Rolling the DICE on Environmental Regulations: A Close Look at the Social Cost of Methane and Nitrous Oxide

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Abstract

The U.S. Environmental Protection Agency utilizes three statistical models to quantify the social cost of carbon (SCC) and has also tried to quantify the costs of other greenhouse gas emissions, including methane and nitrous oxide. It then uses the results of these models, which artificially inflate the dollar value of abated GHG emissions, to justify costly global warming regulations. Previous Heritage Foundation research found that two of these models are far too sensitive to reasonable changes in assumptions for reliable use in policymaking. This study examines the social cost of methane (SCM) and the social cost of nitrous oxide (SCN$_2$O) as determined by the DICE model and finds that the EPA's estimates of these statistics are just as unreliable as its SCC estimates. The next EPA Administrator should initiate a rulemaking process that eliminates from EPA cost-benefit analysis of regulatory actions any use of estimates of the social cost of greenhouse gas emissions until such time as more accurate and reliable models of those costs can be developed.

During his two terms in office, President Barack Obama claimed that global warming is an urgent problem and implemented costly policies in an effort to mitigate climate change.[1] This includes not only very public proposals like the Clean Power Plan and Paris Protocol, but also regulatory measures that are profound in their impact but less visible to the public. Chief among these are Environmental Protection Agency (EPA) estimates of the social cost of carbon (SCC); the social cost of methane (SCM); and the social cost of nitrous oxide (SCN$_2$O), which have artificially inflated estimated benefits from energy and climate regulations.

KEY POINTS

- The EPA uses unreliable estimates of the social cost of carbon (SCC); the social cost of methane (SCM); and the social cost of nitrous oxide (SCN$_2$O) as benchmarks for regulatory impact analysis of energy and global warming policies.

- The integrated assessment models that the EPA uses are far too sensitive to assumptions to be used in devising economic regulations.

- The DICE model is based on an extremely unrealistic time horizon that sums damages over the course of 300 years.

- Current assumptions about the Earth's sensitivity to carbon dioxide emissions used by the EPA to estimate the SCM and SCN$_2$O are based on outdated research. More recent studies regarding equilibrium climate sensitivity (ECS) distributions (CO$_2$'s temperature impact) estimate significantly lower probabilities of extreme global warming.

- Updating the ECS distribution, as well as using the OMB discount-rate guidance that the EPA ignored, could reduce SCM and SCN$_2$O estimates by over 80 percent.

The EPA defines these "social cost" metrics as the accumulated economic damages over the course of the next 300 years that are associated with the emission of one ton of the respective chemicals in any given year.[2] A high cost for carbon dioxide, methane, or nitrous oxides emissions would make regulations limiting or reducing these emissions appear like a better investment and, conversely, activities that cause emissions to appear more harmful and less desirable.

Three statistical models are used by the EPA to estimate these metrics: the DICE (Dynamic Integrated Climate-Economy) model; the FUND (Climate Framework for Integrated Climate-Economy) model; and the PAGE (Policy Analysis of the Greenhouse Effect) model.[34] In earlier research, we looked at both the DICE and the FUND models' estimates of the social cost of carbon.[5] In this study, we provide a close examination of the DICE model regarding the SCM and SCN_2O.

As found in previous research, the DICE model is far too sensitive to assumptions to have the capacity to be able to provide meaningful or legitimate policy advice. The next EPA Administrator should therefore eliminate from the agency's cost-benefit analysis of regulatory actions any use of estimates of the social cost of greenhouse gas emissions until such time as more accurate and reliable models of those costs can be developed.

The DICE Model and Its Shortcomings

William Nordhaus has developed various versions of his DICE model over the past two decades. The version used by the EPA employs five different scenarios regarding projections of economic growth, population growth, CO_2 emissions, and other factors.

Through a series of equations representing economic and environmental activity as well as a damage function, the DICE model generates its estimates via Monte Carlo simulation. One of the primary inputs into the damage function is the projected rise in the sea level due to a variety of factors including melting of ice caps and thermal expansion from temperature increases.[6] From this damage function, the SCM and SCN_2O are estimated. The EPA has used the average value of these estimates as the primary point estimates of these "social costs."[7]

1. See, for example, transcript, "Press Conference by the President," The White House, November 3, 2010, http://www.whitehouse.gov/the-press-office/2010/11/03/press-conference-president (accessed March 11, 2014), and Barack Obama, "Remarks by the President in State of the Union Address," January 20, 2015, https://www.whitehouse.gov/the-press-office/2015/01/20/remarks-president-state-union-address-january-20-2015 (accessed January 7, 2017).

2. The official definition of the social cost of carbon is the economic damages per metric ton of CO_2 emissions. For further discussion, see Fact Sheet, "Social Cost of Carbon," U.S. Environmental Protection Agency, December 2015, https://www3.epa.gov/climatechange/Downloads/EPAactivities/social-cost-carbon.pdf (accessed January 7, 2017).

3. For the DICE model, see William D. Nordhaus, "RICE and DICE Models of Economics of Climate Change," Yale University, November 2006, http://www.econ.yale.edu/~nordhaus/homepage/dicemodels.htm (accessed November 6, 2013). For the FUND model, see "FUND—Climate Framework for Uncertainty, Negotiation and Distribution," http://www.fund-model.org/ (accessed November 6, 2013). For the PAGE model, see MIT Center for Collective Intelligence, Climate CoLab, "PAGE," http://climatecolab.org/resources/-/wiki/Main/PAGE (accessed January 8, 2017).

