https://www.bls.gov/opub/reports/consumer-expenditures/2020/home.htm#:~:text=%E2%80%8B%20Source%3A%20U.S.%20Bureau%20of%20Labor%20Statistics.&text=Average%20annual%20expenditures%20decreased%202.7,(from%20%2461%2C224%20to%20%2463%2C036).

[39] Claessens, Stijn and M. Ayhan Kose, 2011. “Recession: When Bad Times Prevail,” International Monetary Fund, Finance & Development. https://www.imf.org/external/pubs/ft/fandd/basics/recess.htm

the impact of the inverse-EIS on the interest rate; and vice versa. This implies that if either variable is zero, then the interest rate coincides with the time discount rate.

Nordhaus explains:

> 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…
>
> 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 EIS 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 EIS. For example, using the *Review's* economic growth, a zero rate of time discount requires an EIS of 3 to produce a 4 percent rate of return. If we adopt the Stern EIS of 1, then we need a time discount rate of 2.7 percent per year to match observed rates of return.
>
> The … DICE-2007 model … [is] different from these equilibrium calculations because of population growth and non-constant 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 1½ percent per year with an EIS of 2. These yield an equilibrium real interest rate of 5½ 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…

Nordhaus mentions that the Ramsey equation was derived for a fixed population, and constant interest rate, whereas the DICE model features a time varying population and time varying interest rate. For sake of clarity, below I derive the Ramsey equation for the DICE model.

A4.3 Formal Derivation of Ramsey Equation

Consider the formal derivation of the version of the Ramsey equation used in DICE. For sake of argument, I use two successive periods (or dates), ending in 2020 and 2025 respectively.

In DICE-2016, the MRS (described in Section 4 and the appendix to Section 4) is given by

$MRS = dC_{2025} / dC_{2020}$ along the highest achievable W-indifference curve

$= \partial W/\partial C_{2020} \; / \; \partial W/\partial C_{2025}$

where C is aggregate consumption, not per capita consumption. The social welfare function W has the form

$W = \sum_t (1+\rho)^{-t} L(t)\, u(c_t)$

where c_t is per capita consumption,

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

and $L(t)$ is the population size at date t. The first derivative $u'(c_t)$ is given by

$u'(c_t) = c_t^{-\alpha}$

Compute $\partial W/\partial C_t$ by using the chain rule $\partial W/\partial c_t \; \partial c_t/\partial C_t$. Observe that the ratio $\partial W/\partial c_{2020} \; / \; \partial W/\partial c_{2025}$ will contain the term $(c_{2020} / c_{2025})^{-\alpha}$. Notably, the ratio c_{2025} / c_{2020} is the growth rate of per capita consumption from 2020 to 2025.

Taken together, the above discussion implies that

$MRS = (1+\rho)\,(c_{2025} / c_{2020})^{\alpha}$

The terms $L(2020)$ and $L(2025)$ cancel during the application of the chain rule, as

$\partial c_t/\partial C_t = 1/L_t$

Equality between MRS and MRT implies that at the optimal solution, the per capita consumption growth rate is given by

$(c_{2025} / c_{2020}) = [MRT\ ((1+\rho)]^{1/\alpha}$

From the discussion in Section 4,

$MRT = [1+MPK - \delta_k]$

Let $r(t)$ be the interest rate prevailing at date t specifying the interest to be paid during period $t+1$. As discussed above, in a competitive economy,

$1 + r(t) = MRT$

at date t and therefore,

$(c_{2025} / c_{2020}) = [(1+r(2020))\ ((1+\rho)\ ]^{1/\alpha}$

By expressing the left-hand side of the above equation by the symbol $1+g$ (for gross growth rate) and take the logarithm of both sides of the equation to obtain:

$$ln(g) = 1/\alpha \, [ln(1+r) + ln(1+ \rho)]$$

Here subscripts have been dropped for ease of notation. As is standard, $ln(1+r)$ is the instantaneous discount rate used for continuous compounding. Rearranging the above equation to solve for $ln(1+r)$ to obtain:

$$ln(1+r) = ln(1+ \rho) + \alpha \, ln(g)$$

Now apply the approximation $ln(1+x) \approx x$ to the preceding equation to obtain the version of the Ramsey equation used in DICE:

$$r = \rho + \alpha g$$

In interpreting the Ramsey equation, keep in mind that it is a relationship derived from a first order maximizing condition for g. Expressed to reflect this interpretation, the Ramsey equation becomes

$$g = (r - \rho)/\alpha = r/\alpha - \rho/\alpha$$

Notice that in this version of the equation, g is proportional to the EIS $1/\alpha$, which in turn multiplies the interest rate net of the time discount parameter. This version of the equation explains why the sensitivity of the growth rate to the rate of interest.

A4.4 Hyperbolic Discounting

Exponential discounting refers to the case when the time discount rate is constant over time. Exponential discounting is a feature of intertemporal rationality in the sense that relative “time weights” between subsequent periods are preserved as time evolves. In consequence, people who make optimizing long-term plans keep to those plans as time evolves.

People who do not discount exponentially, in contrast, are prone to being dynamically inconsistent. This means that when they make optimizing long-term plans at a point in time, they are inclined to revise those plans as time evolves. Dynamic inconsistency means that they change their minds.

The market time discount rate in Heal and Millner varies with time, and is therefore non-exponential. I would make five points in this regard.

The first point is that the Heal-Millner discount rate trajectory exhibits the key features of what is known as a hyperbolic discounting trajectory.

The second point is that the optimal solution associated with the Heal-Millner discount rate trajectory is a compromise between the Nordhaus optimum and the *Stern Review* optimum. The trajectories associated with hyperbolic case tend to be bracketed by the corresponding trajectories for the Nordhaus analysis and the *Stern Review* analysis.

The third point is that there is experimental evidence suggesting that at the individual level, people do not have single time discount rates. Instead they discount different goods and services at different rates. In particular, they are most prone to exhibit hyperbolic discounting when it comes to goods and services associated with climate change.[40]

The fourth point is, and this is in my view, the hyperbolic discount rate is more reflective of self-control issues than aggregation issues. I find it difficult to believe that over time, with the arrival of new generations, economic agents will in the main become more patient than their predecessors.

The fifth point is to recall Fisher's contention that self-control is more challenging for people having low incomes. Figures 5 through 8 in Section 2 display the contrast in trajectories for developed countries such as the US and developing countries such as China and India. Emissions in the US and European Union have already peaked, but not so China and India which continue to rise sharply. There are many additional factors to consider here, including population growth.

My point is that emission abatement might be more difficult in the developing world than in the developed world. The situation with China is complex. China began its modernization in 1978, and the results were remarkable. Four decades later, its per capita GDP rose by 25-fold, lifting more than 800 million Chinese out of severe poverty and in many cases famine. This astonishing accomplishment comprised more than 70 percent of the total reduction in global poverty.[41]

Still, in 2023, per capita national income in China, at $12,580 USD, lay below the World Bank's threshold of $13,845 for qualifying as being a "high income" country. In contrast, in 2022, per capita national income in Japan was approximately $42,440, and in the US was

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[40] This finding is consistent with the multicommodity planner-doer framework. See Shefrin, Hersh, 2020. "Unfinished Business: a Multicommodity Intertemporal Planner–Doer Framework," *Review of Behavioral Finance*, Vol. 12 No. 1, pp. 35-68. https://doi.org/10.1108/RBF-10-2019-0148

[41] See Wei Lingling and Stella Yifan Xie, 2023. "China's 40-Year Boom Is Over. What Comes Next?" *The Wall Street Journal*, August 20. https://www.wsj.com/world/china/china-economy-debt-slowdown-recession-622a3be4?mod=WTRN_pos1&cx_testId=3&cx_testVariant=cx_164&cx_artPos=0.

$76,400. China has high aspirations, and being well below aspirations induces present bias and risk seeking behavior. This reflects Irving Fisher's perspective about low self-control.

The hyperbolic discount rate is typically expressed using the functional form

$f_h(t) = 1/(1+ \delta t)$

in contrast to the exponential function, which is

$f_e(t) = 1/(1+\delta)^t$

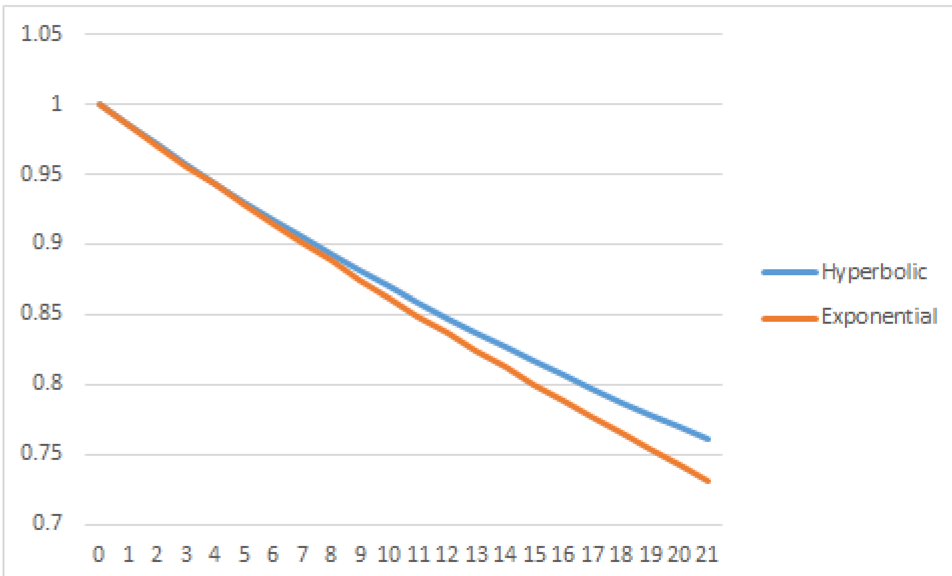

Figure A1 Comparison of hyperbolic discount rate function and exponential discount rate function.

Figure A1 illustrates the comparison between the two functions. Notice that the two discount rate functions are similar for small *t*, but the exponential function declines more rapidly than the hyperbolic function. This is consistent with the idea that in the hyperbolic case, the greatest impatience is at low *t*. Experimental evidence is very strong that the strong majority of subjects exhibit hyperbolic discounting.[42]

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[42] Karp, Larry, 2004. "Global Warming and Hyperbolic Discounting." Working paper, University of California, Berkeley.
Strotz, Robert, 1956. "Myopia and Inconsistency in Dynamic Utility Maximization," *Review of Economic Studies*, 23, 165–180.
Ainslie, George, 1991. "Derivation of 'Rational' Economic Behavior from Hyperbolic Discount Curves," *American Economic Review*, 81(2), 334–340.
Benhabib, Jess, Alberto Bisin, and Andrew Schotter, 2004. "Hyperbolic Discounting: An Experimental Analysis," Working paper: New York University

A4.5 Comments in the *Review* About Climate Risks

Below are comments indicating what the *Review* states about major climate risks:

> At some point, the risks of experiencing some extremely damaging phenomena begin to become significant. Such phenomena include:
>
> - Irreversible losses of ecosystems and extinction of a significant fraction of species.
> - Deaths of hundreds of millions of people (due to food and water shortages, disease or extreme weather events).
> - Social upheaval, large-scale conflict and population movements, possibly triggered by severe declines in food production and water supplies (globally or over large vulnerable areas), massive coastal inundation (due to collapse of ice sheets) and extreme weather events.
> - Major, irreversible changes to the Earth system, such as collapse of the Atlantic thermohaline circulation and acceleration of climate change due to carbon-cycle feedbacks (such as weakening carbon absorption and higher methane releases) – at high temperatures, stabilisation may prove more difficult, or impossible, because such feedbacks may take the world past irreversible tipping points…(p. 293)

A4.6 Additional Commentary About Damage Function Revision

In describing the damage function in DICE-2016, Nordhaus states the following:[43]

> **Damage Function Revision**
>
> The major change in DICE-2016R is the method for estimating the damage function. In earlier versions until 2010, we relied on either estimates gathered by the team at Yale or

Richards, Timothy J. and Gareth P. Green, 2015. "Environmental Choices and Hyperbolic Discounting: An Experimental Analysis," *Environ Resource Econ* (2015) 62:83–103. DOI 10.1007/s10640-014-9816-6

[43] The damage function is a critical element of climate risk. For a general discussion of environmental risks, see Chichilnisky, Graciela, and Geoffrey Heal. 1993. "Global Environmental Risks." *Journal of Economic Perspectives*, 7 (4): 65-86.

by surveys. The 2013 version relied on the Tol survey of damages (6, 7). This survey contained numerous errors and could not be used in the present version. The basic method for setting the damage function was similar to that in the DICE-2013R model as described in ref. 3. The method for calculating the damage function is described here. We examined different damage estimates and used these as underlying data points and then fitted a regression to the data points. We also added an adjustment of 25 percent for omitted sectors and nonmarket and catastrophic damages, as explained in ref. 3.

