



February 13, 2023

To: Environmental Protection Agency

Subject: Economic Comments on the EPA External Review Draft of Report on the Social Cost of Greenhouse Gases (Docket No. EPA-HQ-OAR-2021-0317)

The Institute for Policy Integrity at New York University School of Law¹ respectfully submits this comment letter on the Environmental Protection Agency's (EPA) draft report on the social cost of greenhouse gases (Draft Report).² Policy Integrity—a non-partisan think tank dedicated to improving the quality of government decisionmaking through advocacy and scholarship in the fields of administrative law, economics, and public policy³—frequently engages in regulatory proceedings involving the social cost of greenhouse gases. Our economics director, Dr. Peter Howard, is a leading expert on the valuation of climate damages and is among the most cited experts in the Draft Report.

The Draft Report faithfully implements the roadmap laid out in 2017 by the National Academies of Sciences, and reflects a thoughtful and evidence-based approach to valuing incremental climate damages. The Draft Report represents a significant improvement over the climate-damage valuations developed by the Interagency Working Group on the Social Cost of Greenhouse Gases (Working Group). Given the widespread economic consensus that those Working Group values represent lower-bound estimates, including the Working Group's own repeated recognition, it is appropriate and expected for the social costs of greenhouse gases to increase significantly with the incorporation of the latest scientific and economic research.

Although EPA carefully develops and justifies its revised climate-damage valuations, it could bolster its justification and assessment in several key respects. In particular, EPA's estimate of the social cost of greenhouse gases remains conservative, as parameter updates based on empirical evidence will likely further increase the agency's valuations. Specifically, this comment letter makes the following recommendations:

- EPA's discount rate range is too high based on the evidence presented by the agency. Moreover, omitted impacts lead to a further underestimation of the social discount rate. In consideration of the available evidence, EPA should shift down its short-run, risk-free discount rate range to 0.5%–2.5% with a central rate of 1.5%.

¹ This document does not purport to represent the views, if any, of New York University School of Law.

² EPA External Review Draft of Report on the Social Cost of Greenhouse Gases (Sept. 2022) (Docket No. EPA-HQ-OAR-2021-0317) [hereinafter Draft Report].

³ Policy Integrity is submitting a separate comment letter on the Draft Report supporting EPA's decision to assess climate damages from a global perspective and offering further legal precedent supporting this approach.

- EPA should more strongly emphasize that omitted impacts bias the agency’s climate-damage estimates downwards. Furthermore, the agency should take steps to address these omissions where relevant published literature is available, including by augmenting the sector-specific damage functions (DSCIM and GIVE) as relevant studies become available and by engaging in its own systemic literature review of omitted impacts.
- EPA’s selection of the Howard and Sterner’s (2017) meta-analysis-based damage function should be adjusted to account for additional information in Howard and Sterner (2022), including potential adjustments to EPA’s central estimate of non-catastrophic damages and its corresponding variance. Furthermore, EPA should augment this analysis with Dietz et al.’s (2021) expected tipping point damage function.⁴
- For purposes of transparency, EPA should make explicit its certainty-equivalent discount rate by specifying the extended Ramsey rate and its underlying parameters.⁵ EPA should also provide further explanation of its decisions underlying this expression.
- EPA should calculate marginal and total social costs of climate change for each of the Shared Socioeconomic Pathways (SSPs),⁶ as this calculation, though not directly relevant for the social cost of greenhouse gases, would be very useful for policymakers.
- EPA should update its estimates, including each module, at least every five years. For damage functions, EPA should include damage estimates for omitted sectors as they become available.

We expand upon these suggestions in turn below.

I. EPA’s Discount Rate Range Is Too High, and Should Be Shifted Down to a Range of 0.5% to 2.5% with a Central Rate of 1.5%

In the Draft Update, EPA primarily relies on recent evidence of market rates to select a near-term discount range of 1.5% to 2.5% with a central estimate of 2%.⁷ The agency focuses on

⁴ Simon Dietz et al., *Economic Impacts of Tipping Points in the Climate System*, 118 PROCS. OF THE NAT’L ACAD. OF SCI. 5 (2021). (See Dietz et al. (2021)’s reduced form damage equation that approximates their structural meta-regression results.)

⁵ Draft Report, *supra* note 2, at 60.

⁶ Keywan Riahi et al., *The Shared Socioeconomic Pathways and Their Energy, Land Use, and Greenhouse Gas Emissions Implications: An Overview*, 42 GLOBAL ENV’T CHANGE 153 (2017).

⁷ Draft Report, *supra* note 2, at 6.

the risk-free consumption interest rate, as captured by the return on long-run Treasury securities (consistent with the approach already applied in Circular A-4⁸).

EPA relies mainly on four lines of evidence for its assessment of the short-run discount rate. Specifically, it: 1) calculates the average real rates of return to 10-year Treasury notes over last 30 and 50 years using three adjustments for expected inflation⁹; 2) cites Bauer & Rudebusch's (2021) estimation of the long-run equilibrium discount rate using data on real rate of return to 10-year Treasury notes;¹⁰ 3) cites discount rate forecasts from the Congressional Budget Office¹¹ and the Social Security Administration;¹² and, 4) providing additional support using the normative approach, cites the average social discount rate found by multiple expert elicitations (Drupp et al., 2018; Pindyck. 2019; Howard and Sylvan, 2020).¹³ Focusing primarily on the first line of evidence, as the Office of Management and Budget applied it to estimate a consumption discount rate in the current Circular A-4, EPA concludes that the appropriate discount rate range for the social cost of greenhouse gases is 1.5% to 2.5%, with a central estimate of 2%.¹⁴

A closer evaluation of these various indicators, however, suggests that EPA's discount rate range is conservative and that the literature supports a lower range of discount rates. As detailed below, evidence supports a discount rate range from 0.5% to 2.5%, with a central estimate of 1.5%.

A. Analysis of Treasury notes supports a discount rate range of 1% to 2.5%, with a central rate between 1.5% and 2%

As noted above, EPA primarily focuses on the methodology applied in Circular A-4 to estimate an updated central discount rate of 2%.¹⁵ It calculates the average real rate of return to the ten-year Treasury Bill over two time periods (1991–2020 and 1973–2020) using three adjustments for inflation expectations (the ten-year average of the consumer price index (CPI), the ten-year average of the Livingston Survey, and the perceived inflation target rate). Using the

⁸ See OFF. OF MGMT. & BUDGET, CIRCULAR A-4, at 33–34 (2003) (analyzing discount rates based on return on 10-year treasury notes).

⁹ Draft Report, *supra* note 2, at 58 & tbl.2.4.1.

¹⁰ Michael D. Bauer & Glenn D. Rudebusch, *The Rising Cost of Climate Change: Evidence from the Bond Market*, REV. ECON. & STAT., 58 (2021).

¹¹ *Id.* (citing CONGRESSIONAL BUDGET OFFICE, THE 2021 LONG TERM BUDGET OUTLOOK (2021), <https://www.cbo.gov/publication/56977> [hereinafter CBO 2021a]).

¹² *Id.* (citing U.S. SOCIAL SEC. ADMIN., THE 2021 ANNUAL REPORT OF THE BOARD OF TRUSTEES OF THE FEDERAL OLD-AGE AND SURVIVORS INSURANCE AND FEDERAL DISABILITY INSURANCE TRUST FUND tbl.II.C1 (2021), <https://www.ssa.gov/OACT/TR/2021/> [hereinafter SSA 2021a]).

¹³ Moritz Drupp et al., *Discounting Disentangled*, 10 AM. ECON. J.: ECON. POL'Y 109, 118 (2018); Robert S. Pindyck, *The Social Cost of Carbon Revisited*, 94 J. ENV'T ECON. & MGMT. 140, 140 (2019); Peter H. Howard & Derek Sylvan, *Wisdom of the Experts: Using Survey Responses to Address Positive and Normative Uncertainties in Climate-Economic Models*, 162 CLIMATIC CHANGE 213, 221–23 (2020).

¹⁴ Draft Report, *supra* note 2, at 59.

¹⁵ *Id.* at 57, 59.

30-year time period suggests a discount rate range of 1.55–1.98%, whereas using the 50-year period points to a higher range of 2.12%–2.80%.¹⁶

EPA states that it “places greater focus” on the 30-year time-horizon, highlighting “evidence of structural shifts in the interest process beginning in the 1990s” found in the economics literature as the basis for prioritizing more recent data.¹⁷ Nonetheless, EPA concludes that a higher rate of 2.5% (consistent with a 50-year time period) may be justified if the downward trend in the real interest rate is not persistent—in other words, in the possibility that a structural change in the economy did not occur despite contrary evidence.¹⁸ Despite claiming to prioritize the 30-year rate, EPA bases its central rate and discounting range on both the 30- and 50-year rates.

Given the strong empirical evidence pointing to a structural break occurring in 1991, it is not clear why EPA puts the 1.5% discount rate (which assumes a structural break) on equal footing as the 2.5% rate (which assumes no break). Indeed, EPA notes that the academic literature supports this break,¹⁹ such that it favors the 1991 to 2020 period over the 1973 to 2020 period for calculating the consumption discount rate.²⁰ This 30-year period points to a preferred rate between 1.5% to 2.0% with an average rate of 1.7%. Given the strong support for a structural break, EPA should give more weight to data from the last 30 years in determining the appropriate social discount rate.

Moreover, recent empirical also evidence points to a continued decline in the social discount rate after the structural break in 1991—indicating a lower-bound rate below 1.5%. EPA notes that the academic literature identifies a subsequent downward trend in the return to Treasury notes after the structural break.²¹ In fact, it even applies this trend in its interpretation of the Bauer and Rudebusch estimates using ten-year Treasury notes.²² Data for the real return to the one-year and ten-year Treasury bills support the continued downward trend in the equilibrium discount rate: For instance, the real discount rate in the 2010s appears to equal 1% or less.²³ Thus, the continued downward trend in the return to Treasury notes identified in the literature after 1991 supports the possibility of a social discount rate of 1% or lower.

¹⁶ *Id.* at 58 & tbl.2.4.1 (“The average real returns are lower under the shorter time period, reflecting the decline in real interest rates over recent decades.”).

¹⁷ *Id.* at 59.

¹⁸ *Id.* at 59 (finding a range of 1.55% to 2.80% with an average estimate of 2.09%, though the EPA focuses on an upper range of 2.5% as the average returns from 1973 to 2020 across all three inflation calculations).

¹⁹ *Id.* at 59 (“Recent studies have found empirical evidence suggestive of a structural break in the interest rate process sometime during the 1990s that has been associated with *declining equilibrium interest rates in recent decades* (e.g., Del Negro et al. 2017, Christensen and Rudebusch 2019, and Bauer and Rudebusch 2020). Based on empirical evidence, Bauer and Rudebusch (2021) utilize the year 1991 as a breakpoint when considering potential shifts in long-run mean of the interest rate process. Given the evidence of structural shifts in the interest process beginning in the 1990s, and the precedent for using 1991 as a reasonable and empirically formed breakpoint.” (Emphasis added)).

²⁰ *Id.* at 58.

²¹ *Id.* at 59.

²² *Id.* at 58 (noting that Bauer & Rudebusch observe higher real interest rates when “using a longer time series of long-term government securities”).

²³ Bauer & Rudebusch, *supra* note 10, at 41-43 fig.1, fig. 2, and tbl.1.