4. U.S. Interagency Working Group on Social Cost of Carbon, "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866," May 2013, revised November 2013, http://www.whitehouse.gov/sites/default/files/omb/assets/inforeg/technical-update-social-cost-of-carbon-for-regulator-impact-analysis.pdf (accessed November 6, 2013).

5. David Kreutzer and Kevin Dayaratna, "Scrutinizing the Social Cost of Carbon: Comment to the Energy Department," The Daily Signal, September 16, 2013, http://blog.heritage.org/2013/09/16/scrutinizing-the-social-cost-of-carbon-comment-to-the-energy-department/ (accessed January 8, 2017); Kevin Dayaratna and David Kreutzer, "Building on Quicksand: The Social Cost of Carbon," The Daily Signal, February 12, 2014, http://blog.heritage.org/2014/02/12/building-quicksand-social-cost-carbon/ (accessed January 8, 2017); Kevin D. Dayaratna and David W. Kreutzer, "Loaded DICE: An EPA Model Not Ready for the Big Game," Heritage Foundation *Backgrounder* No. 2860, November 21, 2013, http://www.heritage.org/research/reports/2013/11/loaded-dice-an-epa-model-not-ready-for-the-big-game; Kevin D. Dayaratna and David W. Kreutzer, "Unfounded FUND: Yet another EPA Model Not Ready for the Big Game," Heritage Foundation *Backgrounder* No. 2897, April 29, 2014, http://www.heritage.org/research/reports/2014/04/unfounded-fund-yet-another-epa-model-not-ready-for-the-big-game; Kevin Dayaratna and David Kreutzer, "Social Cost of Carbon Statistical Modeling Is Smoke and Mirrors," *Natural Gas and Electricity*, Vol. 30, Issue 12 (July 2014), pp. 7–11.

6. U.S. Office of Management and Budget, "Regulatory Analysis," Circular A-4, September 17, 2003, http://www.whitehouse.gov/omb/circulars_a004_a-4/ (accessed September 14, 2013); Paul C. "Chip" Knappenberger, "An Example of the Abuse of the Social Cost of Carbon," Cato Institute, August 23, 2013, http://www.cato.org/blog/example-abuse-social-cost-carbon (accessed September 14, 2013).

7. William D. Nordhaus, "The 'DICE' Model: Background and Structure of a Dynamic Integrated Climate–Economy Model of the Economics of Global Warming," Cowles Foundation for Research in Economics at Yale University, *Discussion Paper* No. 1009, February 1992, http://cowles.yale.edu/sites/default/files/files/pub/d10/d1009.pdf (accessed January 8, 2017). The EPA provided the authors with the MATLAB code to run the recent version of DICE used in this analysis but is not responsible for our results.

As with any model, however, the DICE model is dependent on a series of assumptions. These assumptions include a discount rate, a time horizon, and specification of an equilibrium climate sensitivity (ECS) distribution. In earlier research, we examined the DICE model by performing a sensitivity analysis with respect to changes in these assumptions. We concluded that the model is not a dependable tool for regulatory use regarding carbon dioxide.[8] In this study, we take a closer look at the impact of the choice of ECS distributions in the DICE model's estimates of SCM and SCN$_2$O.

Assumptions Made in the DICE Model

Before looking at the impact of the ECS distribution, we first review a number of assumptions made in the DICE model as well as other statistical models used to estimate the SCM and SCN$_2$O.

Discount Rate. Those of us who are alive today can take many actions that would be expected to provide benefits for those who will live decades or centuries from now. For example, we could pay down the national debt, increase investment in any number of industries, or simply save more in order to leave a larger bequest to our heirs.

The rationale for the EPA's economic regulations that employ the DICE SCC estimates is that altering CO$_2$, methane, and nitrous oxide emissions today is a form of investment that provides benefits in the future.[9] As with any investment, however, the future benefits need to be compared to the value of alternative investments and not just to the plain dollar value of current costs. The tool for making that comparison is discounting, and the choice of discount rate is critical both to correctly comparing the costs and benefits of climate policy and to accurately estimating the SCC.

That discount rate should be one that reflects the best alternative return available, not the worst. As Cass Sunstein and David Weisbach have written, "If we are going to increase the amount we leave for the future, it is incumbent on us not to do [so] in a way that wastes resources."[10] Investment in firms listed on the New York Stock Exchange has returned earnings of nearly 7 percent per year (after accounting for inflation) over the past two centuries. After adjusting for the impact of corporate taxes, the social rate of return on the New York Stock Exchange rises to more than 7.5 percent.[11] Though there is no guarantee that this rate of return will continue for centuries into the future, it is a reasonable benchmark.

In fact, the Office of Management and Budget (OMB) stipulates that a 7 percent discount rate be used as part of this type of cost-benefit analysis along with the 3 percent discount rate used by the EPA. Other discount rates can also be used when justified.[12] Researchers at the EPA have ignored the OMB guidance and have estimated the SCM and SCN$_2$O using only 2.5 percent, 3 percent, and 5 percent discount rates.[13] To better assess the model's sensitivity, we estimated these metrics using a 7 percent discount rate, as we did in our past analysis of both the DICE model and the FUND model.[14]

Time Horizon. As noted, the DICE model attempts to forecast economic damages years into

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8.   Kreutzer and Dayaratna, "Scrutinizing the Social Cost of Carbon"; Dayaratna and Kreutzer, "Building on Quicksand"; Dayaratna and Kreutzer, "Loaded DICE"; Dayaratna and Kreutzer, "Social Cost of Carbon Statistical Modeling Is Smoke and Mirrors."

