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Thank you Chairman Rouda, Ranking Member James Comer, and members of the Subcommittees on Environment and Oversight for inviting me to speak today.

My name is Michael Greenstone, and I am the Milton Friedman Professor in Economics and Director of the Becker Friedman Institute and Energy Policy Institute at the University of Chicago. I also serve as co-director of the Climate Impact Lab, a multi-disciplinary collaboration of researchers working to quantify the long-term impacts of climate change. My own research focuses on estimating the costs and benefits of environmental quality, with a particular emphasis on the impacts of government regulations.

I appreciate the opportunity to speak with you today about the social cost of carbon, future damages stemming from federal inaction against climate change, and the federal government's ideal policy response. I will make several points today that I first summarize here:

1. The social cost of carbon (SCC) is the cost to society of polluting an additional ton of CO_2. The SCC enables regulators to account for potential benefits to society through lower carbon emissions and also points towards the optimal price on carbon required to address excess greenhouse gas emissions. The US government SCC was approximately \$50 per ton of CO_2 as of 2016, using a discount rate of 3%.

2. A smaller SCC of approximately \$1-\$7, which is used by the Trump administration, is based on two faulty sets of assumptions. First, it uses higher discount rates, which are likely inconsistent with the expected nature of real-life payoffs on climate mitigation. Second, it fails to account for damages incurred outside the US, and therefore discourages other countries from making CO_2 reductions that benefit United States citizens.

3. Following recommendations in 2017 from the National Academy of Sciences, an interdisciplinary team I co-direct, called the Climate Impact Lab (CIL), is calculating an updated, data-driven social cost of carbon. Our approach seeks to project changes in mortality, energy use, agricultural yields, labor productivity, and coastal vulnerability due to an additional ton of CO_2; and then monetize those costs to society.

4. The main CIL finding to date is that the increase in the global mortality rate due to climate change-induced temperature changes in 2100 is larger than the current mortality rate due to all infectious diseases. This elevated mortality risk equates to a *partial* social cost of $23.6 per metric ton of carbon emitted today. This result suggests that the federal government may be systematically undervaluing the social costs of CO_2 emissions: the mortality partial SCC we compute is ten times larger than the partial mortality cost underlying the Obama-era SCC, almost half as large as the entire Obama-era estimate, and three to twenty times *larger* than the Trump administration's estimate of the full social cost of carbon.

5. Given the scale of the climate challenge and the urgent need for resources to address other pressing social challenges, it is critical that policy aim to deliver the cheapest reductions in CO_2 emissions today and in the future. The surest way to achieve inexpensive reductions today is to price CO_2 emissions with a carbon tax or by implementing a cap-and-trade program. At the same time, new technologies offer the promise of even cheaper emissions reductions in the future, and there is a compelling case for increasing US government funding for energy research, development, and demonstration (RD&D). Since private firms have insufficient incentives to engage in "basic" energy RD&D, such funding would address this market failure.

I. Social Cost of Carbon

a. History

The United States boasts a long tradition of transparent regulation based on comparing costs and benefits. That tradition began in 1981 when President Ronald Reagan issued an executive order institutionalizing the idea that regulatory action should be implemented only in cases when "the potential benefits to society for the regulation outweigh the potential costs to society." This simple yet powerful idea fundamentally altered the way in which regulations were considered by both Democrats and Republicans.

Fast forward to 2007, when the Supreme Court ruled in Massachusetts vs. U.S. EPA[1] that the US Environmental Protection Agency (EPA) could not sidestep its authority to regulate the greenhouse gases that contribute to global climate change. The laws of the land mandated that in order for the EPA to regulate greenhouse gases, it had to perform a cost-benefit analysis on greenhouse gas emissions.

The social cost of carbon, or SCC, plays a critical role in this analysis. It represents the monetary cost of the damages caused by the release of an additional ton of carbon dioxide into the atmosphere. Simply put, it reflects the cost of climate change—accounting for the destruction of property from storms and floods, declining agricultural and labor productivity, elevated mortality rates, and so forth.

[1] Massachusetts v. Environmental Protection Agency, 549 U.S. 497 (2007).

Although the US needed to incorporate the SCC into its regulations, there was little consensus on how to estimate it. In 2008, the 9th Circuit Court of Appeals ruled[2] that the Department of Transportation needed to update its regulatory impact analysis for fuel economy rules with an estimate of the SCC. The court directed that, "while the record shows that there is a range of values, the value of carbon emissions reduction is certainly not zero." So, the Department of Energy, the Department of Transportation and EPA began to incorporate a variety of individually developed estimates of the SCC into their regulatory analyses. These estimates were derived from academic literature and ranged from zero—which they were instructed by the court to no longer use—to $159 per metric ton of carbon dioxide emitted.