Based on this evidence, there is reasonable support for a discount rate range of 1% or lower, to 2.5%. This evidence also support a central rate between 1.5% to 2%—that is, the range produced by using the 30-year time horizon consistent with strong evidence of a structural break in the early 1990s.

B. A conservative interpretation of Bauer & Rudebusch’s work supports a discount rate range of 0.5% to 2.5% with a central rate between 1.0% and 1.5%

EPA also cites to the work of Bauer and Rudebusch (2021), which uses several sophisticated discount rate models to estimate the long-run equilibrium discount rate and its corresponding schedule over time.²⁴ But a closer inspection of their work reveals that Bauer and Rudebusch support a lower range of discount rates.

EPA focuses exclusively on Bauer and Rudebusch’s estimates using ten-year Treasury notes. Specifically, it cites to a range of 1.3% to 2.4% with a central estimate of 1.9% using data of the nominal return to the ten-year Treasury note from 1969 to 2019 adjusted for inflation using the perceived adjustment target rate.²⁵ EPA also cites a slightly higher estimate range in Bauer and Rudebusch (2021) when using a dataset of long-run government securities stretching from 1798 to 2019.²⁶ While EPA recognizes that Bauer and Rudebusch (2021) observe a much lower discount rate range using data on return to one-year Treasury notes (instead of ten-year notes), it provides this information in a footnote and pays it little attention.²⁷

However, Bauer and Rudebusch themselves express a preference for the estimate derived from one-year Treasury notes. In particular, the authors explain that estimates corresponding to one-year Treasury notes exclude a term premium, which biases upwards the estimates using the 10-year Treasury notes.²⁸ Applying the same analysis to the discount rate estimates corresponding to the one-year Treasury notes instead of ten-year Treasury notes (which was discussed in the previous paragraph), Bauer and Rudebusch (2021) identify a discount rate range of 0.5% to 1.3% with a central estimate of 0.7%.²⁹ This central estimate is consistent with the

²⁴ Bauer & Rudebusch, *supra* note 10.

²⁵ Draft Report, *supra* note 2, at 58.

²⁶ *Id.* at 58 & n.109.

²⁷ *Id.* at 58 n. 108 (citing Bauer and Rudebusch, *supra* note 10, at tbl.1 and tbl.E.1).

²⁸ Michael D. Bauer & Glenn D. Rudebusch, *The Rising Cost of Climate Change: Evidence from the Bond Market*, at 6 (Working Paper, Jan. 17 2021) (discussing “ample evidence that long-term bond yields for maturities of, say, five or ten years include a term premium and thus differ from the expected return of rolling over short-term bonds”); Bauer & Rudebusch, *supra* note 10, at 13, 17 (explaining that the “canonical approach” of using the dynamics of short-term Treasury rates to estimate long-term social discount rates “is the appropriate method to obtain risk-free social discount rates, which include neither a term premium nor a climate risk premium, and it has been used by many previous empirical studies in this literature.” Thus, “for the ten-year real rate series, the level of the estimated trend is generally somewhat higher than for the one-year rate, and the decline in the trend component is also larger: 1.8 percentage points. A portion of this larger decline may be explained by a modest reduction in the term premium in long-term Treasury yields during this sample, as described by Bauer and Rudebusch (2020).”)

²⁹ Bauer & Rudebusch, *supra* note 10, at 12 tbl.1.

recent estimates in the corresponding literature.³⁰ In fact, Bauer and Rudebusch (2021b) imply that their preferred estimate corresponds to a social discount rate of 1%.³¹

Moreover, even the discount rate estimates from Bauer and Rudebusch (2021) corresponding to the 10-year rates suggest a lower discount rate range than EPA applies. Specifically, Bauer and Rudebusch's preferred model is the unobserved-components (UC) model, not the "simple autoregressive (AR) model of Newell and Pizer (2003)" that the authors include to check for robustness.³² As the authors explain, their preferred model is consistent with the inclusion of "structural economic changes" found in the literature.³³ Focusing on their UC model, the preferred estimate is 0.7% or 1.3% for the one-year or the 10-year Treasury notes, respectively.³⁴ In fact, sensitivity analysis over the specification of the UC model (instead of between different types of models) supports lower ranges of 0.6% to 0.7% and 0.9% to 1.3%, respectively.³⁵ Focusing on the longer time-series of 10-year Treasury bills from 1798 to 2019, which EPA also highlights, the central discount rate estimate corresponding to the preferred UC model is 1.5%. However, even this estimate is uncertain, such that the 68% Bayesian confidence interval implies a range from approximately 1% to 2.5%.³⁶ This type of estimate uncertainty applies to all the estimates discussed, above implying a wider and lower range of estimates than EPA adopts.

Putting all of this together suggests that, from this perspective of Bauer and Rudebusch, a conservative interpretation would conclude that the appropriate central discount rate is between 1% to 1.5% with a potential range of 0.5% to 2.5%.

C. Government forecasts support a central discount rate of approximately 1.5%

EPA also cites multiple forecasts as evidence that real interest rates will return to 2%,³⁷ despite recent declines in the real interest rate to near 0%.³⁸ Specifically, the Congressional Budget Office (CBO 2021a) projects that real interest-rate on the ten-year Treasury note will return to near 2% by mid-century.³⁹ EPA also cites the Social Security Administration Trustees' (SSA 2021) projection of annual real fund interest rates of 1.8% to 2.8% with a central estimate of 2.3%.⁴⁰ However, it is not stated why these latter projections are particularly relevant, though

³⁰ *Id.* at tbl. A.1 (showing that the average of recent estimates in the corresponding literature is also 0.7%.)

³¹ Michael D. Bauer & Glenn D. Rudebusch, *Climate Change Costs Rise as Interest Rates Fall* (FRBSF ECON. LTR. 2021–28 (2021)).

³² Bauer & Rudebusch, *supra* note 10, at 11–12.

³³ *Id.* at 9.

³⁴ *Id.* at 12 tbl.1.

³⁵ Michael D. Bauer & Glenn D. Rudebusch, *Online Appendix for "The Rising Cost of Climate Change: Evidence from the Bond Market"* at 8 tbl.D.2 (July 13, 2021).

³⁶ *Id.* at 8 fig. E.1.

³⁷ Draft Report, *supra* note 2, at 58 (citing CONG. BUDGET OFF., THE 2021 LONG TERM BUDGET OUTLOOK (2021), <https://www.cbo.gov/publication/56977> [hereinafter CBO 2021]; SOCIAL SECURITY ADMIN., THE 2021 ANNUAL REPORT OF THE BOARD OF TRUSTEES OF THE FEDERAL OLD-AGE AND SURVIVORS INSURANCE AND FEDERAL DISABILITY INSURANCE TRUST FUND (2021), <https://www.ssa.gov/OACT/TR/2021/> [hereinafter SSA 2021]).

³⁸ Peter Howard & Jason A. Schwartz, *Valuing the Future: Legal and Economic Considerations for Updating Discount Rates*, 39 YALE J. ON REG. 595, 617–18 (2022).

³⁹ Draft Report, *supra* note 2, at 58.

⁴⁰ *Id.* (citing SSA 2021, *supra* note 37, at tbl.II.C1).

presumably it is because the Old-Age and Survivors Insurance and Disability Insurance Trust Funds are “invested in interest-bearing Federal securities.”⁴¹ Even so, these assets can be short-run or long-run assets, so they are not directly connected to the 10-year Treasury bill upon which EPA primarily focuses.⁴²

For multiple reasons, a more complete analysis of government forecasts indicates a lower range of discount rates than EPA applies. For one, the Congressional Budget Office forecasts themselves support a lower range of discount rates. While EPA cites the CBO 2021a forecast that the real interest-rate corresponding to the ten-year Treasury note will reach 2.3% in the long run (by mid-century),⁴³ the Congressional Budget Office also forecasts rates of 1.6% to 1.7% in the medium-run (in 10 to 20 years).⁴⁴ In a recent CBO publication, Gambler et al. (2020) focus on both medium-run and long-run rates indicating their importance.⁴⁵ In fact, in its 2021 and 2022 forecasts, the Congressional Budget Office also calculates average forecasts of 1.3% to 1.5% over the next 30 years.⁴⁶ Given these multiple forecasts of estimates over different time-periods, it is unclear which is the most appropriate to focus on, though some down-weighting is likely appropriate to long-run forecasts as uncertainty increases farther into the future.

Moreover, government forecasts beyond the Congressional Budget Office and Social Security Administration indicate lower discount rates. For example, the Council of Economic Advisors, in a 2017 forecast, cites future forecasts from Blue Chips of between 1.2% to 1.5%.⁴⁷ Presumably, these alternative forecasts hold weight in the U.S. government, as the CBO also compares its own forecast performance against the Blue Chip forecast.⁴⁸

Based on the full range of government forecasts, a central rate closer to 1.5% is appropriate. This is particularly true given the Draft Report’s focus on near-term rates when calibrating the simple Ramsey equation and its implicit inclusion of the precautionary effect (i.e., the preference for additional savings due to growth rate uncertainty) in the certainty-equivalent

⁴¹ Social Security Administration. Old-Age & Survivors Insurance Trust Fund, <https://www.ssa.gov/oact/progdata/describeoasi.html>. (“The Old-Age and Survivors Insurance Trust Fund is a separate account in the United States Treasury...Funds not withdrawn for current cost (benefits, the financial interchange with the Railroad Retirement program, and administrative expenses) are invested in interest-bearing Federal securities, as required by law; the interest earned is also deposited in the trust fund.”)

⁴² Draft Report, *supra* note 2, at 56–58; Jeffrey L. Kunkel, Soc. Sec. Admin., *Social Security Trust Fund Investment Policies and Practices* (Actuarial Note 142, 1999) (explaining that these funds are invested in a combination of short-run and long-run assets; specifically, “these may be either short-term ‘certificates of indebtedness’ or longer-term special issues in the form of notes or bonds”).

⁴³ Draft Report, *supra* note 2, at 58.

⁴⁴ CBO 2021, *supra* note 37, at 34 tbl.A-2; *see also* CONG. BUDGET OFF., THE 2022 LONG TERM BUDGET OUTLOOK (2022) [hereinafter CBO 2022].

⁴⁵ Edward Gamber, Cong. Budget Off., *The Historical Decline in Real Interest Rates and Its Implications for CBO’s Projections*, at 47 (CBO Working Paper 2020-09, 2020).

⁴⁶ CBO 2021, *supra* note 37, at 43 tbl.A-2; CBO 2022, *supra* note 44, at tbl.B-1.

⁴⁷ Council of Econ. Advisers, *Discounting for Public Policy: Theory and Recent Evidence on the Merits of Updating the Discount Rate* (2017), <https://perma.cc/K28D-XXPQ>.

⁴⁸ CONG. BUDGET OFFICE, CBO’S ECONOMIC FORECASTING RECORD: 2021 UPDATE tbl.1 (Dec. 2021), <https://www.cbo.gov/publication/57579>.

social cost of greenhouse gases.⁴⁹ In this case, the average discount rate over time and the medium-run forecast should be given more weight than more speculative long-run projections.