9.   It should be noted that the future impacts of cutting CO$_2$ are so uncertain as to be ambiguous even regarding sign. That is, it may well be that some future generations could be made better off with more current CO$_2$ emissions, which implies that the investment should take the form of subsidizing CO$_2$ emissions. See, for example, Dayaratna and Kreutzer, "Unfounded FUND."

10. Cass R. Sunstein and David A. Weisbach, "Climate Change and Discounting the Future: A Guide for the Perplexed," Harvard Law School Program on Risk Regulation *Research Paper* No. 08-12, Harvard Law School Public Law and Legal Theory *Research Paper* No. 08-20, and Reg-Markets Center *Working Paper* No. 08-19, August 12, 2008, p. 26, http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1223448 (accessed January 8, 2017).

11. David W. Kreutzer, "Discounting Climate Costs," Heritage Foundation *Issue Brief* No. 4575, June 16, 2016, http://www.heritage.org/research/reports/2016/06/discounting-climate-costs.

12. U.S. Office of Management and Budget, "Regulatory Analysis"; Knappenberger, "An Example of the Abuse of the Social Cost of Carbon."

13. Alex L. Marten, Elizabeth A. Kopits, Charles W. Griffiths, Stephen C. Newbold, and Ann Wolverton, "Incremental CH$_4$ and N$_2$O Mitigation Benefits Consistent with the US Government's SC-CO$_2$ Estimates," *Climate Policy*, Vol. 15, Issue 2 (2015), pp. 272–298.

14. Kreutzer and Dayaratna, "Scrutinizing the Social Cost of Carbon"; Dayaratna and Kreutzer, "Building on Quicksand"; Dayaratna and Kreutzer, "Loaded DICE"; Dayaratna and Kreutzer, "Unfounded FUND"; Dayaratna and Kreutzer, "Social Cost of Carbon Statistical Modeling Is Smoke and Mirrors"; Kevin Dayaratna, Ross McKitrick, and David Kreutzer, "Empirically-Constrained Climate Sensitivity and the Social Cost of Carbon," Draft for Comments, April 5, 2016, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=2759505 (accessed January 8, 2017).

TABLE 1

Associated Probabilities of Three ECS Distributions from the Peer-Reviewed Literature

Probability of Temperature Exceeding ...	Outdated Roe-Baker (2007) Distribution	Otto et al. (2013) Distribution	Lewis (2013) Distribution
1.5°C	0.987	0.826	0.691
2.0°C	0.872	0.497	0.111
2.5°C	0.679	0.257	0.01
3.5°C	0.369	0.075	< 0.001
4.5°C	0.205	0.029	< 0.001
5.5°C	0.12	0.015	< 0.001
6.5°C	0.071	0.009	< 0.001

SOURCE: Authors' calculations based on Gerard Roe and Marcia Baker, "Why Is Climate Sensitivity So Unpredictable?" *Science*, Vol. 318, No. 5850 (October 2007), pp. 629–632; Nicholas Lewis, "An Objective Bayesian Improved Approach for Applying Optimal Fingerprint Techniques to Estimate Climate Sensitivity," *Journal of Climate*, Vol. 26, No. 19 (October 2013), pp. 7414–7429; and Alexander Otto et al., "Energy Budget Constraints on Climate Response," *Nature Geoscience*, Vol. 6, No. 6 (June 2013), pp. 415–416.

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the future, but however interesting three-century forecasts may be in academia, they strain credibility when moving to the real world of policy implementation. It is difficult enough to forecast several decades, let alone centuries, into the future. In our previous research, we examined the impact of truncating the time horizon at a still-ambitious end year one and a half centuries from the present rather than the EPA's chosen time frame of 300 years from now.[15]

Equilibrium Climate Sensitivity. Global warming activists, including members of the Obama Administration, consistently argue that global warming is indisputably occurring and that the Earth is warming at catastrophic rates.[16] Although a variety of studies in the peer-reviewed literature suggest that global warming is occurring, there is considerable uncertainty regarding the critical question: the magnitude of the warming, especially projected for three centuries.[17]

Equilibrium climate sensitivity distributions quantify this uncertainty by providing a distribution of values of the Earth's temperature changes in response to a doubling of carbon dioxide emissions. The DICE model utilizes an ECS distribution to simulate temperatures for future years. However, the EPA used an ECS distribution published by Gerard Roe and Marcia Baker in *Science* nearly a decade ago.[18] A close look at this ECS distribution clearly suggests significantly higher probabilities of extreme global warming compared to more up-to-date distributions.

Table 1 contains the probabilities associated with the outdated 2007 Roe–Baker distribution as well as two

15.   Kreutzer and Dayaratna, "Scrutinizing the Social Cost of Carbon"; Dayaratna and Kreutzer, "Building on Quicksand"; Dayaratna and Kreutzer, "Loaded DICE"; Dayaratna and Kreutzer, "Unfounded FUND."

16.   Barack Obama, "President Barack Obama's State of the Union Address," January 28, 2014, http://www.whitehouse.gov/the-press-office/2014/01/28/president-barack-obamas-state-union-address (accessed March 17, 2014); "President Barack Obama's State of the Union Address," January 20, 2015; Barack Obama, "Remarks of President Barack Obama—State of the Union Address as Delivered," January 13, 2016, https://www.whitehouse.gov/the-press-office/2016/01/12/remarks-president-barack-obama-%E2%80%93-prepared-delivery-state-union-address (accessed January 10, 2017).

17.   David W. Kreutzer, Nicolas D. Loris, Katie Tubb, and Kevin D. Dayaratna, "The State of Climate Science: No Justification for Extreme Policies," Heritage Foundation *Backgrounder* No. 3119, April 22, 2016, http://www.heritage.org/research/reports/2016/04/the-state-of-climate-science-no-justification-for-extreme-policies.