A4.7 Subsidies, Carbon Prices, and Inefficiency

In the appendix to Section 3, I discussed the issue of carbon taxes and subsidies being equivalent ways to implement the social cost of carbon, at least in DICE. Notably, DICE is an aggregate single commodity intertemporal model; and this is important because it abstracts from the information role which prices serve in a multicommodity setting. In a market setting involving more than one commodity, using carbon taxes instead of subsidies alters the incentive structures for economic agents so that these agents implicitly factor the cost of carbon into their allocation decisions. In this respect, consider the US Inflation Reduction Act (IRA) of 2022, which uses subsidies, not carbon taxes.

One particular study compares electric sector outcomes achieved with IRA-incentives to a counterpart cap-and-trade approach featuring identical carbon dioxide emissions. The study suggests that under IRA the cost of carbon is approximately $83 per ton in 2030 and 2035, while under cap-and-trade the same emission rates can be achieved at rates between $12 and $15.[44] This finding suggests that even with the revised estimates, carbon continues to be priced in the range of 6 percent to 10 percent of its social cost, a range consistent with DICE-assumptions. Moreover, the reluctance to use a carbon tax or equivalent cap-and-trade mechanism results in abatement being more costly than necessary, by a factor of five-to-seven.

The potential improvement from using cap-and-trade instead of subsidies, more than 80 percent, measures the cost of the behavioral impediments to implementing explicit carbon pricing. This is not to say that the IRA provisions are inferior to what would be achieved under behavioral business-as-usual. As I mentioned in Section 4, in 2023 the EPA estimated the social

[44] See Bistline, John, Neil R. Mehrotra, and Catherine Wolfram, 2023. "Economic Implications of the Climate Provisions of the Inflation Reduction Act," Brookings Papers on Economic Activity, Spring.

cost of carbon to be approximately $190 per ton. Therefore, an abatement cost of $83 per ton is less than the associated benefit of $190 per ton. Of course, a cost of $15 is better than a cost of $83 for the same abatement. Still, the gap between $15 and $190 per ton still signals that the shadow price of carbon is closer to behavioral business-as-usual case than to the social cost of carbon; and the same statement applies to emission rates. The big behavioral question, which is the subject of Section 5, still looms large.

There is also the related issue that the global community continues to subsidize fossil fuels. In 2021, such subsidies reduced the actual global price of carbon by about a third.[45]

A4.8 New and Improved IAMs

In recent years, researchers have worked to modify the DICE integrated assessment model in at least three important ways. The first pertains to the climate equations, and features the replacement of the DICE linear carbon cycle equations with a nonlinear system called Finite Amplitude Impulse Response (FAIR).[46] Part of the modification involved some recalibration to bring the model's projections into closer alignment with those in the IPCC. An important feature of this particular modification is lower the forecasts for temperature increase, bringing them below 2°C.

The second modification is to introduce tipping points into the damage function.

The third modification is to replace the additively separable power function social welfare function in DICE with recursive utility. Rebonato (2021) explains the importance of making this change, once the model is generalized to focus on alternative risky scenarios instead of certainty equivalents.[47] This is because the original formulation forces the coefficient of risk tolerance and the elasticity of intertemporal consumption (EIS) to be equal; and there is no good reason why they need to be equal.[48] I will discuss this issue further in the appendix to Section 6.

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[45] Estimate provided by Kepos Capital.

[46] Hänsel , Martin C., Moritz A. Drupp, Daniel J. A. Johansson, Frikk Nesje, Christian Azar, Mark C. Freeman, Ben Groom, and Thomas Sterner, 2020. "Climate Economics Support for the UN Climate Targets." *Nature Climate Change*, Vol 10, 781–789. www.nature.com/natureclimatechange

[47] Rebonato, Riccardo, 2021. *How To Think About Climate Change: Insights from Economics for the Perplexed But Open-minded Citizen*. Cambridge: Cambridge University Press.

[48] Yagihashi, Takeshi and Juan Du, 2015. "Intertemporal Elasticity of Substitution and Risk Aversion: Are They Related Empirically?" Working paper: Old Dominion University.

Appendix to Section 5

This appendix provides additional detail to the discussion in Section 5 about efforts to block the institution of global carbon taxes. As context, the IMF reports that a tax rate of $35 a ton, in 2030, on carbon dioxide emissions would increase prices for coal, electricity, and gasoline by approximately 100, 25, and 10 percent, respectively.[49] A 0.1 percent reduction in consumption for a household consuming $100,000 per year corresponds to $100. A 2.5 percent reduction for such a household corresponds to $2,500.

A5.1 Unsettling Behaviors During Ronald Reagan's Presidency

Ronald Reagan was US president during most of the 1980s. The testimonies of Carl Sagan and James Hansen occurred during his administration. Despite their testimonies and a bipartisan Congressional effort to develop climate policy during this time, the end result was business-as-usual, and the question is why.

My sense is that the Reagan administration experienced low fear, high hope, and high aspirations for strong long-term economic growth. I suggest that this combination predisposed the members of this administration to act optimistically and to take significant risks in respect to global warming.

Reagan came into office with the view that "government is the problem" along with a promise to weaken regulations, including environmental regulations. For Reagan, future economic growth was a major focal point.

Reagan's reaction to global warming was in marked contrast with his predecessor Jimmy Carter. Carter was a nuclear engineer by training, and understood science. He indicated that he would support the idea of spending $80 billion to develop solar power[50] and other alternatives to fossil fuels. Adjusting for inflation,[51] that amount would have been approximately 80 percent of

[49] See Parry, Ian, 2019. "Putting a Price on Pollution." *International Monetary Fund*. https://www.imf.org/en/Publications/fandd/issues/2019/12/the-case-for-carbon-taxation-and-putting-a-price-on-pollution-parry#:~:text=A%20tax%20of%2C%20say%2C%20%2435,%2C%20and%2010%20percent%2C%20respectively.

[50] To encourage energy independence, President Carter had encouraged the development of solar energy and had solar panels placed on the roof of the White House.

[51] That corresponds to the equivalent of approximately $270 billion in 2022 dollars.

the amount associated with the climate provisions in the Inflation Reduction Act which the US passed in 2022, and as a fraction of GDP almost double the 2022-counterpart.

As I mentioned above, the 1980s were a period when there was Congressional bipartisan interest in producing legislation to address the fear posed by global warming. Al Gore, Senator at the time and subsequently author of *An Inconvenient Truth* and 2007 Nobel Peace prize recipient together with the IPCC, played a key role in this regard, as did his fellow Senator Tim Wirth.

James Hansen's Congressional appearances during the 1980s represented an attempt to counter the resistance from the Reagan administration to the generation of a climate policy. In this respect, the administration sought to censor Hansen. Being part of NASA, Hansen was a government employee. Rich explains that this allowed the Reagan administration to try and restrict remarks he was to make at a Senate hearing in 1987. Hansen overcame this obstacle by testifying as a private citizen, who happened to be a scientist working for the US government. A year later, Hansen provided the key Congressional testimony described in Section 2.

The Reagan administration certainly understood the messages from mainstream climate scientists; and here is how we know. President Reagan's predecessor Jimmy Carter tried hard to lead the US to develop a sensible response to anthropogenic global warming. In June 1980, he signed into law the Energy Security Act. This Act directed the National Academy of Sciences to begin a comprehensive study of the effects of a changing climate, a study titled "Changing Climate."

"Changing Climate" was released in late 1983, during Reagan's presidency. "Changing Climate" had as its focus the social and economic implications of global warming. The chair of the committee that drafted the report was William Nierenberg, who was the director of the prestigious oceanographic institution Scripps. However, Rich points out that at the press conference associated with the release of the document, Nierenberg's message was distinctly different in tone and substance from the contents of the written document.

The written report warned of dire consequences from global warming, and recommended a rapid transition to renewable energy sources. In his oral remarks, Nierenberg did suggest reliance on new technological developments; however, in his oral remarks he emphasized caution and warned against panic, thereby removing the sense of urgency communicated by the written report.

Very important is that Nierenberg's sentiments served to support the priorities of the Reagan administration. A sense of urgency is an important antidote to procrastination, as urgency adds cognitive weight to the mental conception of future concerns, relative to immediate concerns. Specifically, urgency operates by treating future events as if they were imminent, and therefore akin to events in the present. Nierenberg's press conference remarks served to encourage procrastination in dealing with the threats posed by global warming.

To be sure, members of the Reagan administration understood the long term threat posed by global warming. Indeed, President Reagan was pressured to sign a joint statement with Soviet Premier Mikhail Gorbachev, pledging to address the threat of global warming. At the time, the United States and the Soviet Union were the largest emitters of atmospheric carbon dioxide. However, there is no evidence that the Reagan administration ever honored that pledge: for them, hope dominated fear.

Think back to the Ehrlich-Simons debate discussed in Section 4. From an emotional perspective, fear dominated the Ehrlich perspective, meaning the fear stemming from unfavorable outcomes associated with overpopulation. In contrast, Simons was hopeful that market forces would lead humans to adapt successfully to the pressures generated by population growth.

The Reagan administration's perspective was close to that of Simon, not Ehrlich. For that matter, the Reagan administration's perspective had much in common with Nordhaus' perspective, in which hope for technological process rather than fear of dire global warming consequences dominated the administration's attitude. In contrast, fear about the consequences of global warming was the primary emotion driving the concerns of mainstream climate scientists such as James Hansen.

I want to make one more point about the Reagan presidency. In contrast to inaction on global warming, during Reagan's term the US did sign a major international agreement to limit emissions of chlorofluorocarbons (CFCs).

Why CFCs and not (other) greenhouse gases?

During the 1970s and 1980s, a great concern arose about a global skin cancer threat connected to the creation of what came to be described as an "ozone hole" in the Earth's atmosphere. The threat related to emissions of CFCs which are also greenhouse gases. People around the world felt a sense of urgency about the threat of contracting skin cancer. This urgency provided the energy to produce in 1987 an international treaty known as the Montreal Protocol, to govern the reduction of CFC emissions.

Nathaniel Rich points out that in reality, although there was a depletion of ozone concentration in the atmosphere, there was no “ozone hole” or “hole in the ozone layer” as there is no layer of ozone in the atmosphere. The term itself was intended initially merely as a communication device. However, psychologically, it was salient, and that salience generated a strong fear reaction.[52]

A5.2 Unsettling Behaviors During George H. W. Bush’s Presidency

Bush followed Reagan as president. As a candidate, Bush campaigned as someone who would mitigate greenhouse gas emissions. However, as president, he delegated the issue to his chief of staff, John Sununu and the head of the Environmental Protection Agency, William Reilly.

In addition to having been a career politician, Sununu had a PhD in mechanical engineering from the Massachusetts Institute of Technology. Confident in his own technical ability, Sununu was skeptical of Hansen’s climate models. Rich writes that Sununu had a one of Hansen’s models installed on his desktop computer, so that he could investigate its properties. After doing so, Sununu concluded that Hansen’s model was “poppycock.”

Rich reports that the Hansen model which Sununu studied featured a “one dimensional” assumption, meaning that the model treated the atmosphere as a vertical line, rather than a three-dimensional volume. Sununu was especially critical of the way Hansen’s equations modeled the carbon cycle discussed in Section 3. He judged that the Hansen model underestimated the ability of the oceans to absorb heat, thereby overestimating the extent of global warming.

Sununu was also skeptical of a claim Hansen made in his 1988 Congressional testimony that the very hot summer of 1988 constituted proof that anthropogenic climate change was indeed underway. Sununu continued the Reagan administration’s efforts to censor Hansen’s remarks before Congress.

[52] The focus on the “ozone hole” took attention away from addressing global warming, as psychologically, attention is a limited resource. See Simons, Daniel J, and Christopher F. Chabris, 1999. “Gorillas in Our Midst: Sustained Inattentional Blindness for Dynamic Events,” *Perception*, Volume 28 Issue 9, 1059–1074. https://doi.org/10.1068/p281059. In addition, the chlorofluorocarbon industry might not have exerted the same lobbying power as the oil industry (discussed below).

Sununu was not just critical of Hansen. He was skeptical of mainstream scientists such as Carl Sagan, who several years earlier had been warning about aerosols creating another ice age, not global warming. He was skeptical of Paul Ehrlich whose predictions about overpopulation had proved to be highly inaccurate. In short, his skepticism about scientists' grand theories and predictions was general.

Most importantly, Sununu's skepticism led him to minimize any US effort to combat global warming, including support for international cooperation on the threat. Shortly before George Bush took office, the World Meteorological Organization and the United Nations Environment Programme created a UN body called the Intergovernmental Panel on Climate Change (IPCC) to study anthropogenic climate change. In 1989, a multination delegation met in Noorwijk, the Netherlands, to assess whether the findings of the IPCC were strong enough to justify an international treaty.