D. Expert elicitations support a discount rate range of 0% to 3%, with a central rate between 1.0% to 2.0% depending on the extent to which the damage functions capture relative prices

Beyond market interest rates (i.e., the descriptive approach to calibrating rates), EPA also cites to surveys of experts on discount rates and climate change. Specifically, it cites a median discount rate of 2% found in Drupp et al. (2018), Pindyck (2019), and Howard & Sylvan (2020).⁵⁰ EPA also cites to a higher mean between 2.3% to 2.7% found in these surveys, although research indicates that the median is more appropriate than the mean for selecting normative parameters like a discount rate.⁵¹

Despite EPA focusing predominantly on descriptive arguments in justifying a central discount rate of 2%, economists place greater weight on normative arguments when selecting the appropriate value for a social discount rate.⁵² Potentially due to this limited focus, EPA misses several additional papers supporting a rate of 2%. In a recent expert elicitation, Gollier et al. (2022) find a median discount rate of 2% when surveying top-decile ranked economists according to IDEAS/RePEc. In a recent working paper, Nesje et al. (2022) find that philosophers support a discount rate of approximately 2%, similar to economists.⁵³ Based on the evidence, EPA should place equal weight on descriptive and normative arguments for the social discount rate and conduct a full review of the normative discount rate literature.

Even so, the normative approach supports rates below 2% as well, like the descriptive approach. While EPA is correct that the median social discount rate found across groups of economic experts on discount rates and climate change is consistently 2%,⁵⁴ experts find a lower discount rate when they explicitly consider relative prices.⁵⁵ In particular, the experts surveyed in Drupp et al. (2018) that explicitly accounted for relative prices supported a lower discount rate

⁴⁹ Draft Report, *supra* note 2, at 63.

⁵⁰ Drupp et al. (2018), *supra* note 13, at 118; Pindyck (2019), *supra* note 13, at 140 (2019); Howard & Sylvan (2020), *supra* note 13, at 213, 221–23.

⁵¹ Howard & Sylvan (2020), *supra* note 13, at 11; *see also* Martin Hansel et al., *Climate Economics Support for the UN Climate Targets*, 10 NAT. CLIMATE CHANGE 781 (2020).

⁵² Drupp et al. (2018), *supra* note 13, at 118, 121. (“A clear finding from our data is that a large majority of experts (80 percent) think that [descriptive and normative] dimensions are relevant (see Figure 1, panel F). However, they generally recommend that governmental institutions should place greater weight on normative issues in determining the SDR; this has a mean (median) weighting of 61.53 percent (70 percent). When considering extremes, 14 percent (5 percent) of experts placed 0 (100 percent) weight on positive considerations, while 42 experts were divided equally between the two rationales; making this the modal response.”)

⁵³ Frikk Nesje, et al., *Philosophers reinforce economists' support for UN climate targets, but disagree on why*, at 3 (2022).

⁵⁴ Drupp et al. (2018), *supra* note 13, at 118; Pindyck (2019), *supra* note 13; Howard & Sylvan (2020), *supra* note 13, at 223; Christian Gollier et al. *The Discounting Premium Puzzle: Survey Evidence from Professional Economists* 14–16 (Working Paper 1345, 2022).

⁵⁵ Drupp et al. (2018), *supra* note 13, at 123.

range of 0% to 2% with a central estimate of 1%.⁵⁶ This suggests the use of a lower discount rate range for EPA's purposes than the median (or mean) rates alone would suggest.

In particular, the integrated assessment model damage functions incorporate non-market impacts, including willingness to pay for health and ecological services such as biodiversity. However, these damage functions have historically failed to account for the increased value of non-market goods and services due to their growing relative scarcity from climate and non-climate factors.⁵⁷ Relative prices can be implicitly captured by adjusting downward the social discount rate to account for the slower growth rate in per-capita consumption of non-market goods and services relative to market goods and the limited substitutability of market goods for these non-market goods.⁵⁸ In the case of the Howard and Sterner (2017) damage function—one of the three damage functions that EPA incorporates—this downward adjustment applies as relative prices were not factored into the damage function. However, the downward adjustment for relative prices does not fully apply to the other two damage functions as EPA accounts for future increases in the value of statistical life (such that the health impacts vary with the GDP per capita income path).⁵⁹

Additionally, aside from the effects of relative prices, heterogeneity among experts suggests a broader range of rates than EPA adopts. For instance, Howard and Sylvan (2020) find a 90th percent confidence interval of between 0% to 4.5%.⁶⁰ However, this does not factor in the uncertainty underlying individual's opinions. Drupp et al. (2018) considers the range held by individuals inquiring about their lower- and upper-bound rates in addition to the central estimate of the social discount rate. In this case, the authors find that 90 percent of discount-rate experts would be comfortable with a social discount rate between 1% and 3%.⁶¹

Based on this evidence, experts appear to support a range from 0% to 3% with a central estimate between 1% and 2% (depending on the effects of relative prices).

E. Omitted impacts lead to a further overestimation of the social discount rate, and further supports the EPA in selecting a lower discount rate range of 1% to 2%

EPA should recognize that omitted impacts imply an overestimate in the discount rate as well. This implication supplies even further basis to reduce the discount rates the agency applies.

The reason for this overestimation is straightforward: First, the simple Ramsey framework implies a positive correlation between the discount rate and the growth rate of per-

⁵⁶ *Id.*

⁵⁷ Howard & Schwartz, *supra* note 38, at 632–33; Peter H. Howard, Inst. for Pol'y Integrity, *Omitted Damages: What's Missing from the Social Cost of Carbon* 31–33 (2014); Michael Hoel & Thomas Sterner, Discounting and relative prices, 84 CLIMATIC CHANGE (2007); Thomas Sterner & U. Martin Persson. *An Even Sterner Review: Introducing Relative Prices into the Discounting Debate*, 2 REV. ENV'L ECON & POL'Y (2008).

⁵⁸ See Christian Gollier, *Ecological Discounting*, 145 J. ECON. THEORY 812 (2010). Christian P. Traeger, *Sustainability, Limited Substitutability, and Non-Constant Social Discount Rates*, 62 J. ENV'T ECON. & MGMT. 215 (2011).

⁵⁹ Draft Report, *supra* note 2, at 128. However, the DSCIM and GIVE do not currently include the impacts of climate change on ecological services and biodiversity. When these impacts are included, their relative price should be explicitly accounted for or the discount rate should be adjusted downward.

⁶⁰ Howard & Sylvan (2020), *supra* note 13, at 223.

⁶¹ Drupp et al. (2018), *supra* note 13, at 128.

capita consumption. And second, because larger climate impacts negatively impact the growth rate of consumption per capita—particularly as the damage functions become steeper as temperature increases—they result in a discount-rate decrease.⁶² Thus, omitted impacts not only bias the social cost of greenhouse gases downwards by directly lowering damages, but also by increasing the discount rate via a higher economic growth rate. See Appendix A below that proves that the simple Ramsey equation increases with omitted damages if the three damages functions used by EPA (2022) are well approximated by $D_t = \alpha_1 T_t^{\alpha_2}$, where α_1 is the damage coefficient representing the % loss of GDP for a 1°C increase in global average surface temperature above its pre-industrial level, and α_2 is the corresponding damage exponent.⁶³

Omitted impacts may also inflate the certainty-equivalent social cost of greenhouse gases by decreasing the variability in the growth rate of per-capita consumption and producing an overly strong correlation between global GDP and the amount of climate damages (i.e., increasing the climate beta). Increasing the variability in the growth rate of per-capita consumption leads to an increase in the magnitude of the precautionary effect, leading to lower discount rate. Increasing damage variability also has an unclear effect on the insurance effect, as (1) the risk premium can be calibrated in multiple ways (hence, the equity premium puzzle),⁶⁴ and (2) climate beta has an unclear sign.⁶⁵ In the case of EPA’s model, which implicitly uses consumption-based capital asset pricing model formula, the net effect of a reduction in damage variance resulting from omitted damages is potentially positive: the precautionary effect becomes more negative, as discussed above, but the directional impact on the insurance effect is unclear as it depends on the responsiveness of the climate beta to changes in the damage variance. In particular, the omission of explicitly represented environmental and social tipping points strongly decreases damage variance and increases the “climate beta” by eliminating strong non-linearities from the climate-economic system likely decreasing the discount rate.⁶⁶

As omitted impacts lead to a likely upwardly biased discount rate schedule, a potential solution is to use a lower and/or wider discount rate range. This supplies one additional reason—on top of the empirical reasons discussed above—for using a lower discount rate range.

* * *

Looking at all of this evidence in totality, EPA applies overly conservative central and lower-bound discount rates. Specifically, the evidence presented herein supports a range of social discount rates of 0.5% to 2.5% with a central estimate of 1.5%.

Based on this information, EPA should consider calculating the social cost of greenhouse gases using five discount rates: 0.5%, 1.0%, 1.5%, 2.0%, and 2.5% (with 1.5% as the central

⁶² Draft Report, *supra* note 2, at 51, 54–55 (“When using the Ramsey formula to estimate the SC-GHG, the per capita consumption growth rate, g_{gtt} is calculated net of baseline climate change damages as estimated by the damage modules described in Section 2.3.”)

⁶³ *Id.* at 51 fig. 2.3.2

⁶⁴ Simon Dietz et al., *The Climate Beta*, 87 J. ENV’T ECON. & MGMT. 271 (2018).

⁶⁵ Derek Lemoine, *The Climate Risk Premium: How Uncertainty Affects the Social Cost of Carbon*, 8 J. ASSOC. ENV’T & RES. ECON. 27, 29 (2021). Howard & Schwartz (2022), *supra* note 38, at 629–31.

⁶⁶ Howard & Schwartz (2022), *supra* note 38, at 626–31. Lemoine (2021), *supra* note 65, at 27.

rate). This alternative range appears to better overlap the multiple lines of evidence that EPA provides.⁶⁷

II. EPA Should More Strongly Emphasize that Omitted Impacts Bias Climate-Damage Estimates Downwards, and Take Steps To Address These Omissions

EPA appropriately emphasizes that the Draft Update “likely underestimate[s] the marginal damages from [greenhouse gas] pollution” as a result of both “conservative methodological choices” and “numerous categories of damages that are not currently quantified.”⁶⁸ In fact, practically all of the impacts that were omitted from the Working Group’s estimates—and some that were included in those estimates—are still unquantified here. Accordingly, EPA appropriately dedicates an entire section of the report to highlighting omitted damages and other modeling limitations that, “taken together . . . make it likely that the SC-GHG estimates presented in [the Draft Report] underestimate the damages from [greenhouse gas] emissions.”⁶⁹

Although EPA properly characterizes its climate-damage valuations as underestimates, it can do more to emphasize the point and take steps to address it. For one, if EPA does not adjust the discount rates downward as suggested above, it should at least note that discounting supplies an additional basis for underestimation. Moreover, EPA should commit to incorporating omitted damages into its estimates both now and in the future.

A. If EPA does not lower the discount rate, it should least recognize discounting as an additional basis for underestimation of the social cost of greenhouse gases

While EPA appropriately notes that both its conservative modeling choices and the continued presence of omitted damages likely undervalue the true social cost of greenhouse gases, it does not recognize that its selection of discount rates is conservative and thereby contributes to this undervaluation.⁷⁰ If EPA does not decrease its range of discount rates, as recommended above,⁷¹ it should at least incorporate the arguments from that section into its dedicated discussion of reasons that the Draft Update’s climate-damage valuations are likely underestimates.