18.   Gerard H. Roe and Marcia B. Baker, "Why Is Climate Sensitivity So Unpredictable?" *Science*, Vol. 318, No. 5850 (October 26, 2007), pp. 629–632.

Probability Density Functions of Outdated-Roe Baker (2007), Otto et al (2013), and Lewis (2013) ECS Distributions
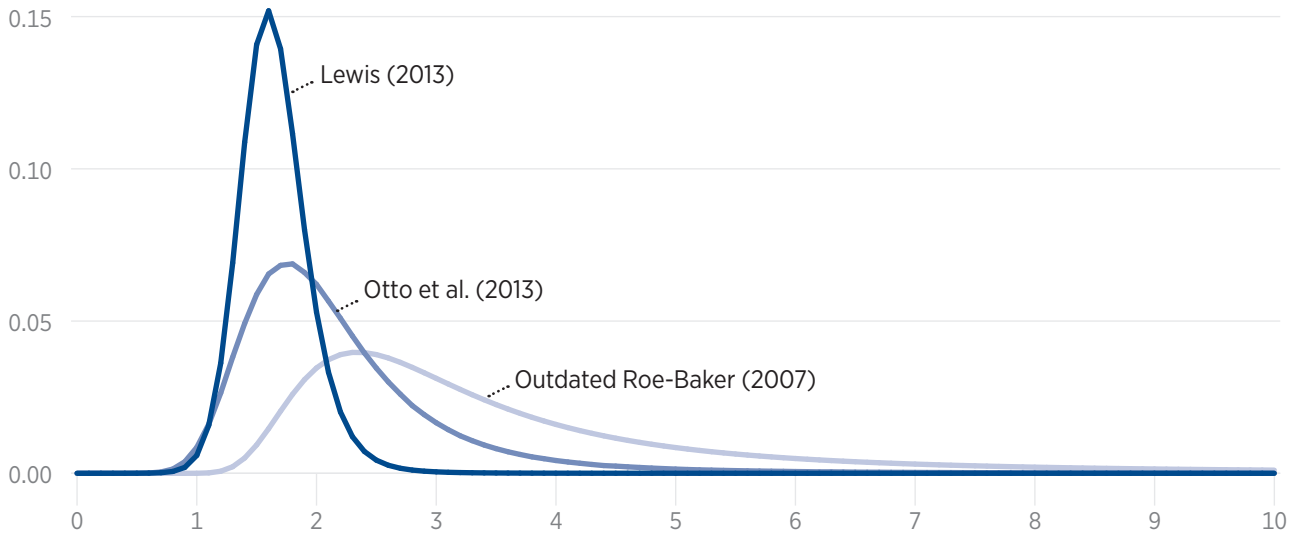
SOURCE: Authors' approximations based on Gerard Roe and Marcia Baker, "Why Is Climate Sensitivity So Unpredictable?" *Science*, Vol. 318, No. 5850 (October 2007), pp. 629–632; Nicholas Lewis, "An Objective Bayesian Improved Approach for Applying Optimal Fingerprint Techniques to Estimate Climate Sensitivity," *Journal of Climate*, Vol. 26, No. 19 (October 2013), pp. 7414–7429; and Alexander Otto et al., "Energy Budget Constraints on Climate Response," *Nature Geoscience*, Vol. 6, No. 6 (June 2013), pp. 415–416.

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more up-to-date distributions published by Alexander Otto et al. in 2013 and by Nicholas Lewis in 2013.[19]

Chart 1 provides visual representations of these three ECS distributions. As Chart 1 illustrates, the outdated 2007 Roe–Baker distribution has a much fatter right-tail probability than the more up-to-date 2013 Otto et al. and Lewis distributions. As a result, the Roe–Baker probability distribution predicts a significantly higher probability of extreme global warming than the other two probability distributions suggest. In other words, the severity of global warming under the outdated Roe–Baker distribution used by the EPA is grossly overstated with respect to the other two distributions.

Just like the SCC, the SCM and SCN_2O, as estimated by the EPA, are based on the evaluation of an arbitrarily chosen damage function of sea level rise and temperature change. Two of the primary causes behind sea level rise are thermal expansion, induced by warming of the oceans, and the melting of land-based ice. Since more up-to-date ECS distributions estimate lower probabilities of extreme global warming, it makes sense that the more recent distributions suggest lower sea level rise and therefore reduced SCC estimates. We examined the DICE model estimates of the SCM and SCN_2O using more up-to-date ECS distributions as well as the 7 percent discount rates mandated by the OMB.

The following two tables show how sensitive the DICE model is both to updating the ECS distribution and to employing the 7 percent discount stipulated in the OMB's guidance document.[20]

19. Nicholas Lewis, "An Objective Bayesian Improved Approach for Applying Optimal Fingerprint Techniques to Estimate Climate Sensitivity," *Journal of Climate*, Vol. 26, No. 19 (October 2013), pp. 7414–7429, http://journals.ametsoc.org/doi/pdf/10.1175/JCLI-D-12-00473.1 (accessed January 8, 2017); Alexander Otto, Friedericke E. L. Otto, Olivier Boucher, John Church, Gabi Hegerl, Piers M. Forster, Nathan P. Gillett, Jonathan Gregory, Gregory C. Johnson, Reto Knutti, Nicholas Lewis, Ulrike Lohmann, Jochem Marotzke, Gunnar Myhre, Drew Shindell, Bjorn Stevens, and Myles R. Allen, letter to the editor, "Energy Budget Constraints on Climate Response," *Nature Geoscience*, Vol. 6, No. 6 (June 2013), pp. 415–416.