Although William Reilly supported strong action at Noorwijk, Sununu had more political power, and his skepticism led him to ensure that the US withheld support.

Rich suggests that in 1989, but for US resistance, the global community was prepared to make significant commitments to combat climate change; and therefore, the failure to produce an agreement at Noorwijk was serious.

In hindsight, Hansen was right and Sununu was wrong. As I discussed in Section 2, Hansen's predictions from 1981 and 1988 proved to be accurate. I would not fault Sununu for entertaining some skepticism, especially in connection with the predictions made by Ehrlich and Sagan. However, I do believe that Sununu exhibited psychological pitfalls associated with overconfidence, confirmation bias, and the principle of representativeness.

Sununu was overconfident about his own ability. He focused on Hansen's one-dimensional model, but overlooked the analysis of three-dimensional models which Hansen and his coauthors analyzed, even in the 1981 paper. Keep in mind the difference between being smart and being overconfident. People high in overconfidence can be very smart, just not as smart as they think they are,

Sununu exhibited confirmation bias by forming a hard conclusion about Hansen's predictions being poppycock, and not keeping an open mind for evidence that anthropogenic global warming was indeed underway. Indeed, Rich reports that Sununu silenced White House staff for raising the issue of global warming.

Representativeness is a psychological principle in which people make judgments based on stereotypic thinking, focusing on how representative is an object to the class to which it belongs.[53] Representativeness bias constitutes overreliance on stereotypic thinking. Sununu judged that Hansen fit the stereotype of scientists such as Ehrlich and Sagan whose grand predictions were based on models with unrealistic assumptions. In fairness to Sununu, I should say that Hansen himself has recently said that he went out on a limb in his 1988 testimony, because many of scientific colleagues were not yet ready to endorse his conclusions.[54]

In a two-system psychological framework, the phenomena I have just discussed are part of fast system 1 thinking. Sununu is an intelligent person with significant system 2 slow thinking capabilities; however, these were not strong enough to overcome his system 1 processes.

When doing the research for his book, Rich interviewed Sununu to ask him about his role in the Noorwijk conference. Sununu responded by saying that the global community had been engaging in cheap talk, and at that point was unwilling to incur the costs required to undertake significant abatement. He did not admit to having been overconfident, exhibiting confirmation bias, or succumbing to representativeness bias.

I should add that although Hansen's predictions have largely been accurate, it seems to me that he too exhibited overconfidence. In his 1988 testimony he asserted that he was 99 percent confident that the evidence at the time indicated that anthropogenic global warming was a real phenomenon. Most psychological studies of overconfidence conclude that the vast majority of people establish excessively narrow confidence intervals for difficult judgmental tasks. Just remember that Ehrlich and Sagan were also very confident in their predictions. Being right and being overconfident are not the same thing.

The climate policy political dynamic in the US during first decade of the twenty-first century mirrored the dynamic from the 1980s and 1990s; and that dynamic only strengthened the guardrails maintaining the behavioral business-as-usual trajectory.

Just to be clear: the psychological and political forces at work during the first decade of this century were the dominant drivers of climate inaction, which is why I apply the adjective "behavioral" to "business-as-usual." As I stressed in Section 4, the Nordhaus-Stern debate which

[53] Kahneman, Daniel and Amos Tversky, 1972. "Subjective Probability: A Judgment of Representativeness," *Cognitive Psychology*, Vol 3, Issue 3, 430-454.
[54] *Frontline* series, 2022: "The Power of Big Oil," https://www.pbs.org/wgbh/frontline/documentary/the-power-of-big-oil/

took place in 2007, while it generated important insights, had virtually no impact on moving the global economy away from doing business-as-usual.

A5.3 Unsettling Behaviors During the Presidencies of George W. Bush and Barack Obama

There are three important parallels between the period 2001-2010 and the twenty years that preceded it.

The first parallel pertains to John Sununu blocking the emergence of a climate policy during the Presidency of George H.W. Bush, and overriding the efforts of EPA chief William Reilly. Just over ten years later, during the Presidency of George W. Bush, Vice President Dick Cheney blocked the efforts of EPA chief Christy Todd Whitman from moving forward on a carbon cap. Cheney had been an executive in the energy industry before becoming Vice-President, and he used his political office to advance the interests of the industry.

The second parallel pertains to the effort by President Barack Obama in 2010 to pass a cap-and-trade bill that would limit carbon dioxide emissions, and thereby to induce a higher price on carbon dioxide. As had happened with the BTU tax, the Koch brothers used the group Americans for Prosperity, which they funded, to undertake a grassroots campaign aiming to defeat the proposal. As had happened with the BTU tax, the House of Representatives passed the cap-and-trade bill; however, the grassroots effort successfully focused on key Senators.[55] As had happened twelve years before, the outcome of the subsequent midterm elections resulted in the Democrats losing control of both houses of Congress.

The third parallel pertains to the messages broadcast to the nation's somatic markers, associating climate policy with costs but no benefits. For example, Grover Norquist is a political entity who is well known for his efforts to minimize taxes. His organization does so by supporting Republican candidates who sign a pledge not to support tax increases, and opposing Republican candidates who do not. Similar to the 1993 campaign in Oklahoma which associated only "losses" to a carbon tax, Norquist's messaging emphasized that a carbon tax is a tax on

[55] The election of Barack Obama produced an energetic political backlash against Obama's legislative priorities, especially national healthcare. There was great resistance from the libertarian-leaning segment to the Affordable Care Act, which came to be called Obamacare. Working through Americans for Prosperity, the Koch brother added the opposition to climate change public policies to their anti-regulation agenda.

almost every consumer activity from driving automobiles to heating homes, to flying to vacation spots. Clearly, Norquist appealed to people's vulnerability to experiencing present bias.

The three parallel issues I just mentioned were not just history repeating itself, but history repeating itself with much greater intensity. Cheney's intervention was more than a Sununu-bias issue, but the infusion of fossil fuel industry interests into White House priorities.

A5.4 Unsettling Behaviors of Climate Skeptics

Cognitive dissonance is a major issue in the psychology of skepticism. According to cognitive dissonance theory, people have difficulty reconciling beliefs they wish to hold with facts presented to them which are inconsistent with their beliefs. The difficulty presents itself as dissonance, and they are prone to resolving this dissonance by constructing illogical explanations with which they become comfortable. It is rationalization behavior, not rational behavior.

Below, I discuss four contributors to the climate change skepticism campaign: S. Fred Singer, Lee Raymond, Bjørn Lomborg, and Steven Koonin. Cognitive dissonance plays a part in the perspectives of each one, in the form of motivated reasoning, and is very strong in some.

A5.4.1 S. Fred Singer: Motivated Reasoning to the End

I begin with Singer, who in the mid-1980s expressed skepticism about anthropogenic global warming being a serious issue with which to be concerned.

In 1986, Singer was an accomplished atmospheric physicist who was serving as chief scientist of the Transportation Department, and was also emeritus professor of environmental sciences at the University of Virginia. At the time, he began writing articles for *The Wall Street Journal* which warned about unfounded scientific claims involving overpopulation, global cooling, the ozone hole, and nuclear winters. Singer voiced a clear concern that scientists were devising grand theories about dire consequences, which while unsubstantiated with firm evidence, suggested the need for major government action.

Not surprisingly, Singer was critical of claims made by Paul Ehrlich and Carl Sagan. In Section 2, I mentioned Carl Sagan's role in pronouncements about aerosols causing global cooling and the next ice age. Interestingly, Sagan and Singer engaged in something of a televised debate in 1991 during the Gulf War when Iraq set hundreds of Kuwaiti oilfields ablaze. Sagan warned of a global disaster from the smoke generated by Iraq's actions, an effect similar to the eruption of a major volcano. Singer argued that there would a local effect but it would be short-lived. When the smoke cleared, if you will excuse the pun, we learned that neither scientist had correctly predicted the outcome; however, the actual outcome was much closer to Singer's view than to Sagan's view. Singer was no crank, at least at the time.

Singer began to write more frequently and more passionately about global warming, especially after Hansen's testimony in 1988. He expressed the view that anthropogenic global warming belonged to the same camp as overpopulation, global cooling, and nuclear winters. In this regard, he constantly reiterated his position that evidence was lacking to support the theories being advanced, and where evidence did exist leaned in the direction of being disconfirming, not confirming. I should also add that Singer was highly skeptical of regulation, especially international regulation, deriding bureaucrats, "utopians," and "central planners" who claimed to be "saving the planet."[56]

My view of Singer's writings on global warming in the 1980s and early 1990s is that they helped combat confirmation bias on the part of mainstream climate scientists, and those who make policy based on the recommendations of these scientists. His critiques were a call to rely on the weight of evidence, rather than emotional arguments reflecting fear. The debate with Sagan was an indication that his views merited consideration.

In respect to Hansen's 1988 testimony and scientific work, Singer was clear to say that if the average global temperature were to rise by about 0.4°C during the 1990s, we would surely notice; and if not, then we would lack evidence in support of Hansen's theoretical model.

It is easy to succumb to hindsight bias, and look back at the 1980s and 1990s as if it were obvious to most scientists that global warming was a real phenomenon requiring immediate and strong action. Hansen himself stated that he went out on a limb during his 1988 testimony, acknowledging that at the time his view was not widely accepted among his professional peers.

Indeed, in 1998 Hansen and his coauthors published a paper in the *Proceedings of the National Academy of Sciences* to say that the experience of the 1990s suggested that other factors, besides greenhouse gas emissions, might be the key long-term drivers of the Earth's climate.[57]

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[56] Singer, S., 1992. "Fred Earth Summit Will Shackle the Planet, Not Save It," *The Wall Street Journal*, 19 February.
[57] Hansen, James E., Makiko Sato, Andrew Lacis, Reto Ruedy, Ina Tegen, and Elaine Matthews, 1998. "Perspective:

Subsequently, the evidence shifted in the direction of Hansen's predictions from 1981 and 1988. Still, Hansen's 1998 publication provided evidence that Hansen worked to mitigate confirmation bias. By this I mean that he did not ignore disconfirming information, but considered it and gave it weight in testing his original hypotheses.

In contrast, I suggest that Singer exhibited a strong case of confirmation bias, or in this case "motivated reasoning" because we are discussing a view Singer held. To be sure, Singer had reputational capital associated with his critique of anthropogenic global warming. Over time, as the evidence mounted in support of anthropogenic global warming being a valid and serious phenomenon, Singer clung to his original position.

As context for Singer's motivated reasoning, consider that the IPCC's Second Assessment Report, released in 1995, featured a twelve-word statement which read: "The balance of evidence suggests a discernible human influence on global climate." Section 8 of the report provided a description of uncertainties associated with the analysis.

Singer was displeased with the IPCC's conclusion and critical of the fact that one of the two summaries in the draft of Section 8 was excluded from the final document. In retrospect, it is difficult to see as germane the exclusion of redundant material about uncertainties, in order to conform to the overall document style featuring only one summary per chapter.

By 2012 evidence was mounting that the estimates in the preceding IPCC reports were biased downward.[58] In other words, global warming effects turned out to have been larger than the IPCC had projected. This statement applied across a wide set of dimensions such as the rate at which Arctic ice was melting, the rate at which ice sheets in Greenland and Antarctica were melting, the rate of sea level rise, the rate of ocean acidification, and the rate at which permafrost was unthawing.

In support of my judgment of Singer's motivated reasoning, consider three points.

Climate forcings in the Industrial era," *Proc. Natl. Acad. Sci. USA,* Vol. 95, Octoboer, 12753–12758. See also the argument advanced by climate scientist Richard Lindzen, "Climate Change: What Do Scientists Say?" https://assets.ctfassets.net/qnesrjodfi80/1JFsobvmVy084GO60awOKo/031f9093785ca9eddc75832ad46a0fec/lindzen-climate_change_what_do_scientists_say-transcript.pdf. As an accomplished atmospheric scientist, Lindzen argues that in a system as complex as Earth's climate, carbon dioxide is unlikely to impact the overall temperature of the planet.

[58] See Scherer, Glenn, 2012. "IPCC Predictions: Then Versus Now," *Climate Central*. https://www.climatecentral.org/news/ipcc-predictions-then-versus-now-15340.

First, the Charney report and Hansen's global warming theory focus very clearly on the central relationship between atmospheric carbon dioxide concentration measured in parts per million and global temperatures. In all of his writings for *The Wall Street Journal*, from 1996 until his death in 2020, Singer never mentioned parts per million of carbon dioxide in the Earth's atmosphere. However, in one of his articles, he did cite a 1991 study from the National Academy of Sciences suggesting that modest global warming might benefit agriculture production.[59] Some in the denial camp have amplified this position, arguing that increased atmospheric carbon dioxide is good for plants, and those who eat plants.