⁶⁷ See David Anthoff & Johannes Emmerling, *Inequality and the Social Cost of Carbon*, 6 J. ASSOC. ENV’T & RES. ECON. 243, 263 (2019); INTERAGENCY WORKING GRP. ON THE SOCIAL COST OF CARBON, TECHNICAL SUPPORT DOCUMENT: SOCIAL COST OF CARBON FOR REGULATORY IMPACT ANALYSIS UNDER EXECUTIVE ORDER 12866, at 21 (2010) (showing that a rate of 0.5% would imply an elasticity of marginal utility of consumption at the lower end of the range used in the literature of 0.5 to 0.7). Despite its possibility of holding in the real world, we recognize that a parameter value this low may cause computational challenges, such as social cost of greenhouse gas estimates asymptotically going to infinity. If such problems arises, a conservative adjustment would be to consider a range of 1.0% to 2.0% with a central estimate of 1.5%.

⁶⁸ Draft Report, *supra* note 2, at 2.

⁶⁹ *Id.* at 72.

⁷⁰ See *supra* Part II.A.

⁷¹ *Id.*

B. EPA should augment the sector-specific damage functions (DSCIM and GIVE) as relevant published studies become available from the model developers

Currently, independent experts are working on quantifying some of the key impact categories that are omitted from EPA’s estimates. For instance, the Climate Impact Lab—the team behind EPA’s Data-driven Spatial Climate Impact Model (DSCIM) damage function—currently lists conflict and migration as additional research areas.⁷² Similarly, Resources for the Future—the team behind the Greenhouse Gas Impact Value Estimator (GIVE) damage function—indicates that future damage sectors will include “biodiversity, labour productivity, conflicts, and migration.”⁷³ EPA should commit to incorporating reliable quantifications of omitted impacts as they become available in the future. However, social cost of greenhouse gases estimates will likely always be underestimates to a certain extent, as economics will likely undervalue or omit certain hard-to-measure climate impacts.⁷⁴

C. EPA should perform its own systemic literature review to address omitted impacts using relevant published studies

Beyond waiting for Climate Impact Lab and Resources for the Future to update their damage functions, EPA should actively review the published literature to determine if it can include any currently omitted impacts.

Labor productivity provides a particularly strong example. DSCIM currently captures climate impacts on labor productivity, while GIVE and Howard and Sterner (2017) omit this impact. While independence of estimates is critical, EPA should use standard benefit-transfer methodologies to adapt these damages for the other two models in order to avoid excluding empirically established impacts. Then, when labor productivity is successfully addressed by one of the other two damage functions, EPA can adopt this alternative estimate, so as to benefit from independence in damage estimates.⁷⁵

Beyond the low-hanging fruit of including labor productivity, EPA should review the literature as recommended by National Academies of Sciences to determine if it can identify any relevant studies for inclusion and then update the damage functions until updates from the developers become available.⁷⁶

Tipping points are particularly important to include as they directly impact the damage function and the discount rate through changes to the economic growth rate, damage mean and variance, and climate beta. Various types of relevant tipping points are included in and excluded from EPA’s integrated assessment models, to varying extents. EPA’s models, like the IAMs used by the Working Group, include most climate tipping points—such as impacts on water vapor, cloud cover, snow cover, ice cover, and ocean carbon cycles—through their simple climate

⁷² Climate Impact Lab, <https://impactlab.org/>.

⁷³ Kevin Rennert et al., *Comprehensive Evidence Implies a Higher Social Cost of CO₂*, 610 NATURE 687, 691 (2022).

⁷⁴ *Id.*

⁷⁵ Draft Report, *supra* note 2, at 50, 81.

⁷⁶ Nat’l Acad. Sci., Engineering & Med., *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide* 155–56 (2017) (“In the near term, initial steps that could be undertaken include: a comprehensive review of the literature on climate impacts and damage estimation.”)

model or implicitly with the equilibrium climate sensitivity parameter.⁷⁷ However, EPA’s modular climate-economic model lacks a singular abstract tipping point used in the Working Group’s damage models, which directly impacts human welfare through lost consumption.⁷⁸ This singular tipping point in DICE and PAGE represents environmental tipping points triggered by climate change more generally—like the collapse of the Atlantic Meridional Overturning Circulation and North Atlantic convection, increased frequency of the El Niño-Southern Oscillation, changes in frequency and intensity of monsoons, the melting of the Antarctic and Greenland ice sheets,⁷⁹ and/or the bleaching and loss of coral reefs.⁸⁰ Moreover, EPA’s model also omits various tipping points that are also excluded from the Working Group’s models—namely social tipping points (mass migration, endogenous technology change, and conflict-development traps), interactions within the greater environmental system associated with runaway climate change from warming-triggered emissions of additional greenhouse gases (the melting of methane hydrates and permafrost and diebacks of the amazon and boreal forests), and interactions between society and the climate system that affect emissions through feedback effects (see Table 1 in Howard and Livermore, 2021).⁸¹ The omission of these critical feedbacks is problematic given their potential catastrophic nature and the resulting insurance premium.

Given the existence of multiple interconnected tipping points with various types of impacts, it is important to explicitly model multiple economically significant tipping points. In the traditional social-cost integrated assessment model literature (i.e., DICE, FUND, and PAGE), in a series of one-time model extensions, modelers integrate a single individual tipping point in scientific detail into these IAMs. Specifically, to avoid stylized representation that characterizes early IAMs’ representation of tipping points, these models capture the geophysical dynamics underlying the tipping point using reduced form equations. However, as these modified IAMs fail to capture interactions between the tipping points, the SC-GHGs increase with temperature and then unrealistic drop after crossing the triggering threshold as the cost becomes sunk. An exception is the recent version of PAGE, known as, PAGE-ICE, which captures two feedback effects – permafrost carbon and surface albedo –in a reduced form by using emulators.⁸² Even so, this literature fails to capture multiple tipping points and their interactions, despite more accurately representing their individual dynamics.

⁷⁷ *Id.*

⁷⁸ *Id.* (FUND did not include climate-environmental tipping points, as defined by Howard and Livermore (2021), or ocean sinks. More generally, IAMs do not account for social-ecological system feedbacks trigger by climate change that are not associated with the climate system beyond its triggering.)

⁷⁹ Draft Report, *supra* note 2, at 71 (noting that ice sheet melting is captured in FaIR).

⁸⁰ *Id.*; see also Robert E. Kopp et al., *Tipping Elements and Climate–Economic Shocks: Pathways Toward Integrated Assessment*, 4 EARTH’S FUTURE, at 351–55 (2016).

⁸¹ Peter Howard & Michael A. Livermore, *Climate-Society Feedback Effects: Be Wary of Unidentified Connections*, 15 INT’L REV ENV’T & RES. ECON. 1, 31–36 fig.1 (2021). Rennert et al. (2022), *supra* note 73 (To the extent that experts considered the effect of climate feedbacks on greenhouse gas emissions, they may be incorporated in the Resources for the Future Socioeconomic and Emissions Projections. However, Rennert et al. (2022) does not discuss the possibility of positive feedbacks involving greenhouse gas emissions). Nat’l Acad. Sci. (2017), *supra* note 76, at 154–56 (suggesting that FaIR does not account for these feedback effects).

⁸² Howard & Livermore, *supra* note 81, at 9; see also Dmitry Yumashev et al., *Climate Policy Implications of Nonlinear Decline of Arctic Land Permafrost and Other Cryosphere Elements*, 10 NAT. COMM’NS 1 (2019).

Many of these omitted tipping points are simultaneously modeled in the stochastic dynamic integrated assessment model literature. Cai et al. (2019)⁸³ calibrates the probability of triggering climate tipping points using an expert elicitation by Kriegler et al. (2009);⁸⁴ this is an approach recommended by National Academy of Sciences.⁸⁵ The Kriegler et al. (2009) survey included a variety of tipping points: the reorganization of the Atlantic Meridional Overturning Circulation, the melting of the Greenland ice sheet, the disintegration of the West Antarctic ice sheet, the dieback of the Amazon rainforest, and the shift to a more persistent El Niño regime. Moreover, Lemoine and Traeger (2016) model three abstract tipping points that each reflect a particular outcome of triggering real-world tipping points: a higher equilibrium climate sensitivity parameter from triggering additional greenhouse gas emissions, longer lifetimes of gases in the atmosphere from weakening carbon sinks, and higher economic damages.⁸⁶ Both papers reflect the existence of a domino effect: the triggering of one tipping point increases the probability of triggering other tipping points.⁸⁷ However, both papers represent a relatively abstract and/or stylized representation of tipping points, despite capturing multiple tipping points and their possible interactions.⁸⁸

More recent work by Dietz et al. (2021) addresses both the realistic representation of tipping points and their interactions, such that EPA can integrate this study into its climate-economic model. Specifically, Dietz et al. (2021) build a structural meta-analysis of eight tipping points that the authors introduce into an integrated assessment model.⁸⁹ The authors review the tipping point literature identifying 52 relevant papers of which 21 studies have the necessary geophysical foundations. The authors then integrate these eight tipping points (permafrost carbon feedback, ocean methane hydrates, Arctic Sea ice/surface albedo feedback, Amazon dieback, Greenland Icesheet disintegration, West Antarctic Icesheet disintegration, slowdown of the Atlantic Meridional Overturning Circulation, and changes in the variability of the Indian summer monsoon) in multiple ways into their integrated assessment models. These tipping points interact directly through the model or via modeling assumptions calibrated using Kriegler et al. (2009), though these connections reflect both positive and negative correlations. This analysis represents the most sophisticated analysis in the literature capturing multiple explicit tipping points, and is the ideal strategy that the EPA should adopt to integrate those damages into its valuations, as it avoids stylized representations of tipping points and their consequences.⁹⁰ While EPA should include this modeling strategy into the modular IAM, the resulting damage valuations would

⁸³ See Yongyang Cai, Timothy M. Lenton & Thomas S. Lontzek, *Risk of Multiple Interacting Tipping Points Should Encourage Rapid CO₂ Emission Reduction*, 6 NAT. CLIMATE CHANGE 520 (2016).

⁸⁴ See Elmar Kriegler et al., *Imprecise Probability Assessment of Tipping Points in the Climate System*, 106 PROC. NAT. ACAD. SCI. 5041 (2009).

⁸⁵ Nat'l Acad. Sci. (2017), *supra* note 76, at 156.

⁸⁶ Derek Lemoine & Christian P. Traeger, *Economics of Tipping the Climate Dominoes*, 6 NAT. CLIMATE CHANGE 514 (2016).

⁸⁷ *See id.*; *see also* Cai et al., *supra* note 83..

⁸⁸ Dietz et al. (2021), *supra* note 4, at Supplementary Information 5 tbl.1.

⁸⁹ Dietz et al. (2021), *supra* note 4.