20. For a more detailed discussion, see the Appendix.

TABLE 2

Social Cost of Methane, 2020

ECS Distribution	3%	7%
Roe-Baker	$932.08	$270.04
Otto et al.	$540.67	$184.01
Lewis	$360.33	$138.93

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 3

Social Cost of N₂O, 2020

ECS Distribution	3%	7%
Roe-Baker	$12,632.40	$1,882.21
Otto et al.	$7,570.67	$1,295.90
Lewis	$5,175.93	$988.68

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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Using the Roe–Baker distribution and only the 3 percent discount rate, the DICE model calculates a $932.08 SCM for the year 2020. However, using the more up-to-date distribution from Lewis and the 7 percent discount rate, the DICE model calculates a $138.93 SCM. Combined, these two reasonable changes cause the calculated value of the SCM to drop by 85 percent.

We notice a similar phenomenon with the social cost of nitrous oxide. In particular, doing the same substitution to calculate the SCN_2O produces an even larger drop in the calculated value for 2020. In this case, the SCN_2O drops 92 percent when using the Lewis ECS distribution and the 7 percent discount rate.

What is particularly interesting about these results is how the distributional properties of the SCM and SCN_2O change as a result of alterations in the ECS distribution and the discount rate. In particular, when based on more up-to-date ECS distributions and higher discount rates, the distributions' probability masses become translated toward potential values that are notably lower than the EPA's estimates by as much as 60 percent. The distributions also appear to have lower standard deviations as a result of these changes.

These results signify not only great uncertainty about the EPA's estimates of the SCM and SCN_2O, but also the tremendous sensitivity of the DICE model. Though our focus in this paper is the DICE model's sensitivity to reasonable changes in two parameters (the ECS distribution and the discount rate), concerns about the accuracy of the DICE model go well beyond these sensitivities.[21]

Implications for the Environment

We ran the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC) to find the impact of theoretically eliminating methane and nitrous oxide emissions from the United States completely. The World Bank has estimated levels of CH_4 and N_2O emissions for the United States as well as for the entire world.[22] Assuming that the United States provides a constant fraction of these emissions over the rest of the century, Heritage Foundation simulations using the MAGICC model indicate that completely eliminating all methane emissions from the United States would result in a reduction of less than 0.03 degrees Celsius and an overall reduction of less than 0.27 centimeters in sea level rise. Eliminating all nitrous oxide concentrations from the United

21. For example, Robert Pindyck says that "IAM-based analyses of climate policy create a perception of knowledge and precision, but that perception is illusory and misleading." Robert Pindyck, "Climate Change Policy: What Do the Models Tell Us?" *Journal of Economic Literature*, September 2013, pp. 860–872. See also Anne E. Smith, David Harrison, and Meredith McPhail, *A Review of the Damage Functions Used in Estimating the Social Cost of Carbon*, prepared for the American Petroleum Institute by NERA Economic Consulting, February 20, 2014, https://www.afpm.org/WorkArea/DownloadAsset.aspx?id=4111 (accessed January 9, 2017).

22. University Corporation for Atmospheric Research, "MAGICC/SCENGEN," http://www.cgd.ucar.edu/cas/wigley/magicc/ (accessed January 9, 2017); The World Bank, "Nitrous Oxide Emissions (Thousand Metric Tons of CO2 Equivalent)," http://data.worldbank.org/indicator/EN.ATM. NOXE.KT.CE?view=chart (accessed January 9, 2017); The World Bank, "Methane Emissions (Kt of CO2 Equivalent)," http://data.worldbank.org/indicator/EN.ATM.METH.KT.CE (accessed January 9, 2017)

States would have an impact of less than 0.02 degrees Celsius on global temperatures and an impact of less than 0.17 centimeters on overall sea level rise.

Thus, given its sensitivity to reasonable changes in assumptions and the fact that regulatory policies implied by the model would have no meaningful impact on the climate, policymakers would be well advised to refrain from using the DICE model in devising regulations.

Conclusion

The integrated assessment models that the EPA uses to calculate the social costs of carbon dioxide, methane, and nitrous oxide are not legitimate for regulatory analysis. They are unsubstantiated tools that regulators can use to justify costly regulations or thwart new investments. Our results, in line with our previous work regarding the SCC, clearly demonstrate the DICE model's tremendous sensitivity to reasonable changes in assumptions for both the SCM and the SCN_2O. Estimates of sea level rise, a primary driver for climate change–related economic damages, also change considerably when the outdated Roe–Baker distribution used by the EPA is altered to reflect more up-to-date distributions.

The issues raised in this study are not the only problems associated with the DICE model. For example, as noted, the model is based on an extremely unrealistic time horizon that sums damages over the course of 300 years. Additionally the damage function used by the EPA in estimating these statistics is arbitrary and unjustified.

Given these issues, the DICE model, albeit an interesting academic exercise, is not nearly robust enough to serve as a meaningful statistical model for regulatory policy. Policymakers should therefore refrain from using these integrated assessment models in devising regulatory policy. Using these models would only mislead the public and their representatives as to the costs and benefits of regulations and government activities intended to counter global warming.

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Appendix

This appendix contains detailed results regarding means, standard deviations, and percentiles from our Monte Carlo simulations using the DICE model for a variety of choices of discount rates and ECS distributions. The following results are for the SCM.