Second, after arguing for years that equilibrium sea levels were not rising, but instead were exhibiting natural variation, Singer finally acknowledged, in 2017, that sea levels were indeed rising; however, he contended that although the rise was a mystery, the cause was certainly not global warming.

Third, when asked if he ever went to sleep at night worrying that his views about global warming might be wrong, Singer's response was crisp and clear. He provided a one-word answer: "Never!"

The response of "never" reflects the psychological phenomenon known as "base rate overweighting" or "conservatism."[60] You can think of base rate information as an unconditional probability distribution, such as a Bayesian prior. You can think of "singular information" as akin to a conditioning event associated with new information.

Bayes rule provides a way to update a prior probability belief to reflect new information. The evidence from psychological studies is robust that most people do not update their beliefs as Bayesians. People are prone to overweight base rate information in some situations, and to overweight singular information in other situations. Psychological studies suggest that relative salience of information is a key determinant of which bias is more likely to prevail.

For Singer, it was base rate information that prevailed. It seems to me that Singer overweighted base rate information about global warming, to the point of denying the validity of new information that supported the validity of climate models used by mainstream climate

[59] Singer, S. Fred, 1993. "Bookshelf: Environmental Fear-Mongers Exposed," *The Wall Street Journal*, April 28.
[60] Edwards, Ward, 1982. "Conservatism in Human Information Processing," in *Judgment under Uncertainty: Heuristics and Biases*, edited by Daniel Kahneman, Paul Slovic, and Amos Tversky. pp. 359 – 369, Cambridge University Press. Published online by Cambridge University Press: 05 May 2013. DOI: https://doi.org/10.1017/CBO9780511809477.026.

scientists.[61] Singer criticized other scientists for not backing their theoretical predictions with hard evidence. However, Singer ignored evidence that did not confirm his view of anthropogenic global warming.

A5.4.2 Lee Raymond: Messages Crafted to Confuse

Lee Raymond was a major contributor to the skepticism campaign. Raymond was ExxonMobil's chief executive officer between 1999 and 2005. During his term as CEO, ExxonMobil increased funding for groups that engaged in the creation of doubt about global warming. Moreover, Raymond himself became a chief spokesperson for raising skepticism about anthropogenic global warming.[62]

Raymond continually delivered the message that the state of climate science was unsettled, and that it would be unwise to incur large costs in the fact of great uncertainty. One of his standard claims was acknowledging that the climate is indeed changing, and then pivoting to say that it is always changing so that we are simply witnessing natural variation. In making this argument, Raymond would sidestep statements made by Hansen about it being clear that climate change data could not be explained by natural variation. He also sidestepped the findings of Exxon scientists done in prior years, which was highly consistent with the analysis of mainstream climate scientists. Both behaviors are consistent with cognitive dissonance and motivated reasoning.

Raymond's arguments were designed to counteract the general public's tendency to perceive risk on two psychological dimensions, dread and ambiguity (or degree of understanding). People are prone to attach high risks to activities whose outcomes induce dread and whose elements they feel they do not understand.[63] Raymond's messages were intended to

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[61] The Bayesian approach fails if the prior attaches zero probability to an event which occurs with positive probability. This is because the Bayesian posterior, based on Bayes' rule, cannot shift probability mass to an event to which the prior has (erroneously) attached zero probability. Indeed, Bayes rule reduces to a singularity in this case. Singer appears to have attached zero probability to global warming having an anthropogenic component. A similar statement applies to "non-sceptics" such as me: We too need to attach nonzero probability to our views being wrong, and be willing to revise accordingly in the face of compelling evidence.

[62] Raymond's successor, Rex Tillerson, continued ExxonMobil's funding of groups seeking to raise doubts about global warming, but at the same time made public statements suggesting that ExxonMobil had begun to take the climate threat seriously. For a discussion about this duplicity, see Christopher M. Matthews and Collin Eaton, 2023. "Inside Exxon's Strategy to Downplay Climate Change," *The Wall Street Journal*, Sept. 14. https://www.wsj.com/business/energy-oil/exxon-climate-change-documents-e2e9e6af.

[63] See Slovic, Paul, 1987. "Perception of Risk," *Science*, Vol 236, Issue 4799, 280-285.

alleviate feelings of dread and offer assurance that climate change was a normal state of affairs that humans had learned to deal with over the centuries.

A5.4.3 Bjørn Lomborg: Using Nordhaus' Analysis to Downplay the Urgency of Taking Early Action

Bjørn Lomborg has been a fixture in public discussions about global warming. Lomborg is articulate and charismatic. He describes himself as a skeptical environmentalist, and is the author of a book with that title[64] and another with the title *Cool It*.[65]

By and large, Lomborg promotes Nordhaus' perspective that the costs of global warming will likely be modest, admitting that most of his messages are not original but the restatements of others. His main message is that fears about global warming are exaggerated, and that the global community would be better off focusing on other social problems.

During the Nordhaus-Stern debate, Lomborg was a strong critic of Stern.[66] The Grantham Institute headed by Stern, points out that Lomborg has a track record of misrepresenting the results of climate research.[67]

In recent years, with the rising presence of Swedish activist Greta Thunberg, Lomborg has suggested that Thunberg has significantly overstated the sense of urgency about global warming, noting that people will adapt to rising temperatures, and that the world will not come to an end because of it.[68] On this last point, I would remind readers that a sense of urgency can be critical for overcoming problems with self-control; and moving off the business-as-usual trajectory requires self-control.

In respect to adaptation, Lomborg takes a similar position to Richard Tol (see Section 4 and its appendix). Both argue that humans will adapt to rising temperatures in the same way as Saudis have learned to survive in hot desert conditions by using technology such as air

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[64] Lomborg, B. 2001. The Skeptical Environmentalist. Measuring the Real State of the World. *Cambridge University Press*, Cambridge.
[65] Lomborg, Bjørn, 2010. *Cool It: The Skeptical Environmentalist's Guide to Global Warming*. Knopf Doubleday.
[66] Lomborg, Bjørn, 2006. "Stern Review; The Dodgy Numbers Behind the Latest Warming Scare." *The Wall Street Journal*, 1 November 2006.
[67] See the comments of Bob Ward: https://www.lse.ac.uk/granthaminstitute/news/a-nobel-prize-for-the-creator-of-an-economic-model-that-underestimates-the-risks-of-climate-change/.
[68] https://www.youtube.com/watch?v=0Te5al2APrQ

conditioning. Critics of this position point out that this argument confuses climate with weather, by which they mean that a hotter climate will produce much more damage than higher temperatures. The fallacy, critics argue, is in treating temperature differences across space at a given time with temperature differences for the planet across time.

Lomborg has been a controversial figure in climate debates, with many mainstream climate scientists having urged Cambridge University Press (CUP) not to publish his work *The Skeptical Environmentalist*. CUP refused the request, offering Lomborg's critics an opportunity to respond in print, an opportunity they did not seize. For the record, I would support CUP's decision to publish. That said, the underlying psychological issues are important, as they reflect the relative impact of different nudge techniques, whether the nudges have positive or negative influence, and who is to say.[69] Keep in mind that mainstream scientists might have the weight of the evidence on their side, but as Tversky and Griffin emphasize, not the psychological strength of the argument. This is the conundrum faced by publishing houses in situations such as the one CUP experienced with Lomborg's book. It is also a conundrum for mainstream climate scientists who need to learn how to develop strong arguments when the weight of the evidence is insufficient to convince those they are trying to influence.

A5.4.4 Steven Koonin: Sending Unsettling Messages About Climate Science Being Unsettled

A book by Steven Koonin, published in 2021, entitled *Unsettled*, continues to raise doubts about mainstream climate scientists.[70] For the sake of addressing confirmation bias, this is a book worth reading. That said, in Koonin's lectures, he explains that what he means by "unsettled" is not so much disagreement among climate scientists about the connection between greenhouse gas emissions and past anthropogenic climate change. Rather it is about how strong future climate policy should be, noting that what we need is "orthodontia" instead of "tooth extraction." As an example of "orthodontia," he points to Nordhaus' policy recommendations from DICE. I

[69] See Harrison, Chris, 2004. "Peer Review, Politics and Pluralism," *Environmental Science & Policy,* 7, 357–368. This article describes the controversy surrounding the publication by Cambridge University Press of Lomborg's book *The Skeptical Environmentalist*.

[70] Koonin, Steven E., 2021. *Unsettled: What Climate Science Tells Us, What It Doesn't, and Why It Matters*, Dallas: Benbella Books. Also see the interview with Koonin at https://www.youtube.com/watch?v=-3Fu0GqUO2Y.

would add that Nordhaus' recommendations entail the global temperature reaching 3.5°C by the end of the century, with Koonin apparently regarding such a state of affairs as acceptable.

In any event, we are still closer to behavioral business-as-usual trajectory than Nordhaus' recommended trajectory based on DICE; and as I mentioned in Section 4, during 2021 Nordhaus effectively doubled his recommended carbon price. Nevertheless, those opposed to emissions abatement interpret Koonin's work as confirming their prior view that climate science is unsettled, thereby exhibiting cognitive dissonance and motivated reasoning.

Appendix to Section 6

Hope based on technologies for alternative energy and greenhouse gas removal comprise the themes of Section 6. Hope features an emphasis on favorable outcomes in situations involving risk. In this appendix, I discuss the importance of technology and cost reduction when psychological factors lead to behavioral business-as-usual behavior, with greenhouse gases being priced well below their respective social costs.[71] A key implication of the analysis is that favorable outcomes attached to hope will require very dramatic cost reductions in the associated technologies.

Technological progress and negative carbon emissions are modeled within DICE. Figures 14 through 18 illustrate a key feature in the structure of DICE, namely the date it becomes possible for the economy to become carbon negative. This date is 2160.

The figures very clearly describe what occurs between the date the economy achieves net zero emissions, meaning the rate of abatement reaches 100 percent, and when it transitions to becoming carbon negative. During the interim, the cost function associated with abatement continues to decline, because of technological improvements. However, the atmospheric temperature continues to rise, as depicted in Figure 18. The temperature only begins to decline after 2160, when the economy becomes carbon negative. By 2285, along the Stern trajectory, the temperature falls below 1°C above preindustrial levels.

[71] In respect to cost reduction, see Liebreich, Michael, 2023. "Liebreich: Net Zero Will Be Harder Than You Think – And Easier. Part I: Harder," BloombergNEF, September 6. https://about.bnef.com/blog/liebreich-net-zero-will-be-harder-than-you-think-and-easier-part-i-harder/?utm_source=Email&utm_campaign=727582&utm_medium=Newsletter&utm_content=BNEFSeptNL&tactic=727582&pchash=

Figures 14 through 18 make clear the importance of making investments to achieve net negative carbon emissions much earlier than 2165. Below, I discuss scenarios for doing so, assuming that the global community will fail to price carbon at its social cost. Specifically, I analyze how some of the key trajectories associated with the behavioral business-as-usual case will change as a result of the introduction of new technologies for alternative energy and greenhouse gas removal.[72] Because the development of these technologies involves risk, part of this appendix is devoted to risk-based integrated assessment models.

Technology is likely to play an important role in respect to the evolution of markets and public policy. In this regard, I envision roles for satellite surveillance, big data, artificial general intelligence, and blockchain. Advances in these technologies are embodied within Nordhaus' general assumptions about technological progress, which I discussed in Section 3. Key issues which arose in the Ehrlich-Simon debate loom large here.

There are major regulatory efforts underway to develop consistent, comparable, reliable climate disclosures associated with offset markets. These markets will serve to price greenhouse gas emissions, although not as efficiently as a well-structured global emissions tax.

Section 6 mentions compliance markets and voluntary markets as the two institutions for the trading of greenhouse gas credits. These markets will play an important role in respect to greenhouse gas removal. In 2023, these markets were still small, relative to the task at hand.

In 2023, the voluntary market was worth approximately $2 billion, while the compliance market was worth approximately $851 billion across only 30 markets worldwide. By 2030, the voluntary market was expected to grow to between $10 billion and $40 billion.[73] The associated volumes were modest, and there are limits to what the voluntary market can accomplish.[74] In 2022, the volume traded on the voluntary markets was about 2 billion tons, with only 230 million

[72] There are additional issues about technology and carbon pricing besides those discussed here. For some striking examples about technological advances in producing meat without animals, and carbon barometer-linked bonds, see http://www.forbes.com/sites/hershshefrin/2023/07/06/bold-imaginative-climate-ideas-proposed-at-academic-conference/.

[73] See Terrapass, 2023. "Overall Size of Carbon Offset Markets: How Big Are They?" https://terrapass.com/blog/overall-size-of-carbon-offset-markets#:~:text=The%20voluntary%20and%20compliance%20carbon,across%20only%2030%20markets%20worldwide.