⁹⁰ *Id.*

likely still represent an underestimate due to missing tipping points and connections, as well as omitted non-market impacts.⁹¹

An alternative to explicitly modeling multiple tipping points and their inter-connectedness is to model their expected damages and their underlying variance. Dietz et al. (2021) provide a reduced-form estimate of the damage function from tipping points. Specifically, “tipping points reduce global consumption per capita by around 1% upon 3° C warming and by around 1.4% upon 6° C warming, based on a second-order polynomial fit of the data. In some runs, damages exceed 4%,” indicating positive skewness.⁹² However, this approach is less desirable than explicit modeling, as it is reliant on other modeling assumptions made by the authors that may be inconsistent with EPA’s model. For example, the model excludes non-market impacts such as biodiversity and human health while assuming that half of climate impacts affect economic growth rather than consumption levels. Moreover, this method does not capture the impact of non-linearities on the precautionary and the insurance values of climate mitigation.⁹³

Regardless of how EPA models currently omitted climate tipping points, including them would be a critical step toward the National Academies long-term goal of modeling feedback effects between the various IAM modules.⁹⁴ For example, climate change can impact society, which can in turn lead to changes in greenhouse gas emissions. These climate-society feedback effects could be critical. Howard and Livermore (2021) propose a reduced form methodology to capture these and other critical feedback effects between the various modules.⁹⁵ EPA should start considering these challenges and make a first step of including tipping points within modules, as discussed above.

Beyond environmental and social tipping points, EPA should also review the literature on other omitted impacts. Impacts should be included based on the availability of published studies with sufficient detail and the magnitude of potential impact. Critical impacts to include are environmental services and biodiversity; air pollution due to rising heat, methane converting to ozone, and wildfires; inland flooding; and freshwater availability, among others.⁹⁶

III. EPA’s Application of the Howard and Sterner Damage Function Is Conservative, and the Agency Should Consider Making Adjustments To Better Capture the Full Scope of Climate Impacts

EPA appropriately selects the Howard and Sterner (2017) damage function, as it is the most up-to-date meta-regression estimate of global damage estimates for the agency’s purposes.⁹⁷ While EPA offers compelling reasons for selecting this damage function and applies

⁹¹ *Id.* at 7.

⁹² *Id.* at 5.

⁹³ *Id.* at 2, 7.

⁹⁴ Nat’l Acad. Sci. (2017), *supra* note 76, at 156, 186–87.

⁹⁵ See Howard & Livermore (2021), *supra* note 81.

⁹⁶ Draft Report, *supra* note 2, at 73 table 3.2.1.

⁹⁷ *Id.* at 47–48 (“Howard and Sterner (2017) provide a more recent peer-reviewed meta-analysis of existing damage studies (published through 2016) and account for additional features of the underlying studies.”); *see also* Peter H.

it in an appropriate manner, EPA’s application of Howard and Sterner (2017) is conservative. Accordingly, EPA should consider adjusting its application in several ways to better capture the full scope of climate impacts.

A. EPA should consider applying an alternative damage estimate from Howard and Sterner (2017) rather than relying solely on their most conservative estimate

EPA should consider selecting an alternative damage estimate from Howard and Sterner (2017), as it selects the paper’s most conservative estimate (or, at minimum, EPA should widen the uncertainty bands to reflect uncertainty in the regression specification).⁹⁸ Howard and Sterner (2017) present multiple damage specifications that vary by (1) whether estimates corresponding to large temperature changes (i.e., greater than or equal to 4° C) are included, and (2) the set of impact channels controlled for and included in the final estimate.⁹⁹ EPA focuses on Specification (7) in Table 2 of Howard and Sterner (2017), which includes damages estimates corresponding to large temperature increases, rather than the authors’ preferred specification (4) that excludes damage estimates corresponding to temperature changes of 4° C or more. However, as explained in Howard and Sterner (2022), damage estimates above 4° C are highly uncertain and conservative, thereby producing a likely undervaluation of climate damages.¹⁰⁰

Howard and Sterner (2022) provide two additional reasons for dropping damage estimates corresponding to temperature increases above 4°C. First, the authors explain and then empirically demonstrate that the standard errors for estimates increase rapidly for temperature increases around 4°C due to the limited data and substantial uncertainties leading the standard fixed effect weights to collapse to zero for these estimates.¹⁰¹ The explosion of standard errors above 4°C implies that relying on damage estimates corresponding to temperature changes below 4°C is more accurate, as the damage estimates corresponding to high temperature changes are highly speculative, and it is better to rely on extrapolations to higher temperature levels above 4°C using the quadratic damage function. Second, Howard and Sterner (2022) redefine their catastrophic variable as a catastrophic risk premium consistent with earlier definitions in DICE, instead of using a more general definition that conflates catastrophic risk premiums with catastrophically high temperatures, catastrophically high draws from the underlying damage distributions, and poor estimate quality.¹⁰² The resulting estimate is consistent with Howard and Sterner’s (2017) preferred estimate in Specification (4) regardless of whether damage estimates

Howard & Thomas Sterner, *Few and Not So Far Between: A Meta-Analysis of Climate Damage Estimates*, 68 ENV’T & RES. ECON. 197 (2017).

⁹⁸ Draft Report, *supra* note 2, at 49.

⁹⁹ *Id.* at 48. See also Howard & Sterner (2017), *supra* note 97, 211–15 tbl.2.

¹⁰⁰ Peter H. Howard & Thomas Sterner, *Between Two Worlds: Methodological and Subjective Differences in Climate Impact Meta-Analyses* 12, 19 (Resources for the Future Working Paper 22-10, 2022).

¹⁰¹ *Id.* at 19, 33 figure 2. (“HS applies inverse temperature as a proxy variable for standard errors. Implicitly, HS assumes that the variance of a damage estimate is linear in temperatures up to 4°C and then infinite thereafter, such that the weight drops to 0 percent. An alternative approach is to leverage the limited number of standard deviation estimates to estimate the appropriate functional form (Tol 2009)... We conduct sensitivity analysis and confirm that damage variance increases rapidly above 3.5°C nonlinearity (see Figure 2) and that a quartic function also performs well.”)

¹⁰² *Id.* at 13; Howard (2014), *supra* note 57, at 36, 47, 75.

corresponding to temperature increases greater than 4° C are included.¹⁰³ For these reasons, Howard and Sterner (2022) recommend extrapolating damages from high temperature increases rather than estimating them directly.

B. EPA should incorporate catastrophic impacts and productivity effects into the damage function

EPA excludes the coefficients corresponding to catastrophic and productivity as currently defined in Howard and Schwartz (2017; 2022), noting the “need for improved methods for quantifying and incorporating these types of important elements of damages.”¹⁰⁴ But these “improved methods” already exist, and so EPA need not wait for “future updates” to incorporate them.¹⁰⁵

With respect to catastrophic impacts, there are numerous methods that EPA can incorporate into the meta-regression. In particular, the DSCIM and GIVE models feature methods for including specific tipping points and feedback effects as discussed above. Moreover, Dietz et al. (2021) provide a structural meta-analysis that could be combined with Howard and Sterner (2017). Specifically, Dietz et al.’s (2021) reduced-form damage function discussed above, which approximates their structural meta-analysis damage estimates in the paper, can be included in the model to capture tipping points in a relatively consistent manner. If EPA does so, it should reflect the uncertainty and skewness underlying these impacts found by the authors.¹⁰⁶

The productivity variable captures a growth effect,¹⁰⁷ as it models loss of production inputs, and indirect market effect.¹⁰⁸ Bosello et al (2010) and Roson and van der Mensbrugghe (2012) emphasizes this latter interpretation,¹⁰⁹ highlighting that CGE models capture indirect market effects such as inter-sector damages, shifting demand, and changes in trade and regional production.¹¹⁰ It is not clear *a priori* whether these indirect effects reduces or exacerbate climate damages, which is reflected in differing outcomes in the models.¹¹¹ Thus, the primary effect of

¹⁰³ See Howard & Sterner (2022), *supra* note 100, at 37 tbl.SM.7. Beyond reasons of efficiency and robustness, there is also a practical reason that EPA need not directly estimate damages above 4°C: because those damages are highly unlikely to occur this century, and thus have limited weight in the overall calculation as a result of discounting.

¹⁰⁴ Draft Report, *supra* note 2, at 48–49.

¹⁰⁵ *See id.*

¹⁰⁶ Dietz et al. (2021), *supra* note 4, at 1, 4.

¹⁰⁷ Unlike panel models, these CGE growth impacts are still reflected as a percentage loss of GDP, as the impacts are to input availability, productivity, and demand allowing for re-optimization.

¹⁰⁸ Rob Dellink, Elisa Lanzi & Jean Chateau, *The Sectoral and Regional Economic Consequences of Climate Change to 2060*, 72 ENV'T & RES. ECON. 328 (2019). (“At the global level, almost half of the projected GDP loss of 2% can be attributed to the indirect effects on capital, which may be interpreted as growth effects. In other words, by 2060 the projected economic consequences on GDP levels and on GDP growth are of similar size.”)

¹⁰⁹ Fabio Eboli, Ramiro Parrado & Roberto Roson, *Climate-Change Feedback on Economic Growth: Explorations With a Dynamic General Equilibrium Model*, 15 ENV'T & DEV. ECON 515 (2010); Roberto Roson & Dominique Van der Mensbrugghe, *Climate Change and Economic Growth: Impacts and Interactions*. 4 INT’L J SUSTAINABLE ECON. 270 (2012).

¹¹⁰ Eboli et al (2010), *supra* note 109, at 2; Roson & Van der Mensbrugghe (2012), *supra* note 109, at 2.

¹¹¹ Eboli et al. (2010), *supra* note 109, at 3. Dellink et al. (2019), *supra* note 108, at 328. For example, Eboli et al (2010) at Dellink et al. (2019) find that the impacts move in different directions. Though Eboli et al. (2010) explain that the direction of the indirect impacts are unclear, as adaptation and trade imply that indirect market impacts reduce damages and demand shifts (and damage interactions) have the opposing effect.

including these methods would be a wider variance.¹¹² Consistent with the Howard and Sterner (2017) recommendation, EPA should at least factor in these productivity impacts into its calculation of standard errors.¹¹³

C. EPA should consider updating the underlying dataset of Howard and Sterner (2017) in the future as data becomes available

While Howard and Sterner's (2017) methodology sensibility incorporates a wide range of existing climate-damage estimates, new global damage studies are becoming available such as Piontek et al. (2021) and O'Neill et al. (2022).¹¹⁴ Consequently, new meta-regressions using this data will also become available, including Howard and Sterner (2022), Tol (2022),¹¹⁵ and potentially a new DICE damage function based on meta-regression. EPA should consider how to address this new data and estimates in future updates.

When the time comes to review this new data, EPA should adopt the most up-to-date methodologies laid out in the meta-analysis literature, as reflected in Howard and Sterner (2017; 2022).¹¹⁶ For one, EPA should conduct a comprehensive literature search. It should then define *a priori* selection criteria. Care should also be taken when reviewing the data, as there is a long history of climate damage meta-analyses incorrectly citing data due to the complexity of its interpretation (by, for example, failing to adjust for the temperature level in the baseline year of the study). With respect to data, this involves carefully reading and classifying the underlying data of studies, ideally by two independent analysts.¹¹⁷ Specifically, many available estimates omit various impacts included in Working Group's damage estimates, with several of them capturing only a very limited sliver of market impacts excluding even sea-level rise (for example, Desmet and Rossi-Hansberg, 2015),¹¹⁸ such that additional methodological control

¹¹² Marshall Burke, Solomon M. Hsiang & Edward Miguel, *Global Non-Linear Effect of Temperature on Economic Production*, 527 NATURE 235 (2015); Richard G Newell, Brian C. Prest & Steven E. Sexton. *The GDP-Temperature Relationship: Implications for Climate Change Damages*. 108 J. ENV'T ECON. & MGMT. 102,445 (2021). The inclusion of this set of productivity impacts from CGE models is less controversial than the level versus growth debate underlying the temperature panel data estimates. To avoid this controversy, EPA could drop the panel data estimates, and include the productivity impacts exclusively from CGE models.