TABLE 4

Average SCM Baseline, Using Outdated Roe-Baker (2007) ECS Distribution

Year	Discount rate: 2.5%	3%	5%	7%
2020	$1,227.26	$932.08	$438.26	$270.04
2025	$1,383.17	$1,061.31	$511.10	$318.73
2030	$1,575.94	$1,222.76	$605.03	$382.87
2035	$1,768.72	$1,384.22	$698.97	$447.02
2040	$2,001.04	$1,580.31	$815.72	$528.00
2045	$2,233.36	$1,776.40	$932.46	$608.99
2050	$2,505.54	$2,007.58	$1,072.59	$707.36

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 5

Average SCM–ECS Distribution Updated in Accordance with Otto et al. (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$690.74	$540.67	$280.38	$184.01
2025	$779.91	$616.30	$326.11	$215.99
2030	$891.79	$712.14	$385.78	$258.55
2035	$1,003.67	$807.98	$445.45	$301.12
2040	$1,139.32	$924.95	$519.72	$354.79
2045	$1,274.97	$1,041.92	$593.98	$408.47
2050	$1,434.50	$1,180.18	$683.01	$473.45

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 6

Average SCM–ECS Distribution Updated in Accordance with Lewis (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$450.06	$360.33	$201.53	$138.93
2025	$507.95	$410.41	$233.64	$162.23
2030	$581.79	$474.91	$276.18	$193.71
2035	$655.63	$539.40	$318.73	$225.19
2040	$745.51	$618.40	$371.76	$264.89
2045	$835.39	$697.41	$424.80	$304.60
2050	$941.08	$790.74	$488.24	$352.49

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 7

Average SCM Percentage Changes as a Result of Updating ECS Distribution in Accordance with Otto et al. (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	–43.72%	–41.99%	–36.02%	–31.86%
2025	–43.61%	–41.93%	–36.19%	–32.23%
2030	–43.41%	–41.76%	–36.24%	–32.47%
2035	–43.25%	–41.63%	–36.27%	–32.64%
2040	–43.06%	–41.47%	–36.29%	–32.80%
2045	–42.91%	–41.35%	–36.30%	–32.93%
2050	–42.75%	–41.21%	–36.32%	–33.07%

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 8

Average SCM Percentage Changes as a Result of Updating ECS Distribution in Accordance with Lewis (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	−63.33%	−61.34%	−54.02%	−48.55%
2025	−63.28%	−61.33%	−54.29%	−49.10%
2030	−63.08%	−61.16%	−54.35%	−49.41%
2035	−62.93%	−61.03%	−54.40%	−49.62%
2040	−62.74%	−60.87%	−54.42%	−49.83%
2045	−62.59%	−60.74%	−54.44%	−49.98%
2050	−62.44%	−60.61%	−54.48%	−50.17%

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 9

Average Standard Deviation SCM Baseline, Using Outdated Roe-Baker (2007) ECS distribution

Year	Discount rate: 2.5%	3%	5%	7%
2020	$619.27	$437.81	$159.97	$81.83
2025	$692.11	$495.22	$187.31	$98.02
2030	$779.71	$565.10	$221.91	$119.08
2035	$867.33	$635.00	$256.51	$140.14
2040	$971.05	$718.64	$299.36	$166.86
2045	$1,074.81	$802.30	$342.20	$193.58
2050	$1,194.08	$899.48	$393.51	$226.26

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 10

Average 2.5th Percentile SCM Baseline, Using Outdated Roe-Baker (2007) ECS Distribution

Year	Discount rate: 2.5%	3%	5%	7%
2020	$436.37	$346.47	$192.27	$132.76
2025	$492.64	$394.77	$222.77	$154.78
2030	$566.45	$458.79	$264.32	$185.26
2035	$640.26	$522.80	$305.86	$215.74
2040	$732.90	$603.78	$359.49	$255.57
2045	$825.54	$684.76	$413.13	$295.40
2050	$937.50	$783.28	$479.46	$345.16

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 11

Average 97.5th Percentile SCM Baseline, Using Outdated Roe-Baker (2007) ECS Distribution

Year	Discount rate: 2.5%	3%	5%	7%
2020	$2,832.95	$2,017.82	$782.88	$430.62
2025	$3,174.54	$2,288.24	$915.40	$511.85
2030	$3,599.38	$2,629.12	$1,089.37	$621.23
2035	$4,024.23	$2,969.99	$1,263.34	$730.62
2040	$4,538.79	$3,388.11	$1,484.88	$873.29
2045	$5,053.34	$3,806.22	$1,706.42	$1,015.96
2050	$5,653.77	$4,299.99	$1,976.87	$1,193.83

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 12

Average Standard Deviation SCM–ECS Distribution Updated in Accordance with Otto et al. (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$402.55	$294.79	$121.73	$67.94
2025	$452.69	$335.27	$142.59	$80.96
2030	$513.53	$384.88	$168.94	$97.77
2035	$574.39	$434.50	$195.30	$114.58
2040	$647.22	$494.41	$228.00	$135.83
2045	$720.08	$554.32	$260.70	$157.09
2050	$805.11	$624.80	$300.04	$183.08

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 13

Average 2.5th Percentile SCM–ECS Distribution Updated in Accordance with Otto et al. (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$249.25	$200.78	$117.37	$84.54
2025	$280.29	$228.00	$135.75	$98.44
2030	$320.77	$263.90	$160.74	$117.73
2035	$361.25	$299.80	$185.72	$137.02
2040	$410.39	$343.62	$216.70	$161.15
2045	$459.52	$387.44	$247.67	$185.28
2050	$517.06	$439.00	$284.51	$214.17