[74] Episode 1 of the podcast series "Conversations in GGR." Interview by host Terri Pugh with guest Sebastian Manhart, Senior Policy Advisor at Carbonfuture, who discussed the Carbon Unbound NYC 2023 conference.

tons being of high quality.[75] Most of the demand side was populated by a handful of high-margin, low emission firms. To exert a meaningful impact, the voluntary markets will need to cover tens of billions of tons per year. Correspondingly, the compliance markets will need to cover hundreds of billions of tons per year.

Developers of greenhouse gas removal technologies were anxious that their ability to expand supply would exceed the growth in associated demand. Going forward, it is likely that government procurement programs will be necessary to generate a sizable portion of that demand.

According to the externalities market theory developed by Ronald Coase, market mechanisms can serve to internalize externalities, thereby obviating the need for the imposition of Pigouvian taxes.[76] For example, consider the case of a dairy farmer whose livestock crosses over into an adjoining grain farmer's property and damages the grain farmer's crop. Suppose that the marginal cost to the grain farmer from the dairy farmer's cheese production is $100 per ton. That is, the impact from the last ton of cheese is to reduce the grain farmer's revenue (and income) by $100. In this case, the appropriate social cost of cheese is $100 per ton.

In a compliance market, the dairy farmer would be compelled to pay the grain farmer $100 for every ton of cheese produced. In a voluntary market, the grain farmer would pay the dairy farmer $100 for every ton of cheese the dairy farmer reduced cheese production, from the inefficient equilibrium level. In a taxation framework, a government entity would levy a $100 tax on cheese production.

Apart from income distribution issues and transaction costs, the overall outcome is equivalent in the three cases. Moreover, a profit maximizing dairy farmer would produce cheese to the point where its marginal profit is zero. Therefore, the profit on the last ton of cheese produced would not cover the $100 cost. As a result, imposition of the cost would induce the dairy farmer to cut back on cheese production.

The social cost of carbon is similar in concept to the social cost of cheese in the preceding example. However, In the case of carbon, transaction costs are highly relevant,

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[75] The quality issue is important. See Coy, Peter, 2023. "To Fight Climate Change, We Need a Better Carbon Market," *New York Times*, August 23. https://www.nytimes.com/2023/08/23/opinion/climate-change-carbon-offsets.html?campaign_id=39&emc=edit_ty_20230824&instance_id=100765&nl=opinion-today&regi_id=67959516&segment_id=142792&te=1&user_id=6e141835ff07c27db27d9269c16188b0.

[76] Coase, Ronald, 1960. "The Problem of Social Cost," *Journal of Law and Economics*, Vol. 3, 1-44. http://www.jstor.org/stable/724810.

especially for compulsory and voluntary markets which require legal frameworks, disclosure of information, and monitoring. Notably, Nordhaus strongly advocates the use of taxation instead of markets. However, we live in a behavioral world, and as a result incur behavioral costs by relying on compliance and voluntary markets instead of taxation.

A6.1 IRENA: Hope for Advances in Alternative Energy and Emissions Reductions

The International Renewable Energy Agency (IRENA) is an intergovernmental organization that serves as a platform to support countries as they decarbonize. In a 2020 report, IRENA describes two carbon emission trajectories for energy-intensive sectors of the economy, one a base case corresponding to business-as-usual and the other what I will call the "optimistic IRENA forecast trajectory" in which the global economy reaches zero carbon dioxide emissions early in the second half of this century.[77] Figure A2 displays both trajectories along with the behavioral business-as-usual case for total industrial emissions from DICE-2016.

In respect to the forecast trajectory, IRENA (2020) identifies four energy-intensive industries and three transport sectors as presenting the most difficult challenges in respect to decarbonization.[78] The report notes that policy changes will be required if the global economy is to transition from the base trajectory to the optimistic-IRENA forecast trajectory. If no such transition occurs, then the report projects that points out that by 2050, seven specific sectors are likely to comprise approximately 38 percent of energy and process emissions and 43 percent of final energy use. Of the seven sectors, four relate to energy-intensive industries and three relate to transportation.

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[77] IRENA (2020), *Reaching Zero with Renewables: Eliminating CO2 Emissions from Industry and Transport in Line with the 1.5oC Climate Goal, International Renewable Energy Agency*, Abu Dhabi. ISBN 978 - 92 - 9260 - 269 - 7 Available for download: www.irena.org/publications.

[78] The four energy-intensive industrial sectors are iron and steel, chemicals and petrochemicals, cement and lime, and aluminum. The three energy-intensive transportation sectors relate to freight and long-haul transport. These are: road freight, aviation, and shipping.

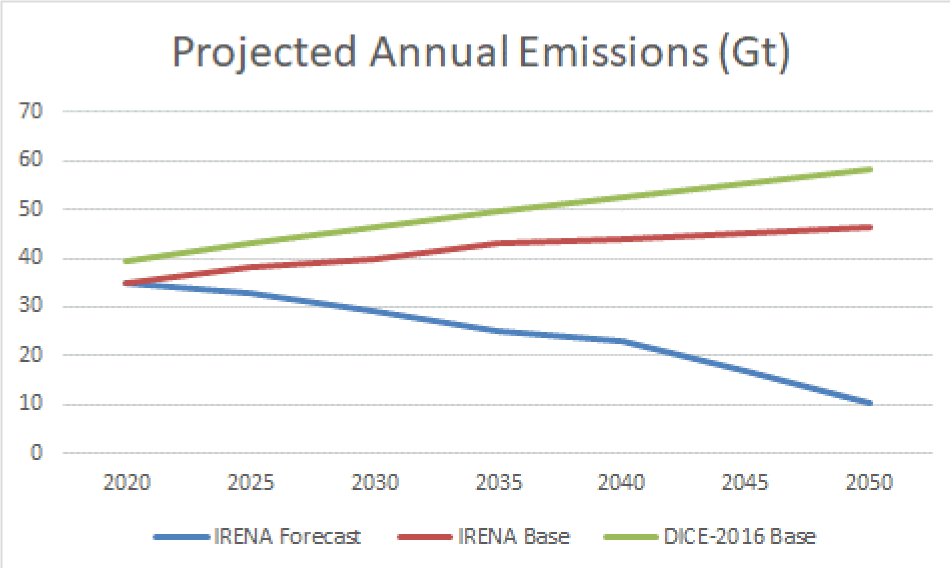

Figure A2 Projected energy- and process-related CO2 annual emissions trajectories from 2020 until 2050 for IRENA, and industrial-related emissions from the behavioral business-as-usual base case for DICE-2016.

According to IRENA (2020), a combination of five emission reduction measures have the potential to reduce industry and transport carbon dioxide emissions to zero. The measures, which are described on page 5 of the report are as follows:

1. Reduced demand and improved energy efficiency;
2. Direct use of clean, predominantly renewable electricity;
3. Direct use of renewable heat and biomass;
4. Indirect use of clean electricity via synthetic fuels and feedstocks; and
5. Use of carbon dioxide removal measures.

These measures represent hope for steady and continuing cost reductions in the production of renewable energy. IRENA (2020) notes that renewable energy technologies, batteries, and associated enabling technologies are proving to be effective and affordable. The report mentions that at the time, none of these measures was currently commercially mature or ready for wide adoption.

On the last point, among the set of obstacles that will need to be addressed are the following: “high costs for new technologies and processes; the need for enabling infrastructure ahead of demand; highly integrated operations and long-established practices; uneven, large and long-term investment needs; gaps in carbon accounting; and business risks for first-movers, including added costs and consequent "carbon leakage" in favour of competitors." (p. 5)

Progress in alternative energy development and adoption was significant after 2020. In 2023, the *New York Times* reported on the degree to which alternative energy sources had begun to replace fossil fuels, and in effect, urged readers to be aware that because of exponential growth bias, they would be surprised by how quickly the transition would take place.[79] The article also documented the nature of obstacles to the diffusion of energy alternatives.

A6.2 ETC: Hope for Removal of Greenhouse Gases from the Atmosphere

The fifth measure described in IRENA (2022) is carbon dioxide removal (CDR), the removal of carbon dioxide from the atmosphere. In this subsection, I consider highlights of a report issued in 2022 by the Energy Transitions Commission (ETC) focusing on the current state and future prospects of carbon dioxide removal technologies.[80]

The Energy Transitions Commission (or ETC) describes itself as "a global coalition of leaders from across the energy landscape committed to achieving net zero emissions by mid-century, in line with the Paris climate objective of limiting global warming to well below 2°C and ideally to 1.5°C." Prominent members of the ETC include representatives from Shell, BP, WRI, the London School of Economics, The Energy and Resources Institute, and Bank of America BAC.

The ETC report, (ETC, 2022) was featured in an article that appeared in the *Wall Street Journal*.[81] ETC (2022) makes the same point made in IRENA (2020), namely that CDR will need to fill the gap between the optimistic emissions trajectory and a net zero trajectory.

ETC (2022) covers the following six areas:

1. Climate targets and implications for carbon budgets;
2. Emission reduction scenarios for closing the gap between emissions currently being projected and their associated target levels;

[79] https://www.nytimes.com/interactive/2023/08/12/climate/clean-energy-us-fossil-fuels.html
[80] Energy Transitions Commission (ETC), 2022. *Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive*. https://www.energy-transitions.org/publications/mind-the-gap-cdr/
[81] Ballard, Ed, 2022. "Shopify Puts Up Cash for Rooftop Carbon-Capture Machines, Tree-Planting Drones San Francisco-based Noya is among early-stage developers that Shopify is backing in its latest round of carbon-removal purchases," *The Wall Street Journal*. March 28.

3. The scale required for different types of CDR, as part of a strategy to achieve net zero emissions by 2050;
4. Managing the risk profiles associated with different types of CDR;
5. Questions about who should pay for removals, and what role will be played by carbon markets; and
6. The actions that need to be undertaken in the 2020s in order to ensure that future removals will occur at sufficient scale.

One of the most insightful discussions is the character of the portfolio approach to CDR. The report describes three categories of solution, namely natural climate solutions; hybrid/biomass solutions with carbon removal and sequestration; and engineered solutions involving direct air capture and storage (meaning CDR).

According to the ETC, by 2030 these solutions will need to be removing 3.6 Gt (meaning 3.6 billion metric tons) of CO2 from the atmosphere, per year. After 2030, engineered solutions will play an especially important role; however, the ETC foresees that engineered solutions will only be removing 0.1 Gt of CO2 from the atmosphere in 2030.

A6.3 New Technologies: Hope for Removing Greenhouse Gases from the Atmosphere

In 2022, Peter Fiekowsky, together with Carole Douglis, published a book entitled *Climate Restoration*. This book discusses four types of technologies for removing greenhouse gases from the atmosphere.[82] These are:

1. The manufacture of synthetic limestone that can permanently sequester carbon in the built environment;
2. Seaweed and marine permaculture which produces ocean forests of kelp which capture very large amounts of CO2;[83]

[82] There are many CDR initiatives. Examples include Project Vesta, Charm Industrial, Prometheus Fuels, Stripe Climate, ClimeWorks, CarbonBuilt, Noya, and Brimstone Energy.

[83] The oceans comprise 71 percent of Earth's surface, which means that the water-to-land ratio is effectively two-to-one. Moreover, oceans hold much more potential for sequestering carbon than their land-based counterparts. Already, oceans hold 99 percent of the planet's carbon, stored as limestone in coral reefs. Oceans have been, and will continue to be a major carbon sink.

3. Iron fertilization in the ocean, using technology which mimics natural processes; and
4. Enhanced atmospheric methane oxidation, which involves augmenting the amount of iron chloride in the lower atmosphere over the ocean. The resulting oxidation leads atmospheric methane to be broken down into carbon dioxide and water.

The argument in *Climate Restoration* is that during the 2020s, progress in developing these technologies will be sufficient to remove 1 trillion tons of carbon dioxide from the atmosphere between 2030 and 2050. Doing so will entail removing an average of 50 Gt a year. At the same time, cost reductions in renewable energy sources will be sufficient to make fossil fuels much less competitive against renewables, resulting in a major transition from the latter to the former. Fiekowsky and Douglis also make the case that curtailing population growth will contribute positively to addressing the threat posed by global warming.

Since 1760, humans have emitted more than 1.5 trillion metric tons of carbon dioxide into the atmosphere. Remarkably, about two thirds of emissions have occurred since the publication of the Charney report in 1979. Fiekowsky and Douglas point out that 460 ppm is more than 50 percent higher than levels human beings have ever experienced. Preindustrial concentrations of carbon dioxide were below 300. Their book identifies a path for restoring the carbon dioxide concentration to the vicinity of 300. In this regard, they are much more optimistic than the IPCC or the ETC, and suggest that this goal is achievable by the year 2050.

Fiekowsky and Douglis focus on a goal involving the removal and permanent sequestration of one trillion tons of atmospheric carbon dioxide by the year 2050. They argue that the technologies for doing so already exist, and that by 2030 these processes will scale to the point of being able to remove an average of 50 Gt of carbon dioxide a year for the subsequent 20 years. Figure A3 below displays the very hopeful emission trajectory envisaged by Fiekowsky and contrasts it with the trajectories displayed in Figure A2.