¹¹³ Howard & Sterner (2017), *supra* note 97, at 220. ("Instead, given the debate over the impact of climate change on productivity and economic growth (Dell et al. 2012; Burke et al. 2015; Howard 2015), we recommend conducting an analysis of sensitivity to the inclusion of the productivity impact."). Draft Report, *supra* note 2, at 49. This inclusion of the productivity coefficient and its variance into the calculation of the damage variance is further supported by the uncertainty underlying whether climate change impacts GDP levels or GDP growth rates.

¹¹⁴ Franziska Piontek et al., *Integrated Perspective on Translating Biophysical to Economic Impacts of Climate Change*, 11 NATURE CLIMATE CHANGE 563 (2021).

¹¹⁵ See Howard & Sterner (2022), *supra* note 100; Richard S.J. Tol, *A Meta-Analysis of the Total Economic Impact of Climate Change* (preprint, 2022).

¹¹⁶ Howard & Sterner (2022), *supra* note 100; Howard & Sterner (2017), *supra* note 97.

¹¹⁷ Tom D. Stanley et al. *Meta-Analysis of Economics Research Reporting Guidelines*, 27 J ECON. SURV. 390 (2013).

¹¹⁸ Klaus Desmet & Esteban Rossi-Hansberg, *On the Spatial Economic Impact of Global Warming*, 88 J. URBAN ECON. 16 (2015); Bruno Conte et al., *Local Sectoral Specialization in a Warming World*, 21 J. ECON. GEO 493 (2021); José-Luis Cruz & Esteban Rossi-Hansberg, *The Economic Geography of Global Warming* (Nat'l Bur. of Econ. Rsch., 2021); Newell et al., *supra* note 112; Matthias Kalkuhl & Leonie Wenz, *The Impact of Climate Conditions on Economic Production: Evidence from a Global Panel of Regions*, 103 J. ENV'T ECON. & MGMT. 102,360 (2020).

variables may be necessary.¹¹⁹ Finally, EPA should drop or significantly downweigh duplicate estimates, and potentially outdated studies as recently done by Nordhaus.¹²⁰

EPA should also adopt the most up-to-date estimation methodologies laid out in the meta-analysis literature, as represented by Howard and Sterner (2017; 2022). In particular, EPA should account for estimate heteroskedasticity by using fixed or random effects estimators, controlling for damage channels and pathways with methodological control variables, and clustering error terms at the estimation author, method, or model levels. EPA should also consider revising its approach of equally weighting estimates by age, author, methodology and identification strategy. For example, higher-quality and more recent studies presumably merit greater analytical weight.¹²¹

IV. EPA Should Make Explicit Its Certainty-Equivalent Discount Rate by Specifying Its Extended Ramsey Rate, and Explain Any Decisions Underlying this Expression

EPA appropriately calibrates a declining discount rate over time, as this is consistent with economic theory and previous integrated assessment models. Furthermore, EPA appropriately calculates a certainty-equivalent social cost of greenhouse gases given uncertainty in economic growth and climate damages.¹²² But EPA could more clearly disclose its work here. In particular, EPA should clearly specify its extended Ramsey equation and the underlying parameters in order to minimize any potential confusion.

A. EPA should provide its implicit discount rate schedule and underlying parameters

For purposes of transparency, EPA should explicitly state the certainty equivalent discount rate schedules and their underlying parameters. This transparency will enable the public, including other federal and state agencies, to better understand the assumptions underlying the certainty-equivalent social cost of greenhouse gases. Lack of understanding may prevent these entities from considering these estimates in their own analyses. For instance, in some benefit-cost analyses, to ensure the use of consistent discount rates, these values may be necessary for other agencies to adjust the discount rate schedule for other assets with different risk profiles (i.e., different betas) or for other reasons. (If EPA does not believe that this is true, it should explain in detail why, as many federal and state agencies are likely unfamiliar with the extended Ramsey discount rate formula.)

Beyond pointing out the relative accuracy of using a constant discount rates to approximate for EPA's declining discount rate schedules,¹²³ EPA should provide the discount rate schedules underlying Figure 2.4.1 of the Draft Update, including the expected and certainly-

¹¹⁹ For example, it may be necessary to include a control variable for whether the underlying study captures impacts from sea-level rise.

¹²⁰ Howard & Sterner (2017), *supra* note 97, at 206, 208; William D. Nordhaus & Andrew Moffat, *A Survey of Global Impacts of Climate Change: Replication, Survey Methods, and a Statistical Analysis* (Nat'l Bur. Econ. Rsch. 2017).

¹²¹ See Howard & Sterner (2022), *supra* note 100.

¹²² Howard & Schwartz (2022), *supra* note 38, at 626, 630.

¹²³ Draft Report, *supra* note 2, at 119 figure A.3.1.

equivalent discount rates.¹²⁴ However, this figure shows only the “certainty-equivalent risk-free discount rate” omitting the risk premium term, which implies that EPA never displays the explicit discount rate in full. EPA should include in the figure and provide the certainty-equivalent discount rates applied in the analysis corresponding to the extended Ramsey, as specified in expression 2.5.2.¹²⁵ Moreover, EPA should also provide the values of the parameters underlying these derivations, including the implicit climate beta schedule, the risk premium parameter/value, and the moments of the climate damage distributions (mean and variance). EPA should also explain the derivation and meaning of these values.

B. EPA should provide its implied climate beta and explain its derivation

The climate beta is an output of the integrated assessment model’s structure and representation of uncertainty.¹²⁶ By calculating a certainty-equivalent social cost of greenhouse gases, which implicitly accounts for the endogenous climate beta underlying the agency’s model, EPA calculates its climate beta conditional on the model’s structure and parameterization.¹²⁷ However, the omission of climate impacts, particularly non-linear environmental and social tipping points and loss of ecological services including biodiversity, leads to a climate beta that is too high.¹²⁸ Moreover, the possibility that climate change impacts economic growth should imply a lower climate beta.¹²⁹ To address the possibility that its climate-economic model’s implicit climate beta is unrealistically high, EPA should attempt to include omitting tipping points and improve the structural representation of the global economy where possible.

Given the ongoing debate over the climate beta’s magnitude and sign, EPA could also conduct sensitivity analysis over the climate beta setting the central value of beta equal to zero. This type of analysis is relatively simple in the context of constant discount rate approximations, as previously used by the EPA and the Working Group. However, in EPA’s modular integrated assessment model context, this alternative beta implies a different model structure or calibration, which may also impact the damage function and marginal damage estimates over time. Therefore, it is not clear how EPA would implement this approach. One possible pathway forward is to ignore the insurance effect until the climate-economics literature resolves this ongoing debate. Even then, this approach implicitly sets the climate beta equal to zero in only the discount rate formula, which could be suboptimal for the reasons discussed above.¹³⁰

Ongoing debate over the climate beta points counsels for a more thorough discussion of the parameter by EPA. In particular, EPA can demonstrate that the insurance premium can be

¹²⁴ *Id.* at 51 fig. 2.4.1.

¹²⁵ *Id.* at 63.

¹²⁶ Dietz et al. (2018), *supra* note 64, at 261.

¹²⁷ Draft Report, *supra* note 2, at 63.

¹²⁸ Howard & Schwartz, *supra* note 38, at 630–31.

¹²⁹ See Lemoine (2021), *supra* note 65; Peter Howard & Derek Sylvan, Inst. for Pol’y Integrity, *Gauging Economic Consensus on Climate Change* 15–16 (2021). Despite the ongoing debate in the literature over whether climate change affects growth rates or GDP levels, Howard & Sylvan find that 76% of respondents to their survey of economists publishing on climate change believe that climate change will eventually impact economic growth. However, EPA focuses on level impacts exclusively.

¹³⁰ Howard & Schwartz, *supra* note 38, at 631.

split into two terms, like Lemoine (2021),¹³¹ even when temperature impacts GDP level and not directly the economic growth rate as Lemoine assumes; see Appendix B. These two terms represent the insurance effect and the scale effect. By splitting the climate beta parameter into two independent terms, it becomes clear that there are two opposing effects on the discount rate (i.e., a negative effect and a positive effect). As EPA more fully captures climate damages by modeling omitted tipping points and other impacts, the negative effect on the discount rate will increase in magnitude, thereby increasing mean damages, damage variance, and the insurance effect. Explaining these two independent effects may reduce debate over the climate beta, as advocates for different beta values may partially be confounding the two effects into one.

C. EPA should provide its risk premium and explain its derivation

By calculating the certainty-equivalent social cost of carbon, EPA implicitly and correctly uses the consumption-based Capital Asset Pricing Model (CCAPM) formula to calculate the risk premium associated with the climate beta. According to the formula, the risk premium equals the product of the elasticity of marginal utility of consumption and the variance of per-capita consumption.¹³² Using a market premium rate is less relevant in this context, as large portions of climate impacts correspond to non-market impacts. For instance, in the Draft Report, health impacts account for the largest share of climate impacts at 46% to 76% captured when using damage functions with sectoral breakdowns.¹³³ Moreover, climate change represents an intergenerational risk for which no market asset is observable. In this context, the risk premiums implied by bond and equity markets¹³⁴ do not apply, as they represent intra-generational market returns.

As discussed earlier, both discount rate experts and climate experts consistently select a central discount rate of 2% (or lower when considering relative prices) as appropriate in inter-generational contexts, including in the climate context. In responding to this question, economists implicitly account for what they believe to be the appropriate discount rate structure,¹³⁵ including the precautionary and insurance effects, as well as other considerations. Drupp et al. (2018) find evidence that the precautionary effect alone does not explain why experts provide social discount rates below the value implied by the simple Ramsey rate; this is consistent with economists accounting for additional considerations.¹³⁶ Moreover, Gollier et al. (2022) find that, while the majority of economists support varying the social discount rate with the riskiness of the project (i.e., accounting for the insurance premium), they only support limited variation in the social discount rate. This appears to be because their implied risk premium is

¹³¹ Lemoine (2021), *supra* note 65.

¹³² Christian Gollier, *Discounting and Growth*, 104 AM. ECON. REV. 535 (2014).

¹³³ Draft Report, *supra* note 2, at 70 tbl.3.1.4. Howard and Sterner (2017), *supra* note 97, at 212. (In addition, Howard and Sterner (2017)'s preferred meta-regression specification finds that non-market impacts represent approximately 80% of non-catastrophic damages. However, across specifications, the authors find considerable variability from 0% to over 100% of non-catastrophic damages).

¹³⁴ Dietz et al. (2018), *supra* note 64, at 271; CHRISTIAN GOLLIER, PRICING THE PLANET'S FUTURE: THE ECONOMICS OF DISCOUNTING IN AN UNCERTAIN WORLD 159–60 (Princeton Univ. Press, 2013)

¹³⁵ Howard & Sylvan (2020), *supra* note 13, at 218.