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 14

Average 97.5th Percentile SCM–ECS Distribution Updated in Accordance with Otto et al. (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$1,738.39	$1,302.49	$582.49	$346.00
2025	$1,958.45	$1,482.76	$680.36	$409.77
2030	$2,229.13	$1,706.80	$806.02	$493.49
2035	$2,499.81	$1,930.85	$931.69	$577.22
2040	$2,825.37	$2,202.52	$1,087.89	$683.08
2045	$3,150.94	$2,474.19	$1,244.08	$788.93
2050	$3,531.86	$2,794.31	$1,431.87	$917.95

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 15

Average Standard Deviation SCM–ECS Distribution Updated in Accordance with Lewis (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$127.78	$99.26	$48.87	$30.24
2025	$144.87	$113.59	$57.10	$35.74
2030	$165.84	$131.30	$67.51	$42.79
2035	$186.81	$149.01	$77.93	$49.83
2040	$212.21	$170.60	$90.88	$58.74
2045	$237.62	$192.19	$103.84	$67.65
2050	$267.62	$217.81	$119.45	$78.51

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 16

Average 2.5th Percentile SCM–ECS Distribution Updated in Accordance with Lewis (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$249.25	$200.78	$117.37	$84.54
2025	$280.29	$228.00	$135.75	$98.44
2030	$320.77	$263.90	$160.74	$117.73
2035	$361.25	$299.80	$185.72	$137.02
2040	$410.39	$343.62	$216.70	$161.15
2045	$459.52	$387.44	$247.67	$185.28
2050	$517.06	$439.00	$284.51	$214.17

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 17

Average 97.5th Percentile SCM–ECS Distribution Updated in Accordance with Lewis (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$753.10	$594.30	$313.25	$206.20
2025	$851.89	$678.46	$364.58	$242.15
2030	$975.71	$784.89	$431.25	$289.72
2035	$1,099.54	$891.32	$497.92	$337.29
2040	$1,249.91	$1,021.35	$580.87	$397.24
2045	$1,400.27	$1,151.37	$663.82	$457.19
2050	$1,577.67	$1,305.41	$763.33	$529.76

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 18

Average SCN$_2$O Baseline, Using Outdated Roe-Baker (2007) ECS Distribution

Year	Discount rate: 2.5%	3%	5%	7%
2020	$19,116.22	$12,632.40	$3,923.03	$1,882.21
2025	$21,086.78	$14,086.24	$4,510.01	$2,203.82
2030	$23,361.58	$15,792.84	$5,233.08	$2,613.04
2035	$25,636.39	$17,499.43	$5,956.16	$3,022.27
2040	$28,213.42	$19,460.17	$6,819.11	$3,522.72
2045	$30,790.45	$21,420.91	$7,682.07	$4,023.18
2050	$33,660.88	$23,631.82	$8,685.32	$4,615.79

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 19

Average SCN$_2$O–ECS Distribution Updated in Accordance with Otto et al. (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$11,190.53	$7,570.67	$2,550.30	$1,295.90
2025	$12,367.28	$8,453.88	$2,928.60	$1,511.91
2030	$13,736.58	$9,498.15	$3,396.89	$1,787.72
2035	$15,105.88	$10,542.43	$3,865.19	$2,063.53
2040	$16,666.84	$11,748.25	$4,424.68	$2,400.25
2045	$18,227.80	$12,954.06	$4,984.17	$2,736.97
2050	$19,977.67	$14,320.57	$5,635.16	$3,134.86

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 20

Average SCN$_2$O–ECS Distribution Updated in Accordance with Lewis (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$7,511.37	$5,175.93	$1,859.94	$988.68
2025	$8,307.58	$5,782.36	$2,132.92	$1,149.92
2030	$9,239.93	$6,503.72	$2,472.69	$1,356.92
2035	$10,172.27	$7,225.09	$2,812.46	$1,563.92
2040	$11,238.98	$8,060.35	$3,218.45	$1,816.25
2045	$12,305.69	$8,895.61	$3,624.44	$2,068.59
2050	$13,505.47	$9,844.27	$4,096.38	$2,365.94

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 21

Average SCN$_2$O Percentage Changes as a Result of Updating ECS Distribution in Accordance with Otto et al. (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	–41.46%	–40.07%	–34.99%	–31.15%
2025	–41.35%	–39.98%	–35.06%	–31.40%
2030	–41.20%	–39.86%	–35.09%	–31.58%
2035	–41.08%	–39.76%	–35.11%	–31.72%
2040	–40.93%	–39.63%	–35.11%	–31.86%
2045	–40.80%	–39.53%	–35.12%	–31.97%
2050	–40.65%	–39.40%	–35.12%	–32.08%

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 22

Average SCN$_2$O Percentage Changes as a Result of Updating ECS Distribution in Accordance with Lewis, End Year 2300

Year	Discount rate: 2.5%	3%	5%	7%
2020	–60.71%	–59.03%	–52.59%	–47.47%
2025	–60.60%	–58.95%	–52.71%	–47.82%
2030	–60.45%	–58.82%	–52.75%	–48.07%
2035	–60.32%	–58.71%	–52.78%	–48.25%
2040	–60.16%	–58.58%	–52.80%	–48.44%
2045	–60.03%	–58.47%	–52.82%	–48.58%
2050	–59.88%	–58.34%	–52.84%	–48.74%

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 23

Average Standard Deviation SCN$_2$O Baseline, Using Outdated Roe-Baker (2007) ECS Distribution

Year	Discount rate: 2.5%	3%	5%	7%
2020	$9,512.32	$5,671.97	$1,376.98	$557.56
2025	$10,462.46	$6,306.67	$1,585.46	$659.57
2030	$11,561.25	$7,049.98	$1,839.64	$788.87
2035	$12,661.08	$7,794.25	$2,093.88	$918.19
2040	$13,919.38	$8,654.50	$2,395.77	$1,076.87
2045	$15,179.22	$9,516.29	$2,697.79	$1,235.56
2050	$16,606.59	$10,500.87	$3,046.93	$1,423.62