In Section 2, I discussed the issue of the "methane emergency." There is now progress in developing technologies for removing methane from the atmosphere. These technologies operate by increasing the rate at which methane is naturally broken down through oxidation, which transforms methane into water and carbon dioxide. Of course, more carbon dioxide in and of itself is problematic, but it is better to have a greenhouse gas that is carbon dioxide than to have an equal amount of methane, given the difference in their respective potencies. I would add two points here. First, it takes methane much less time than carbon dioxide to be naturally broken down in the atmosphere. Therefore, if the global community stops emitting methane, the problem will quickly self-correct. Second, once methane is oxidized, there is nothing to sequester.

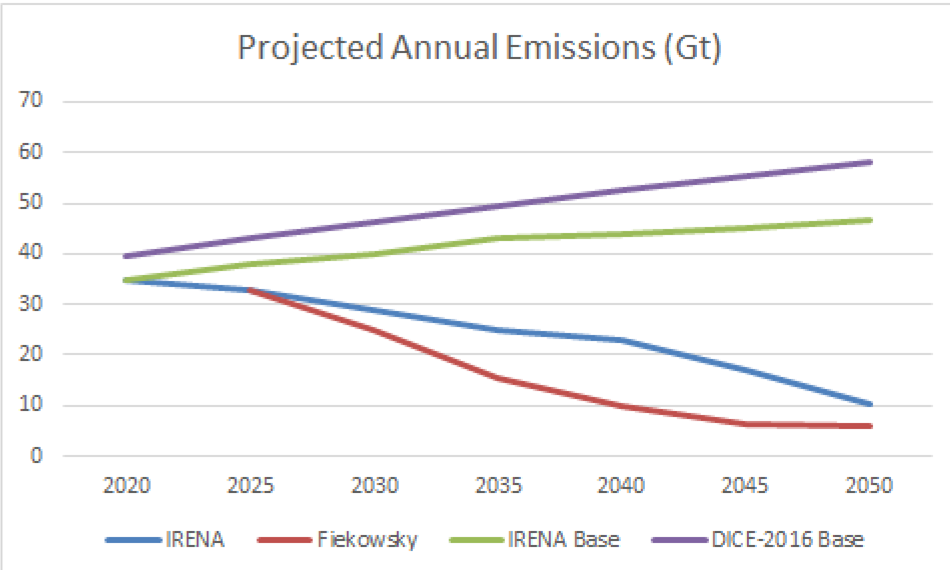

Figure A3 Comparison of projected emissions trajectories: Energy- and process-related CO2 annual emissions trajectories from 2010 till 2050.

A methane removal technology known as "solar chimney" has attracted considerable attention. There is a prototype in Xian, China, applying an approach developed at the University of Minnesota. The hope is that when scaled, this unit will be capable of processing 11,100 metric tons of methane per year.[84]

Controlling methane is important for future temperature increases. Methane removal technologies, if scaled globally have the potential to prevent a global temperature rise of at least 0.3 degrees Celsius.

One of the positive developments to emerge from COP26 is the Global Methane Pledge (GMP). The GMP was spearheaded by the US and European Union. Over 120 countries, though not China or Russia, have signed on, pledging that by 2030 they will reduce methane emissions 30 percent below 2020-levels. Interest in GGR will only grow.

[84] See https://www.globalmethanepledge.org/.

A6.4 High Hope Trajectories With CDR and GGR, Viewed Through a DICE-2016 Lens

The climate restoration scenario features a combination of an abatement trajectory associated with renewable energy and the emergence of CDR (and GGR) technologies associated with Fiekowsky's perspective. In this subsection, I consider how the abatement cost functions in DICE need to be modified in order for the CDR trajectory discussed above be behaviorally feasible in Nordhaus' sense, not just physically feasible.

A key theme of this work is that present bias has led the global emissions trajectory to be closer to behavioral business-as-usual than to any reasonable estimate of a global optimum derived from an integrated assessment model. In consequence, the global price of carbon, and for that matter other greenhouse gases, has been much too low, thereby supporting emissions which have been much too high.

The fear is that such a state of affairs will continue, significantly increasing the risks from global warming. The hope is that new technologies for CDR and GGR will emerge to counteract the effects of past high emissions. In this subsection, I analyze how some of the key trajectories associated with the behavioral business-as-usual case will change as a result of the introduction of these new technologies.

What is important to understand is that the emergence of the new technologies alone will not solve the problem of global warming. These technologies need to be sufficiently cheap. IRENA (2020) and Fiekowsky with Douglis (2022) emphasize that the costs of solar energy have fallen dramatically in the last decade to the point where they are less expensive than fossil fuels. They argue that this trend will continue for other alternative energy sources, such as wind power in combination with advances in battery technology.

All of this is to say that we need to understand how the abatement cost functions in DICE would need to change in order for the CDR and GGR technologies described above to be behaviorally feasible, not just physically feasible, within the IAM framework. Abatement costs are a critical driver of the social cost of carbon. The relationship between these two variables is positive. Therefore, a decline in abatement costs, all else being the same, will reduce the social cost of carbon.

A related issue involves the damage function. As I discussed in Section 4, the damage function in DICE-2016 does not feature tipping points. Modifying the damage function to include tipping points tends to produce a higher trajectory for the social cost of carbon. The higher cost signals the importance of reducing emissions in order to prevent tipping points from being reached; and along the optimal trajectory, emissions will decline for this reason. Of course, if the trajectory of the economy follows the behavioral business-as-usual strategy, then the likelihood of experiencing tipping points is much higher than along the optimal trajectory.

The preceding comments serve as backdrop for the main questions to be investigated: what are the main differences between the original behavioral business-as-usual trajectory and a modification of this trajectory to reflect the hoped-for technological advances associated with alternative energy and removal of greenhouse gases from the atmosphere?

The heart of the analysis of the preceding questions focuses on two changes. The first change involves modifying the industrial emissions trajectory for the behavioral business-as-usual case so that it coincides with the Fiekowsky trajectory in Figure A3. The second change involves introducing a new CDR technology to remove and permanently sequester one trillion tons of atmospheric carbon dioxide between 2025 and 2050, at a cost of $0.03 USD per ton. Figure A4 displays the trajectories for CDR and industrial emissions of carbon dioxide that are associated with the climate restoration scenario.

The key question to ask in respect to these modifications pertains to how to modify the abatement cost backstop technology variable so that the modified abatement trajectory is consistent with the Fiekowsky trajectory for industrial emissions. The answer to this question is that relative to the values in the original DICE-2016 model, abatement costs would have to decline by 96 percent by 2025 and by 99 percent by 2035, after which they would stabilize.

The modification is clearly dramatic. Remember that hope and excessive optimism are very similar. Just to be clear what the cost modification means: Abatement costs reflect the presence of clean energy alternatives to fossil fuels. If alternative energy sources are economically competitive with fossil fuels at scale, then abatement costs are low. The dramatic decline in abatement costs described in the previous paragraph reflects exactly this, that alternative energy sources are quickly becoming cost effective with fossil fuels, and at scale. That the decline bottoms out at 99 percent, not 100 percent, reflects the difficulty in decarbonizing some industries, which is a point made in IRENA (2020).

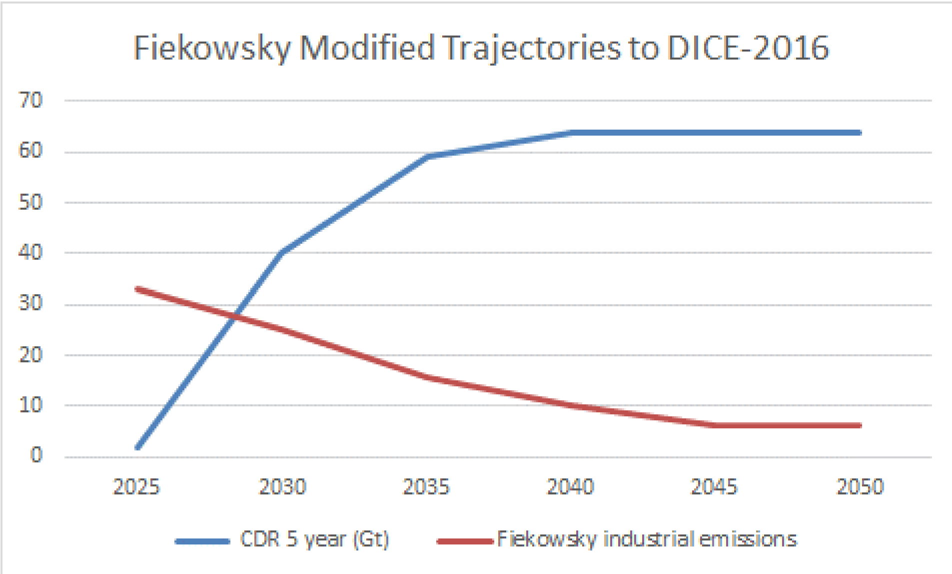

Figure A4 Modified Fiekowsky trajectories to DICE-2016 behavioral business-as-usual case, for industrial emissions of carbon dioxide and amount of carbon dioxide removed from the atmosphere in the five year periods 2025 through 2050.

If the IRENA and Fiekowsky emission trajectories were to unfold, then the implications from the model for atmospheric concentration of carbon dioxide and atmospheric temperature improve significantly. Figure A5 displays the associated trajectories for both. Notice that according to the DICE-2016 model, the hypothesized CDR activity manages to bring atmospheric concentrations of carbon dioxide to about 300, and atmospheric temperature to stabilize around 1.5°C around 2065. I note that in contrast, Fiekowsky and Douglis estimate, with some hesitancy, that temperatures will revert to pre-industrial levels by 2100. In this respect, recall Figure 18 in Section 4, which shows that it takes a century, along the *Stern Review* trajectory, for the atmospheric temperature to decline by 1.5°C once the economy becomes net carbon negative. Keep in mind that this result presupposes there being no tipping points. For the Nordhaus trajectory, the decline over a century is smaller at 1°C.

According to modified DICE-2016, further improvements for the time frame displayed, beyond those depicted in Figure A5, would require a combination of more abatement and more CDR.

Notably, in the scenario described above, the trajectories for the interest rate and price of carbon dioxide are in the vicinity of the behavioral business-as-usual case. In this regard, keep in mind that Nordhaus emphasized the importance of generating an interest rate trajectory which is in line with historical rates. Think of this condition as a behavioral constraint. Likewise, a low trajectory for the price of carbon dioxide is also a behavioral constraint.

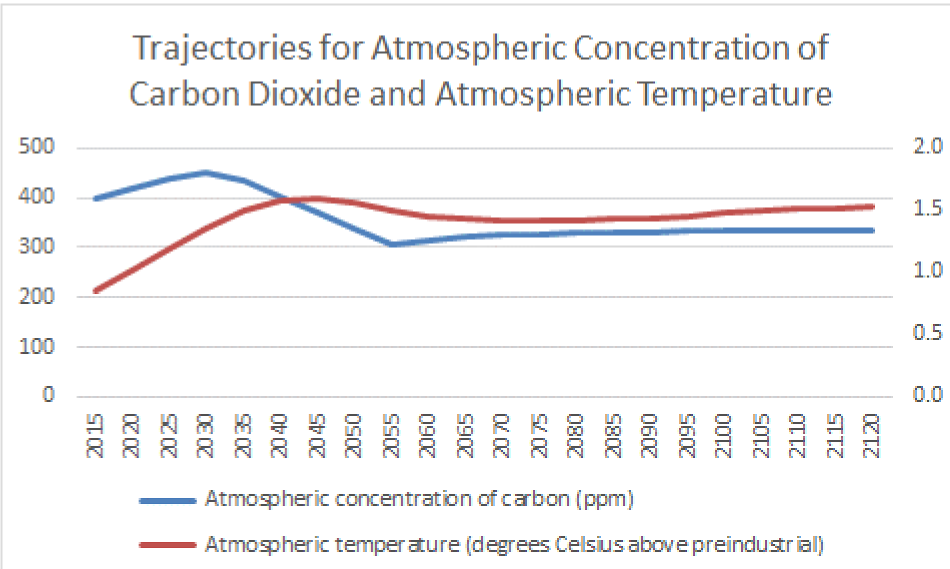

Figure A5 Modified Fiekowsky trajectories to DICE-2016 behavioral business-as-usual case, for atmospheric concentration of carbon dioxide (left axis) and atmospheric temperature (right axis) in the five-year periods 2025 through 2120.