¹³⁶ Drupp et al. (2018), *supra* note 13, at 124.

small, which is consistent with the use of the CCAPM formula.¹³⁷ In fact, Gollier et al. (2022) find that experts' climate discount rate is not significantly different than the risk free rate of interest; this is consistent with the results in Drupp et al. (2018) and Howard and Sterner (2020).¹³⁸

Another explanation for experts supporting low insurance effects is that the climate beta is considerably lower than one. Gollier et al. (2022) find that experts support a lower discount rate for climate change mitigation projects than for healthcare or railroads. The authors note that this may be because economists believe that climate projects are less risky, such that the climate beta is smaller than the beta corresponding to healthcare and railroad infrastructure. This would suggest that the climate beta is lower than the EPA model implies, as discussed in the previous section.¹³⁹ This result would be consistent with higher damage variance than currently observed due to omitted impacts, particularly from the exclusion of tipping points, as well as the need for other structural improvements in the EPA model in future updates. Given the significant uncertainties in the climate beta,¹⁴⁰ particularly given the strong possibility that EPA's implicit estimate of the climate beta exceeds the actual climate beta in the real world, the continued use of the CCAPM formula ensures that the impact of this potential bias is limited. This approach ensures that the EPA's social cost of greenhouse gases is a lower bound, until a more realistic climate beta estimate is possible with a modular integrated assessment model that captures key structural realities in the climate-economy.

V. EPA Should Calculate Marginal and Total Social Costs of Climate Change for Each of the SSPs

EPA deserves credit for developing a state-of-the-art modular integrated assessment model consistent with the suggestions of the National Academy of Sciences.¹⁴¹ This is a powerful tool, which has uses beyond calculating the social costs of greenhouse gases for policymakers. To the extent practicable, EPA should also calculate the social cost of greenhouse gases and the total cost of climate change for each of the SSPs, which span the likely emissions space. Though not needed for regulatory cost-benefit analysis, these values would nonetheless have significant value for policymakers and the public by providing them with the scale of benefits of various global greenhouse gas emission targets.¹⁴² This type of information could help inform public and policymaker opinion of the scale of climate action necessary and/or justifiable.

¹³⁷ Gollier et al. (2022), *supra* note 54, at 15 (“This suggests that risk-adjusting respondents use a relatively small aggregate risk premium to adjust sectoral rates . . . our economic experts want to penalize risky public projects much less than financial markets actually do for private investments.”)

¹³⁸ Gollier et al. (2022), *supra* note 54, at 3; Drupp et al. (2018), *supra* note 13, at 118; Howard & Sylvan (2020), *supra* note 13, at 224.

¹³⁹ Gollier et al. (2022), *supra* note 54, at 13.

¹⁴⁰ Gollier et al. (2022), *supra* note 54, at 11. (“Dietz, Gollier, and Kessler (2018) calibrate the DICE model and show that one should expect a positive climate beta smaller than unity. But clearly, few people have examined this issue, and there is no consensus on it (yet).”)

¹⁴¹ See Nat'l Acad. Sci. (2017), *supra* note 76, at 10.

¹⁴² Draft Report, *supra* note 2, at 20–25, 122.

VI. EPA Should Update Its Model at Least Every Five Years, Except for Damage Functions that Should Be Updated as New Sector-Specific Estimates Become Available

Consistent with the National Academies of Sciences’ recommendation, EPA should update its modular integrated assessment model and its corresponding social cost of greenhouse gases estimates at least every five years. As the Academies explain, “an update cycle of roughly 5 years would balance the benefit of responding to evolving research with the need for a thorough and predictable process.”¹⁴³ Regular timing would help researchers, stakeholders, and agencies prepare for the update process, including completing and providing any necessary inputs or updates to the model.¹⁴⁴ This includes updates to each of the modules, including socio-economic scenarios, the climate model, damages, and the discount rate. For the three damage functions, given the scale of omitted impacts, EPA should update the sectoral damage function as sector damage estimates become available, as discussed above. Finally, EPA should also strive to incorporate the longer-term recommendations of the National Academies, including adding feedback effects between modules if possible.¹⁴⁵

Sincerely,

Peter Howard, Economics Director

(see appendices below)

¹⁴³ See Nat’l Acad. Sci. (2017), *supra* note 76, at 10.

¹⁴⁴ *Id.* at 58–60.

¹⁴⁵ *Id.* at 8, 82–83.

Appendix A. Proof that Simple Ramsey Discount Rate Is Higher Due to Omitted Damages Increasing the Per-Capita Growth Rate

To demonstrate this impact, we start by specifying the simple Ramsey equation

$$r_t = \rho + \eta \times g_t$$

where r_t is the consumption discount rate, ρ is the pure rate of time preference, η is the elasticity of marginal utility of consumption, and g_t is the growth rate of per capita consumption.¹⁴⁶ Based on IAMs, like DICE, we can see that per capita consumption (CPC_t) can be written as

$$c_t = \frac{Y_t \times (1 - D_t)}{L_t} = \frac{Y_t \times (1 - \alpha_1 \times T_t^{\alpha_2})}{L_t}$$

where Y_t is global income/production, L_t is the population, D_t is climate damages measured as a percentage of GDP where $\alpha_1 > 0$ and $\alpha_2 > 0$ (such that $0 \leq D_t \leq 1$).¹⁴⁷ Therefore,

$$g_t = \frac{c_t - c_{t-1}}{c_{t-1}} = \frac{\frac{Y_t(1 - D_t)}{L_t} - \frac{Y_{t-1}(1 - D_{t-1})}{L_{t-1}}}{\frac{Y_{t-1}(1 - D_{t-1})}{L_{t-1}}} = \frac{YPC_t(1 - D_t) - YPC_{t-1}(1 - D_{t-1})}{YPC_{t-1}(1 - D_{t-1})}$$

where YPC_t is income per capita. If we rearrange this equation, we can see that

$$g_t = \frac{\frac{YPC_t}{YPC_{t-1}}(1 - D_t) - (1 - D_{t-1})}{(1 - D_{t-1})} = \gamma_t \frac{(1 - D_t)}{(1 - D_{t-1})} - 1 = \gamma_t(1 - D_t)(1 - D_{t-1})^{-1} - 1$$

where γ_t is the ratio of global output from year to year. Therefore, if the damage parameter α_1 were to increase due to the inclusion of omitted damages,

$$\frac{\partial r_t}{\partial \alpha_1} = \eta \times \frac{\partial g_t}{\partial \alpha_1} = \eta \gamma_t \left[-\frac{1}{1 - D_{t-1}} \frac{\partial D_t}{\partial \alpha_1} + \frac{1 - D_t}{(1 - D_{t-1})^2} \frac{\partial D_{t-1}}{\partial \alpha_1} \right].$$

Therefore,

$$\frac{\partial r_t}{\partial \alpha_1} = \eta \gamma_t \left[-\frac{1 - D_{t-1}}{(1 - D_{t-1})^2} \frac{\partial D_t}{\partial \alpha_1} + \frac{1 - D_t}{(1 - D_{t-1})^2} \frac{\partial D_{t-1}}{\partial \alpha_1} \right],$$

such that

$$\frac{\partial r_t}{\partial \alpha_1} = \frac{\eta \gamma_t}{(1 - D_{t-1})^2} \left[(1 - D_t) \frac{\partial D_{t-1}}{\partial \alpha_1} - (1 - D_{t-1}) \frac{\partial D_t}{\partial \alpha_1} \right].$$

Based on $D_t = \alpha_1 T_t^{\alpha_2}$, which is a relatively good approximation of the damage functional form shapes used by the EPA (2022),¹⁴⁸

¹⁴⁶ Draft Report, *supra* note 2, at 54.

¹⁴⁷ Following Nordhaus's most up-to-date model structure, we assume $D_t = \alpha_1 \times T_t^{\alpha_2}$ and that α_1 is sufficient low, such that $D_t < 1$. If α_1 is large, then we would need to assume the original DICE damage function structure $D_t = \frac{\alpha_1 \times T_t^{\alpha_2}}{1 + \alpha_1 \times T_t^{\alpha_2}}$ and redo our derivation.

¹⁴⁸ Draft Report, *supra* note 2, at 51 fig. 2.3.2.

$$\frac{\partial r_t}{\partial \alpha_1} = \left[\frac{\eta \gamma_t}{(1 - \alpha_1 T_t^{\alpha_2})^2} \right] [(1 - \alpha_1 T_t^{\alpha_2}) T_{t-1}^{\alpha_2} - (1 - \alpha_1 T_{t-1}^{\alpha_2}) T_t^{\alpha_2}].$$

This simplifies to,

$$\frac{\partial r_t}{\partial \alpha_1} = \left[\frac{\eta \gamma_t}{(1 - \alpha_1 T_t^{\alpha_2})^2} \right] [T_{t-1}^{\alpha_2} - \alpha_1 T_t^{\alpha_2} T_{t-1}^{\alpha_2} - T_t^{\alpha_2} + \alpha_1 T_t^{\alpha_2} T_{t-1}^{\alpha_2}],$$

such that

$$\frac{\partial r_t}{\partial \alpha_1} = \left[\frac{\eta \gamma_t}{(1 - \alpha_1 T_t^{\alpha_2})^2} \right] [T_{t-1}^{\alpha_2} - T_t^{\alpha_2}].$$

The first term is positive, i.e.,

$$\frac{\eta \gamma_t}{(1 - \alpha_1 T_t^{\alpha_2})^2} > 0,$$

as $\eta > 0$, $\gamma_t > 0$, and $0 < D_t < 1$ such that $0 < 1 - D_t < 1$ and $0 < (1 - D_t)^2 < 1$. The second term is negative, as

$$T_t > T_{t-1} \rightarrow T_t^{\alpha_2} > T_{t-1}^{\alpha_2}.$$

because $\alpha_2 > 0$.