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 24

Average 2.5th Percentile SCN$_2$O Baseline, Using Outdated Roe-Baker (2007) ECS Distribution

Year	Discount rate: 2.5%	3%	5%	7%
2020	$7,380.88	$5,098.43	$1,847.05	$986.88
2025	$8,163.52	$5,695.66	$2,117.48	$1,147.16
2030	$9,080.70	$6,406.66	$2,454.39	$1,353.13
2035	$9,997.89	$7,117.67	$2,791.30	$1,559.11
2040	$11,047.73	$7,941.25	$3,194.00	$1,810.29
2045	$12,097.56	$8,764.83	$3,596.70	$2,061.48
2050	$13,278.58	$9,700.30	$4,064.74	$2,357.43

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 25

Average 97.5th Percentile SCN$_2$O Baseline, Using Outdated Roe-Baker (2007) ECS Distribution

Year	Discount rate: 2.5%	3%	5%	7%
2020	$39,891.86	$25,542.41	$7,038.60	$3,087.78
2025	$43,746.28	$28,341.05	$8,089.94	$3,630.76
2030	$48,114.75	$31,574.63	$9,376.13	$4,321.33
2035	$52,483.23	$34,808.20	$10,662.32	$5,011.90
2040	$57,339.19	$38,463.93	$12,187.40	$5,856.82
2045	$62,195.15	$42,119.65	$13,712.49	$6,701.73
2050	$67,489.57	$46,165.87	$15,468.36	$7,698.53

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 26

Average Standard Deviation SCN$_2$O–ECS Distribution Updated in Accordance with Otto et al. (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$5,924.79	$3,812.10	$1,060.19	$462.65
2025	$6,520.26	$4,243.28	$1,221.13	$545.16
2030	$7,200.07	$4,744.18	$1,417.73	$649.34
2035	$7,880.09	$5,245.18	$1,614.34	$753.52
2040	$8,643.80	$5,816.76	$1,848.72	$881.38
2045	$9,407.77	$6,388.48	$2,083.11	$1,009.25
2050	$10,251.10	$7,028.60	$2,355.52	$1,161.39

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 27

Average 2.5th Percentile SCN$_2$O–ECS Distribution Updated in Accordance with Otto et al. (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$4,237.01	$2,957.67	$1,119.10	$620.85
2025	$4,682.60	$3,302.32	$1,282.57	$721.29
2030	$5,205.98	$3,713.84	$1,487.19	$851.13
2035	$5,729.36	$4,125.35	$1,691.82	$980.97
2040	$6,326.82	$4,600.57	$1,935.15	$1,138.11
2045	$6,924.28	$5,075.80	$2,178.48	$1,295.26
2050	$7,594.82	$5,614.24	$2,460.23	$1,479.42

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 28

Average 97.5th Percentile SCN$_2$O–ECS Distribution Updated in Accordance with Otto et al. (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$26,524.94	$17,361.69	$5,176.13	$2,401.39
2025	$29,236.45	$19,347.96	$5,954.98	$2,818.26
2030	$32,353.46	$21,670.79	$6,912.45	$3,348.26
2035	$35,470.46	$23,993.63	$7,869.92	$3,878.27
2040	$38,987.55	$26,653.66	$9,011.87	$4,527.26
2045	$42,504.64	$29,313.69	$10,153.81	$5,176.26
2050	$46,404.05	$32,301.76	$11,480.35	$5,945.91

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 29

Average Standard Deviation SCN$_2$O–ECS Distribution Updated in Accordance with Lewis (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$2,043.41	$1,362.01	$429.95	$205.21
2025	$2,260.82	$1,522.51	$494.65	$240.31
2030	$2,512.91	$1,711.37	$573.94	$284.48
2035	$2,765.01	$1,900.22	$653.23	$328.65
2040	$3,053.08	$2,118.82	$748.30	$382.89
2045	$3,341.16	$2,337.43	$843.36	$437.12
2050	$3,665.34	$2,586.16	$954.57	$501.69

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 30

Average 2.5th Percentile SCN_2O–ECS Distribution Updated in Accordance with Lewis (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$4,237.01	$2,957.67	$1,119.10	$620.85
2025	$4,682.60	$3,302.32	$1,282.57	$721.29
2030	$5,205.98	$3,713.84	$1,487.19	$851.13
2035	$5,729.36	$4,125.35	$1,691.82	$980.97
2040	$6,326.82	$4,600.57	$1,935.15	$1,138.11
2045	$6,924.28	$5,075.80	$2,178.48	$1,295.26
2050	$7,594.82	$5,614.24	$2,460.23	$1,479.42

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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TABLE 31

Average 97.5th Percentile SCN_2O–ECS Distribution Updated in Accordance with Lewis (2013)

Year	Discount rate: 2.5%	3%	5%	7%
2020	$12,353.42	$8,382.91	$2,843.91	$1,446.41
2025	$13,665.96	$9,368.49	$3,266.71	$1,687.80
2030	$15,196.03	$10,535.11	$3,789.52	$1,995.19
2035	$16,726.11	$11,701.73	$4,312.32	$2,302.58
2040	$18,475.32	$13,052.00	$4,937.54	$2,677.96
2045	$20,224.54	$14,402.28	$5,562.77	$3,053.34
2050	$22,192.30	$15,937.18	$6,291.56	$3,497.41

SOURCE: Calculations based on Heritage Foundation simulation results using the DICE model.

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