The sources of hope that are manifest in the preceding analysis pertain to cost reductions and ability to scale in respect to alternative energy and CDR, all in an economic system featuring a low price of carbon. In this respect, economists tend to interpret the social cost of carbon as a tax (rate) on carbon dioxide or as the market price emerging from a cap-and-trade system. However, in the DICE framework, the social cost of carbon can manifest itself in the form of any price distortion, such as a subsidy, that alters the relative price of emissions. Therefore, the climate subsidies associated with alternative energy and CDR that were included in the 2022 US Inflation Reduction Act can be viewed as consistent with a higher price of carbon.

To repeat, hope and excessive optimism bias are very similar to each other. IRENA (2020) discusses many of the challenges associated with achieving the IRENA emissions trajectory depicted in Figures A2 and A3. The probability of achieving a trajectory at least as favorable as the IRENA trajectory might be low, given the associated pricing of carbon dioxide.

At this stage, CDR and GGR might be akin to dot-com technologies being developed in the 1990s. Many of the firms which worked on developing new Internet technologies did not survive. However, these firms did develop new technologies on which others built. The visions of the 1990s might not have become reality in the time periods envisaged, but did eventually materialize.

Keep in mind that achieving the IRENA trajectory in the face of behavioral business-as-usual carbon pricing requires sharp reductions in the cost of alternative energy sources. It might well be that the IRENA emissions trajectory is economically feasible in a regime featuring a higher carbon pricing trajectory than the base case.

From the discussion in Section 4, we know that DICE-2016 implies that the carbon price trajectory would have to be higher than the Nordhaus optimal price trajectory, but not as high as the counterpart *Stern Review* trajectory. Because of present bias, these price trajectories are both infeasible, if implemented as carbon taxes or through cap-and-trade. However, for behavioral reasons, they might be feasible if implemented as subsidies. This is because subsidies are framed as being in the domain of gains whereas taxes and prices are framed as being in the domain of losses.[85] In this regard, the appendix to Section 4 makes the point that the optimal solution can be implemented using either a subsidy frame or a tax frame.

One more point: it is certainly possible to begin with the Fiekowsky-modification to DICE-2016 and identify an optimal solution for this case instead of working with behavioral business-as-usual. Doing so leads to optimal carbon prices which are similar in character to the original DICE-2016 values, at least for the duration of the current century. Remember from Sections 3 and 4 that the difference in emissions trajectories, and consumption levels between the behavioral business-as-usual case and the Nordhaus-optimal case are not stark. This is important.

[85] This point is an application of the analysis in Thaler, Richard, 1980. "Toward a Positive Theory of Consumer Choice," *Journal of Economic Behavior & Organization*, Elsevier, vol. 1(1), pages 39-60.

A6.5 Epstein-Zin Recursive Utility and a Generalized Ramsey Equation

There is considerable risk, not to mention uncertainty, associated with the IRENA and Fiekowsky trajectories associated with alternative energy and removal of greenhouse gases from the atmosphere. For this reason alone, it is important to generalize the DICE framework to incorporate risk and uncertainty. In this subsection, I discuss the character of models, such as Cai, Judd, and Lontzek (2019), which generalize the DICE framework to incorporate risk and uncertainty.[86] In particular, I focus on a generalized version of the Ramsey equation.

Recall that in the certainty framework, the (net) interest rate r is equivalent to the return on capital, which is approximated by the Ramsey equation

$$r = \rho + \alpha g$$

Here ρ is the rate of time discount, α is the inverse of the elasticity of intertemporal substitution, and g is the (net) rate of aggregate consumption growth. In particular, r is the interest rate associated with date t, and g is the consumption growth rate from date t to date $t+1$.

The price of date $t+1$ consumption relative to date t consumption is the discount rate $1/(1+r(t))$. Keep in mind that the market value at date t of consumption at date $t+1$ is given by the product of the discount rate and the amount of consumption at date $t+1$.

Extending the framework to incorporate risk involves g being a random variable, depending both on t and an underlying state of nature s_t. In addition to g being stochastic, the discount factor associated with equilibrium prices will also be stochastic. Consider a particular risk g_t, which is to say that the consumption growth rate is stochastic. Analogous to the certainty case, the market value associated with g_t will be given by the expected value of discounted g_t where the discount factor is stochastic. In other words, the market value of a risk is the expected value of the product of the risky payoff and the stochastic discount factor.

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[86] This literature includes contributions such as the following:
Bansal, Ravi, and Amir Yaron, 2004, Risks for the Long Run: A Potential Resolution of Asset Pricing Puzzles, *Journal of Finance* 59, 1481–1509.
Bansal, Ravi, Dana Kiku, and Marcelo Ochoa, 2016. "Price of Long-Run Temperature Shifts in Capital Markets," NBER Working Papers 22529, National Bureau of Economic Research, Inc.
Daniel, Kent D., Robert B. Litterman, and Gernot Wagner, 2018. "Applying Asset Pricing Theory to Calibrate the Price of Climate Risk," NBER Working Paper No. 22795 November 2016, Revised October 2018.
Jensen, Svenn and Christian Traeger, 2014. "Optimal Climate Change Mitigation under Long-Term Growth Uncertainty: Stochastic Integrated Assessment and Analytic Findings. *European Economic Review*, Volume 69, 104-125.
Rudik, Ivan, 2020. "Optimal Climate Policy When Damages are Unknown," *American Economic Journal: Economic Policy*, 12(2): 340–373. https://doi.org/10.1257/pol.20160541.

When the utility function is given by the power function $u(c) = c^{1-\alpha}/(1-\alpha)$, the log of the stochastic discount factor can be expressed as $ln(1/(1+\rho)) - \alpha g$, which equals $-(\rho+\alpha g)$. Here g is a random variable.

The stochastic discount factor can be defined as state price per unit probability. Construct a portfolio in which a single unit of consumption is invested in period t. Let the proportion of this unit being used to purchase claims in a particular $t+1$-state be the probability of this state. This rule is associated with an entropy minimizing portfolio, and corresponds to the portfolio selected by a log-utility investor. The gross amount the portfolio will pay at $t+1$ will then be determined by the inverse of state price; and this amount will be the gross return, because the amount invested at t will be one unit. Use the fact that the state price is the product of the stochastic discount factor and state probability to conclude that the net return in a state will be $\rho+\alpha g$, the Ramsey equation.[87]

Logarithmic utility is a special case of the model corresponding to $\alpha=1$. In this case, the gross return associated with gross consumption growth $(1+g)$ is the product $(1+\rho)(1+g)$, the Ramsey equation is given by $r = \rho+g$ and the log-stochastic discount factor is given by $-(\rho+g)$.

With power utility, both the elasticity of intertemporal substitution (along any realized path) and the coefficient of risk tolerance are given by the value $1/\alpha$.

The Epstein-Zin utility function generalizes power utility to allow for distinct values for these two parameters.[88] Let ψ denote the coefficient of relative risk aversion, and define $\theta = (1-\psi)/(1-\alpha)$.[89]

In the Epstein-Zin framework, a decision maker's payoffs are "experienced utility" at each date. The decision maker generates "experience utility" V_t at date t from a combination of consumption c_t and anticipated future experienced utility from dates $t+1$, $t+2$, … Given that future experienced utility can be stochastic, think of the decision maker at date t as having a certainty equivalent $CE(V_{t+1})$. That is, at date t, the decision maker is indifferent between having

[87] Let π denote state probability and p denote state price. The gross $t+1$-return to investing one unit in period t is $1/p$. The gross $t+1$-return to investing π of a unit in period t is π/p. Since $p = \pi SDF$, $\pi/p = 1/SDF$.

[88] Epstein, Larry G. and Stanley E. Zin, 1989. "Substitution, Risk Aversion, and the Temporal Behavior of Consumption and Asset Returns: A Theoretical Framework," *Econometrica*, Vol. 57, No. 4, 937-969.

[89] Think of ϑ as a measure of the relative degree of risk aversion per unit of substitution aversion. For example, if the coefficient of risk aversion ψ=3, and the coefficient of substitution aversion α=2, then ϑ=2. In this case, the power terms ϑ and ϑ-1 in the expression for the stochastic discount factor are 2 and -1 respectively. Notice that these sum to unity.

experienced utility $CE(V_{t+1})$ with certainty and facing the known risk associated with stochastic V_{t+1}.

In Epstein-Zin, a constant relative risk aversion (CRRA) utility function

$V_{t+1}^{1-\psi}/(1-\psi)$

is applied to evaluate the sub-utility of the stochastic experienced utility stream.[90] $CE(V_{t+1})$ is defined such that $CE(V_{t+1})^{1-\psi}/(1-\psi)$ is equal to the expected sub-utility of the experienced utility stream at date $t+1$. Notice that in contrast to the standard CRRA model, the payoffs which are the arguments of the CRRA utility function in the Epstein-Zin framework are "experienced utility" rather than consumption levels. Therefore, on the face of it, the meaning of parameter values for ψ in the two frameworks is different.

At date t, experienced utility V_t is determined as a function of c_t and $CE(V_{t+1})$:

$V_t = F(c_t, CE(V_{t+1}))$

In this framework, experienced utility at date t+1 reflects anticipated experienced utility at date $t+2$, which enters the above equation recursively. The typical functional form for $F()$ is

$F(c_t,CE(V_{t+1})) = ((1-\beta)\, c_t^{1-\alpha} + \beta CE(V_{t+1}))^{1-\alpha})^{1/1-\alpha}$

where α is the inverse-EIS, and β is the rate of time discount ($1/1+\rho$).

Notice that while the EIS in the standard constant elasticity consumption model pertains to direct substitution between current consumption and subsequent consumption, in the Epstein-Zin framework, the substitution is between current consumption and future experienced utility. Therefore, on the face of it, the meaning of the parameter value for α in the two frameworks is different.

There are two important equations that emerge from the Epstein-Zin framework. The first is for the gross return R_m (at date $t+1$) on the market portfolio, which is

$R_{m,t+1} = [(1+g_t)^{\alpha}/\beta]\ [V_{t+1}/CE(V_{t+1})]^{1-\alpha}$

where g_t is the consumption growth rate from t to $t+1$. Observe that the return function is a product of two terms, the first relating to consumption growth and the second to a ratio which measures realized experienced utility relative to its certainty equivalent.

[90] For $\psi>1$, the arguments of the CRRA function need to be positive in order for the function to be well defined. In this case, the value of the CRRA function will be negative.

With $\alpha>1$, the function $[V_{t+1}/CE(V_{t+1})]^{1-\alpha}$ is a positive, declining function[91] of $[V_{t+1}/CE(V_{t+1})]$. In a favorable event, when $V_{t+1} > CE(V_{t+1})$, the market return is below $[(1+g_t)^{\alpha}/\beta]$; and when $V_{t+1} < CE(V_{t+1})$, the market return is greater than $[(1+g_t)^{\alpha}/\beta]$. Define $\upsilon_{t+1} = [V_{t+1}/CE(V_{t+1})]^{1-\alpha}$.

The second important equation is for the stochastic discount factor, which is given by: [92]

$$SDF = \beta^{\theta}(1+g_{t+1})^{-\theta\alpha} R_{m,t+1}{}^{\theta-1} = [\beta(1+g_{t+1})^{-\alpha}]^{\theta} [1/R_{m,t+1}]^{1-\theta}$$

This last equation is the product of two pricing kernels, the first corresponding to CRRA utility and the second to a term "resembling" logarithmic utility. I will explain below what I mean by the term "resembling."

Notice that when $\psi = \alpha$, $\theta = 1$ so that the above expressions for market return and stochastic discount factor coincide with their standard CRRA counterparts.

As in the discussion above, to generate the generalized stochastic return function, take the logarithm of the stochastic discount function and insert a minus sign. So, first, compute the logarithms of the SDF and R_m using the following two expressions:

$$ln(SDF) = \theta[ln(\beta) - \alpha ln(1+g)] - (1-\theta)ln(R_m)$$

$$ln(R_m) = \alpha ln(1+g) - ln(\beta) + ln(\upsilon)$$

Next, substitute the expression for $ln(R_m)$ into the expression for $ln(SDF)$, use $\beta = 1/(1+\rho)$, and insert a minus sign to obtain the following expression for the entropy-minimizing portfolio:

$$r = [\rho + \alpha g] + (1-\theta)ln(\upsilon)$$

When $\theta=1$, the above expression is the standard Ramsey equation. However, as θ moves away from unity, in either direction, the modifier υ becomes more prominent. The combined expression effectively becomes a "generalized Ramsey equation."

Recall that $\theta = (1-\psi)/(1-\alpha)$. Suppose that $\psi > \alpha > 1$, as is typically assumed. Then $\theta > 1$, and so $(1-\theta)$ is negative. In consequence, the impact of $ln(\upsilon)$ on the return will be to amplify the impact of consumption growth on r_{MV}, not to dampen it. Consider increasing the risk aversion

[91] It is the power of a reciprocal function.