Alternative Ramsey Equation Specification

If we look at EPA's expression A.3.3 ignoring the expected value for now,¹⁴⁹ we can see that the simple Ramsey equation equals

$$r = \rho + \frac{1}{t} \ln \left[\left(\frac{c_t}{c_0} \right)^\eta \right] = \rho + \frac{\eta}{t} (\ln[c_t] - \ln[c_0]) \rightarrow$$

$$r = \rho + \frac{\eta}{t} \left(\ln \left[\frac{Y_t(1 - D_t)}{L_t} \right] - \ln \left[\frac{Y_0(1 - D_0)}{L_0} \right] \right) \rightarrow$$

$$r = \rho + \frac{\eta}{t} (\ln[YPC_t(1 - D_t)] - \ln[YPC_0(1 - D_0)]).$$

Taking the derivative with respect to α_1 , we know that

$$\frac{\partial r}{\partial \alpha_1} = \frac{\eta}{t} \left(-\frac{YPC_t}{YPC_t(1 - D_t)} \frac{\partial D_t}{\partial \alpha_1} + \frac{YPC_0}{YPC_0(1 - D_0)} \frac{\partial D_0}{\partial \alpha_1} \right) = \frac{\eta}{t} \left(\frac{1}{(1 - D_0)} \frac{\partial D_0}{\partial \alpha_1} - \frac{1}{(1 - D_t)} \frac{\partial D_t}{\partial \alpha_1} \right).$$

Based on $D_t = \alpha_1 T_t^{\alpha_2}$, as assumed above, such that $\frac{\partial D_t}{\partial \alpha_1} = T_t^{\alpha_2}$, then

¹⁴⁹ *Id.* at 116.

$$\frac{\partial r}{\partial \alpha_1} = \frac{\eta}{t} \left(\frac{1}{1 - \alpha_1 T_0^{\alpha_2}} \cdot T_0^{\alpha_2} - \frac{1}{1 - \alpha_1 T_t^{\alpha_2}} \cdot T_t^{\alpha_2} \right),$$

such that

$$\frac{\partial r}{\partial \alpha_1} = \frac{\eta}{t} \left(\frac{1}{\frac{1}{T_0^{\alpha_2}} - \alpha_1} - \frac{1}{\frac{1}{T_t^{\alpha_2}} - \alpha_1} \right).$$

We know that $\frac{\partial r}{\partial \alpha_1} < 0$ because

$$T_0^{\alpha_2} < T_t^{\alpha_2} \Rightarrow \frac{1}{T_0^{\alpha_2}} > \frac{1}{T_t^{\alpha_2}} \Rightarrow \frac{1}{T_0^{\alpha_2}} - \alpha_1 > \frac{1}{T_t^{\alpha_2}} - \alpha_1 \Rightarrow \frac{1}{\frac{1}{T_0^{\alpha_2}} - \alpha_1} < \frac{1}{\frac{1}{T_t^{\alpha_2}} - \alpha_1}.$$

Appendix B. Proof that the Climate Beta Can Theoretically Be Positive or Negative

Dietz et al. (2018) defined the climate beta as “the elasticity of the net benefit of the investment with respect to a change in aggregate consumption.” Mathematically, Deitz et al. (2018) and Lemoine (2021) define climate beta as the covariance between consumption per capita without the greenhouse gas emission perturbation (i.e., reference consumption), though net of damages and adaptation and its costs, and the change in damages from this perturbation divided by the variance of reference consumption.¹⁵⁰ Following Dietz et al. (2018)’s notation, I find that

$$\beta_t = \frac{\text{cov}[\ln c_t^{REF}, \ln B_t]}{\text{var}[\ln c_t^{REF}]} \\ = \frac{\text{cov}[\ln\{(1 - s_t)(1 - D_t^{REF})Y_t^{REF}\}, \ln\{(1 - s_t)(1 - D_t^{PERT})Y_t^{PERT} - (1 - s_t)(1 - D_t^{REF})Y_t^{REF}\}]}{\text{var}[\ln\{(1 - s_t)(1 - D_t^{REF})Y_t^{REF}\}]}$$

where adaptation cost is already netted from income. If we assume that the savings rate is a scalar and recognize that $\ln(ab) = \ln(a) + \ln(b)$ then

$$\beta_t = \frac{\text{cov}[\ln\{(1 - D_t^{REF})Y_t^{REF}\}, \ln\{(1 - D_t^{PERT})Y_t^{PERT} - (1 - D_t^{REF})Y_t^{REF}\}]}{\text{var}[\ln\{(1 - D_t^{REF})Y_t^{REF}\}]}$$

by covariance and variance properties. Since the denominator must be positive, beta has the same sign as the numerator

$$\text{cov}[\ln\{(1 - D_t^{REF})Y_t^{REF}\}, \ln\{(1 - D_t^{PERT})Y_t^{PERT} - (1 - D_t^{REF})Y_t^{REF}\}].$$

This also implies that the correlation between marginal damages and consumption per capita net of climate damages and abatement and its costs has the same sign. Again, by the properties of natural logs and covariances, the implies that

$$\text{cov}[\ln\{1 - D_t^{REF}\} + \ln\{Y_t^{REF}\}, \ln\{(1 - D_t^{PERT})Y_t^{PERT} - (1 - D_t^{REF})Y_t^{REF}\}],$$

such that

$$\text{cov}[\ln\{1 - D_t^{REF}\}, \ln\{(1 - D_t^{PERT})Y_t^{PERT} - (1 - D_t^{REF})Y_t^{REF}\}] \\ + \text{cov}[\ln\{Y_t^{REF}\}, \ln\{(1 - D_t^{PERT})Y_t^{PERT} - (1 - D_t^{REF})Y_t^{REF}\}].$$

Note that the first component is negative and the second component is positive, such that they move in opposing directions. This is similar to Lemoine (2021) who splits the insurance premium into damage scaling and growth insurance components.¹⁵¹ This indicates that the dynamic climate beta can be negative or positive.

¹⁵⁰ Dietz et al. (2018), *supra* note 64, at 269; Lemoine (2021), *supra* note 65, at 34.

¹⁵¹ Lemoine (2021), *supra* note 65, at 35–37.

A way to simplify the climate beta is recognize that the denominator can also be rewritten using $\ln(ab) = \ln(a) + \ln(b)$ and the variance properties, such that

$$\begin{aligned}\text{var}[\ln\{(1 - D_t^{REF})Y_t^{REF}\}] &= \text{var}[\ln\{(1 - D_t^{REF})\} + \ln\{Y_t^{REF}\}] \\ &= \text{var}[\ln\{(1 - D_t^{REF})\}] + \text{var}[\ln\{Y_t^{REF}\}] + 2\text{cov}[\ln\{1 - D_t^{REF}\}, \ln\{Y_t^{REF}\}].\end{aligned}$$

Therefore, climate beta can be rewritten as

$$\begin{aligned}\beta_t &= \frac{\text{cov}[\ln\{1 - D_t^{REF}\}, \ln\{(1 - D_t^{PERT})Y_t^{PERT} - (1 - D_t^{REF})Y_t^{REF}\}]}{\text{var}[\ln\{(1 - D_t^{REF})\}] + \text{var}[\ln\{Y_t^{REF}\}] + 2\text{cov}[\ln\{1 - D_t^{REF}\}, \ln\{Y_t^{REF}\}]} \\ &\quad + \frac{\text{cov}[\ln\{Y_t^{REF}\}, \ln\{(1 - D_t^{PERT})Y_t^{PERT} - (1 - D_t^{REF})Y_t^{REF}\}]}{\text{var}[\ln\{(1 - D_t^{REF})\}] + \text{var}[\ln\{Y_t^{REF}\}] + 2\text{cov}[\ln\{1 - D_t^{REF}\}, \ln\{Y_t^{REF}\}]}.\end{aligned}$$

Since gross income before and after the emissions perturbation is the same, then we can further simplify this expression to

$$\begin{aligned}\beta_t &= \frac{\text{cov}[\ln\{1 - D_t^{REF}\}, \ln\{[(1 - D_t^{PERT}) - (1 - D_t^{REF})]Y_t^{REF}\}]}{\text{var}[\ln\{(1 - D_t^{REF})\}] + \text{var}[\ln\{Y_t^{REF}\}] + 2\text{cov}[\ln\{1 - D_t^{REF}\}, \ln\{Y_t^{REF}\}]} \\ &\quad + \frac{\text{cov}[\ln\{Y_t^{REF}\}, \ln\{[(1 - D_t^{PERT}) - (1 - D_t^{REF})]Y_t^{REF}\}]}{\text{var}[\ln\{(1 - D_t^{REF})\}] + \text{var}[\ln\{Y_t^{REF}\}] + 2\text{cov}[\ln\{1 - D_t^{REF}\}, \ln\{Y_t^{REF}\}]},\end{aligned}$$

which we will simplify by substituting in expressions

$$\begin{aligned}\beta_t &= \frac{\text{cov}[\phi_t, \Delta_t] + \text{cov}[\pi_t, \Delta_t]}{\text{var}[\phi_t] + \text{var}[\pi_t] + 2\text{cov}[\phi_t, \pi_t]} \\ &= \frac{\text{cov}[\phi_t, \Delta_t]}{\text{var}[\phi_t] + \text{var}[\pi_t] + 2\text{cov}[\phi_t, \pi_t]} + \frac{\text{cov}[\pi_t, \Delta_t]}{\text{var}[\phi_t] + \text{var}[\pi_t] + 2\text{cov}[\phi_t, \pi_t]}\end{aligned}$$

Since correlation is related to covariance, such that $\text{COV}(X, Y) = \rho_{XY}\sigma_X\sigma_Y$, then we can rewrite these expressions as

$$\beta_t = \frac{\rho_{\phi_t, \Delta_t}\sigma_{\phi_t}\sigma_{\Delta_t}}{\sigma_{\phi_t}^2 + \sigma_{\pi_t}^2 + 2\rho_{\phi_t, \pi_t}\sigma_{\phi_t}\sigma_{\pi_t}} + \frac{\rho_{\pi_t, \Delta_t}\sigma_{\pi_t}\sigma_{\Delta_t}}{\sigma_{\phi_t}^2 + \sigma_{\pi_t}^2 + 2\rho_{\phi_t, \pi_t}\sigma_{\phi_t}\sigma_{\pi_t}}$$

where $\rho_{\phi_t, \Delta_t} < 0$ and $\rho_{\pi_t, \Delta_t} > 0$ because: (1) an increase in reference damages decreases “one minus the damage rate” and increases marginal damages as the damage function is increasing at an increasing rate in temperature; and (2) an increase in reference gross income increases marginal damages. The denominator is positive, as noted earlier, though the sign of ρ_{ϕ_t, π_t} is not clear.

Appendix C. Proof that the Climate Beta Decreases with an Increase in Damage Variance when the Climate Beta Is Positive

We take the derivate of the climate beta with respect to the standard deviation corresponding to damages, such that

$$\frac{\partial \beta_t}{\partial \sigma_{\phi_t}} = \frac{\partial [\rho_{\phi_t \Delta_t} \sigma_{\phi_t} + \rho_{\pi_t, \Delta_t} \sigma_{\pi_t}] \left[\frac{\sigma_{\Delta_t}}{\sigma_{\phi_t}^2 + \sigma_{\pi_t}^2 + 2\rho_{\phi_t \pi_t} \sigma_{\phi_t} \sigma_{\pi_t}} \right]}{\partial \sigma_{\phi_t}}.$$

Therefore,

$$\begin{aligned} \frac{\partial \beta_t}{\partial \sigma_{\phi_t}} = & \rho_{\phi_t \Delta_t} \left[\frac{\sigma_{\Delta_t}}{\sigma_{\phi_t}^2 + \sigma_{\pi_t}^2 + 2\rho_{\phi_t \pi_t} \sigma_{\phi_t} \sigma_{\pi_t}} \right] \\ & - 2\sigma_{\phi_t} [\rho_{\phi_t \Delta_t} \sigma_{\phi_t} + \rho_{\pi_t, \Delta_t} \sigma_{\pi_t}] \left[\frac{\sigma_{\Delta_t}}{(\sigma_{\phi_t}^2 + \sigma_{\pi_t}^2 + 2\rho_{\phi_t \pi_t} \sigma_{\phi_t} \sigma_{\pi_t})^2} \right], \end{aligned}$$

which simplifies to

$$\frac{\partial \beta_t}{\partial \sigma_{\phi_t}} = \frac{\rho_{\phi_t \Delta_t} - 2\sigma_{\phi_t} \beta_t}{\sigma_{\phi_t}^2 + \sigma_{\pi_t}^2 + 2\rho_{\phi_t \pi_t} \sigma_{\phi_t} \sigma_{\pi_t}}.$$

Since the denominator is positive, as noted in Appendix B, and standard deviations are non-negative, the first order condition is negative when beta is positive as in the EPA case, as $\rho_{\phi_t \Delta_t} < 0$.