[92] See the discussion in Epstein and Zin (1989), from pages 955-958, especially equation (6.6). Also see Linton, Oliver, 2019. *Financial Econometrics: Models and Methods*. Cambridge: Cambridge University Press. Also see Linton's lecture note, "F500: Empirical Finance Lecture 9: Intertemporal Equilibrium Pricing, March 12, 2020" at https://obl20.com/wp-content/uploads/2020/03/topic8-1.pdf.

parameter ψ while holding α constant. Doing so increases the value of θ, thereby increasing the influence of $ln(\upsilon)$ on the return.

The case when $\alpha=1$ is special, and corresponds to logarithmic utility. Notice that in this case, $\upsilon(g)=1$, meaning there is no modification to the term $(1+g_t)^{\alpha}/\beta$ in the expression for R_m. Specifically, the term $(1+g_t)/\beta$ does in fact correspond to the case of logarithmic utility in the standard model, and so the generalized stochastic return function r_{MV} for this case is exactly $\rho + g$, the Ramsey equation for the standard consumption-CAPM case involving logarithmic utility.

In the Epstein-Zin stochastic discount function, the second term involves the expression $1/R_{m,t+1}$, which is similar in form to the stochastic discount function for the case of log-utility in the standard consumption-CAPM model. However, if α differs from unity, then the Epstein-Zin function for $R_{m,t+1}$ will differ from the corresponding function for $R_{m,t+1}$ in the consumption-CAPM; and this difference stems from the modifying term $\upsilon(g)$. The existence of this difference is the reason why I use the term "resembling" in the discussion above.

Cai, Judd, and Lontzek (2019) point out that in many cases, the mean trajectory for the stochastic social cost of carbon is close to the trajectory associated with deterministic models. Of course, the stochastic framework provides insight into the higher order moments as well. Their analysis finds that the stochastic process for the social cost of carbon is approximately a random walk, with substantial variance.

Recall that in DICE-2016, the slope of the return function is $\alpha = 1.45$, which given a value of $\rho = 1.5$ *percent* per annum leads to an annual return on capital of around 5 percent. As discussed in Section 4, Nordhaus attaches great importance to choosing parameters that support a mean return on capital which is realistic. This is a behavioral constraint, which for an uncertainty framework requires parameter choices that are realistic across higher order moments, not just the mean.[93]

In DICE-2106, the return on capital declines over time, falling to 3.7 percent in 2100. However, in recent years real interest rates have declined. In the next subsection, I discuss how declining rates have led to changes in the assumed parameter values.

[93] In DICE-2016, Nordhaus employs the value α=1.45. Cai, Judd, and Lontzek (2019) state that solve their model for a broad range of values covering 0.5 ≤ ψ ≤ 20 for the risk aversion parameter and 0.5 ≤ α ≤ 2.0 for the inverse-intertemporal elasticity of substitution.

A6.6 EPA Estimates of Social Cost of Carbon

Historically, the EPA has used the results of economic cost benefit analysis to estimate the social cost of carbon. Prior to 2020, the EPA's estimates had been in line with DICE, which for DICE-2016 estimated the social cost of carbon to be $37 in 2020, rising to $51 in 2030. However, by 2022 the EPA had significantly increased its estimate to approximately $190 per ton (in 2020 dollars) for damages incurred during the period 2020-2080.

The higher estimates reflected the reduction in real interest rates which prevailed after 2010.[94] In 2010, the EPA used a range of interest rates between 2.5 percent and 5 percent with a middle case of 3 percent. By way of contrast, in 2022 the agency used a range of 1.5 percent to 2.5 percent with a middle case of 2 percent.[95]

The EPA based its estimates by averaging the results of the following three studies:[96]

1. a sectoral damage function (based on the Data-driven Spatial Climate Impact Model (DSCIM) developed by the Climate Impact Lab;[97]
2. a sectoral damage function based on the Greenhouse Gas Impact Value Estimator (GIVE) model developed under the Resources for the Future's "Social Cost of Carbon Initiative;"[98] and
3. a meta-analysis-based damage function.[99]

The first two studies above use a risk-based IAM featuring exponential utility. These models also feature the Ramsey equation $r = \rho + \alpha g$, where $\rho \sim 0.02\%$ and $\alpha \sim 1.24$. These values contrast with Nordhaus' parameter values which are $\rho = 1.5\%$ and $\alpha = 1.45$.

Empirically, the decline in real interest rates after 2010 reflects increased saving rates in response to shifting demographics. Demographic changes include longer life expectancy,

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[94] Bauer, Michael D. and Glenn D. Rudebusch, 2021. "The Rising Cost of Climate Change: Evidence from the Bond Market, *The Review of Economics and Statistics*, 1-45. https://doi.org/10.1162/rest_a_01109.
[95] EPA, 2022. *Report on the Social Cost of Greenhouse Gases: Estimates Incorporating Recent Scientific Advances*, September 2022. https://www.epa.gov/system/files/documents/2022-11/epa_scghg_report_draft_0.pdf.
[96] The references for these studies can be found in the EPA report cited in the previous note.
[97] https://impactlab.org/research-area/social-cost/.
[98] Rennert, Kevin, Frank Errickson, Brian C. Prest, Lisa Rennels, Richard G. Newell, William Pizer, Cora Kingdon, Jordan Wingenroth, Roger Cooke, Bryan Parthum, David Smith, Kevin Cromar, Delavane Diaz, Frances C. Moore, Ulrich K. Müller, Richard J. Plevin, Adrian E. Raftery, Hana Ševčíková, Hannah Sheets, James H. Stock, Tammy Tan, Mark Watson, Tony E. Wong & David Anthoff, 2022. "Comprehensive Evidence Implies a Higher Social Cost of CO2," *Nature*, volume 610, 687–692. https://www.nature.com/articles/s41586-022-05224-9.
[99] Howard, Peter.H. and Thomas Sterner, 2017. Few and Not So Far Between: a Meta-Analysis of Climate Damage Estimates. *Environmental and Resource Economics*, 68(1), 197-225.

increased expected retirement horizons, lower productivity growth, rising income inequality, and a focus on economic growth in China and emerging economies. The evidence suggests that low interest rates are likely to persist.

The decline in real interest rates has sharply reduced the gap between the Nordhaus perspective and the *Stern Review* perspective. In this respect, the higher revised social cost of carbon is closer to that of the *Stern Review* than to that of Nordhaus.

After 2007, real rates of return on capital remained largely unchanged, even as real interest rates fell dramatically. Keep in mind that Nordhaus' assumptions pertain to the return on capital, not the rate of interest on government debt. This raises the question of how well supported was the EPA's decision in 2023 to increase its estimate of the social cost of carbon.

A6.7 Determinants of Social Cost of Carbon in a Risk-based IAM

In an important sense, the addition of risk increases the social cost of carbon. Lemoine (2021) develops a risk decomposition to explain why.[100] Lemoine's model involves three sources of risk: consumption volatility, warming risk, and damage risk. These risks impact the social cost of carbon in three ways. All three ways entail using emission reduction technology to transfer consumption across time.

The first impact is not specific to climate, but instead reflects the impact of uncertainty on consumption. Imagine an optimal consumption plan for a two- period problem with no risk; and now consider adding some "white noise" risk to the optimal consumption plan during the second period. The effect of this risk will be to replace the utility of certain period 2 consumption with an expected utility; and it will also lead to the replacement of the marginal utility of certain period 2 consumption with an expected marginal utility. Given concave utility, the expected utility will be less than the utility of the certain consumption, and an expected marginal utility which will be higher than the expected utility of the certain consumption. The higher expected marginal utility in period 2, will induce a shift in consumption from period 1 to period 2. Lemoine refers to this shift as reflecting the need for "precautionary saving."

[100] Lemoine, Derek, 2021. "The Climate Risk Premium: How Uncertainty Affects the Social Cost of Carbon," *Journal of the Association of Environmental and Resource Economists*, volume 8, number 1, 27-57.

The second impact pertains to the need to insure against climate risk. Such insurance alters exposure to low consumption in states of nature where climate damage is severe. Risk aversion will accentuate the sensitivity to this exposure, thereby increasing the willingness to pay to hedge this risk; and a higher willingness to pay in turn increases the social cost of carbon.

The third impact pertains to damages caused by global warming. These damages are assumed to be proportional to output. As a result, abatement in early periods will produce both larger future output and larger future damages. Notably, the higher damages will serve to diminish the value of abatement.

Lemoine establishes that the precautionary saving effect will outweigh the damage effect, and so overall the introduction of risk to the certainty framework will lead to an increase in the social cost of carbon. Using Nordhaus' parameter values, he computes the social cost of carbon, for a 200-year horizon, to be $362 per ton.

A6.8 Mechanism Design and the Social Cost of Carbon

Economists have not achieved consensus on a value for the social cost of carbon, a statement that should come as no surprise to readers of this work. There is simply great uncertainty about how to measure the social cost of carbon. Lemoine (2023) describes how mechanism design theory can be applied in a regulatory setting to address this inherent uncertainty.[101]

Lemoine's model involves the problem faced by a single regulator in a system in which information about the damage costs vary across the industries to be regulated. In the model, the regulator requires firms to be bonded, meaning that they make up front damage deposits to the regulator, with the potential to receive refunds. In exchange for these deposits, the regulator provides firms with "carbon shares" which are tradeable.

The magnitude of refunds is stochastic, and depends on size of aggregate realized damages relative to the damage implicit in the initial deposit. By construction, the value of carbon shares is lower than the associated deposits, with the difference being the tax. In Lemoine's framework, emitting firms can choose to reduce their deposits by reducing their emissions. In line with the discussion about CDR in Section 6, holders of carbon shares might

[101] Lemoine, Derek, 2023. "Informationally Efficient Climate Policy: Designing Markets to Measure and Price Externalities." National Bureau of Economic Research, Working Paper 30535. http://www.nber.org/papers/w30535.

decide to remove the carbon from the atmosphere in order to retire their carbon shares, and thereby recover their deposits.

A6.9 The Big Behavioral Question Is That Much Bigger

The gap between Nordhaus' and Stern's estimates of the social cost of carbon eventually shrank, with Nordhaus having raised his estimate and Stern having reduced his. Nevertheless, the estimates which have emerged from the literature discussed in the present section are significantly higher than those provided by Nordhaus and Stern. This means that the big behavioral question has only gotten bigger. The gap between the optimal trajectory and the behavioral business-as-usual trajectory is that much wider.

Neoclassical economists can hope that the higher estimates for the social cost of carbon will spur global decision makers to transition quickly from the behavioral business-as-usual trajectory towards a trajectory that has support from mainstream environmental economists. Nevertheless, keep in mind that Nordhaus' C-DICE theory indicates that a higher social cost of carbon makes it more difficult to achieve international climate agreements. In respect to the gap associated with the big behavioral question, actual prices for carbon are even lower than the levels predicted by C-DICE for the behavioral business-as-usual case.

My own view is that psychological pitfalls, especially present bias, present huge obstacles to overcome. Keep in mind that in a below aspiration state, a larger gap between current position and aspiration leads to increased appetite for risk; and an increased risk appetite works against pricing greenhouse gases at their social cost.

As I described in Section 5 and its appendix, the EPA has had very little influence when it comes to instituting a policy in which carbon is priced at its social cost. This history does not offer much encouragement that the EPA's sharply revised estimates of the social cost of carbon will have a significant impact on actual policy.

The revised EPA estimates reflect a lower rate of time preference associated with saving behavior. In a neoclassical IAM, there is a single rate of time preference impacting saving behavior and emission abatement behavior. However, the behavioral approach emphasizes that people can be patient in some ways and impatient in others.[102] In particular, increased saving that underlies a decline in the real interest rates does not necessarily translate into pricing carbon near its social cost. Remember that in the behavioral approach, social planners and the individuals whose preferences they aggregate typically display inconsistent and incoherent behaviors.

China and the developing world, not the US and Europe, will likely be the major contributors to future greenhouse gas emissions; and none show signs of pricing greenhouse gases at anywhere near their respective social costs, at least anytime soon.

Keep in mind that carbon prices are a means to an end, not an end in themselves. Ends pertain to the state of the climate, which is critically impacted by greenhouse gas concentrations. In this respect, there is hope, from CDR and GGR, and initiatives such as the climate programs and subsidies which are part of the US Inflation Reduction Act. These programs and initiatives capture key features of the optimal abatement solutions derived from IAMs.

Still, as I discussed in the appendix to Section 4, failing to price carbon dioxide and other greenhouse gases at their respective social costs produces significant inefficiencies, even with subsidies. The costs associated with these inefficiencies appear suboptimal from a neoclassical perspective. From a behavioral perspective, however, these costs might be a manifestation of constraints imposed by human psychology, constraints which appear impervious to nudges.

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[102] Psychologist Walter Mischel attached great emphasis to this point. See Ludden, David, 2018. "The Dark Side of Self-Control," *Psychology Today*. https://www.psychologytoday.com/us/blog/talking-apes/201806/the-dark-side-of-self-control.