To improve consistency in the government's use of the SCC, I, then the chief economist for President Obama's Council of Economic Advisors, along with Cass Sunstein, then the administrator of the White House Office of Information and Regulatory Affairs and now a professor at Harvard, assembled and co-led an interagency working group to determine one government-wide metric. The team consisted of the top economists, scientists and lawyers from four other offices in the Executive Office of the President and six federal agencies, including the EPA and the Departments of Agriculture, Commerce, Energy, Transportation and Treasury.

The process for developing the SCC took approximately a year and included an intense assessment of the best available peer-reviewed research, and significant debate and discussion amongst the team of climate scientists, economists, lawyers and other experts across the federal government. It also included a careful consideration of public comments on the interim values agencies had been using and an interim value determined by the interagency group. Ultimately, the interagency working group determined[3] a central estimate of $21 per metric ton. That estimate has since been revised to reflect scientific advances and as of 2016 was about $50.

b. National Academy of Sciences

To ensure that the next SCC update keeps up with the latest available science and economics, in 2015 the Office of Management and Budget directed the National Academies of Sciences (NAS) to help in providing advice on the pros and cons of potential approaches to future updates, informed by on-going public comments and the peer-reviewed literature. In 2017, the NAS released its recommendations[4] after a comprehensive assessment, for which I served as a reviewer. The NAS report identified important ways to take advantage of our improved understanding of the social and economic impacts of climate change. It proposed a new framework that strengthened the scientific basis, provided greater transparency, and improved characterization of the uncertainties of the estimates.

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[2] *Center for Biological Diversity v. National Highway Traffic Safety Administration,* 538 F. 3d 1172 (9th Cir. 2008).
[3] Interagency Working Group on Social Cost of Carbon, United States Government, *Technical Support Document: Social Cost of Carbon for Regulatory Impact Analysis Under Executive Order 12866.* (February 2010).
[4] National Academies of Sciences, Engineering, and Medicine, *Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide* (2017).

c. Obama Administration

Since its inception, the SCC has been used in roughly 150 federal regulations that cover energy efficiency, forest conservation, fuel-economy standards, and emissions performance standards. Indeed, in many cases the SCC was instrumental in passing these regulations, offering relevant agencies a reliable, transparent tool to calculate the full benefits the new rules would offer to society. All told, a recent paper calculated, federal regulations written to include the SCC in the US have more than $1 trillion of benefits.[5]

In addition, several states have utilized the SCC in their own climate-related policymaking, including California, Colorado, Illinois, New York and others.

- In California, air quality regulators are required by law to consider the social costs of emissions when conducting cost-benefit analyses for new rules.[6] The SCC has recently helped lawmakers weighing state fuel efficiency regulations and figured into assessments of the relative merits of high-speed rail and other major infrastructure projects.
- In Colorado, the state utilities commission is using the SCC in its cost-benefit analysis for energy planning.[7] The state's overall goal is to use the SCC to accelerate a transition from more-expensive assets to cheaper power.[8] For some utilities, that will mean investing in renewable energy rather than natural gas. For others, it will mean retiring coal-fired units early. Across the state, applying the SCC has allowed utilities to capture the full economic effects of various energy choices.
- My home state of Illinois passed a law in 2016 that created Zero Emissions Credits, or ZECs, which put a value on the carbon-free electricity generated not just by renewable energy but also by existing nuclear plants.[9] Illinois utilities are required to purchase ZECs, ensuring that nuclear and other generators receive compensation for producing zero-carbon power. The SCC was taken into account when setting the ZEC price.
- New York regulators have also incorporated the SCC into ZECs issued by the state.[9] As in Illinois, utilities must purchase ZECs, which improves the economics for nuclear generation in New York. State regulators are also considering a plan to use the SCC to set a "carbon charge" in wholesale electricity markets, which would effectively price carbon emissions across the power sector.

The impact of the SCC has also extended internationally. Canada and Mexico recently adopted the current US estimate as its own for use in energy and climate regulation. France, Germany, Norway, and the United Kingdom have all recently used their own SCC estimates in regulatory action.

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[5] Nordhaus, William D. "Revisiting the social cost of carbon." *Proceedings of the National Academy of Sciences* 114, no. 7 (2017): 1518-1523.
[6] California Senate Office of Research. *Social Cost of Carbon: Federal and California Activity*. Paul Jacobs. (2018).
[7] Colorado Senate Bill 19-236 (passed May 3, 2019).
[8] Best, Allen. "Colorado Considers Adding Social Cost of Carbon to Resource Planning Decisions." Energy News Network, (April 10, 2019).
[9] Nuclear Energy Institute. *Zero-Emission Credits* (2018).

d. Trump Administration

In March of 2017, President Trump's Executive Order 13783 disbanded the Interagency Working Group on Social Cost of Greenhouse Gases, withdrawing their official estimates of the SCC. In 2018, the EPA released a regulatory impact analysis for greenhouse gas emission guidelines which established a new SCC between $1 and $7.[10] These new estimates are an order of magnitude smaller than the previous central estimate of $50 for two main reasons, both of which merit individual attention.

First, the new estimates use a higher discount rate of 7% instead of 3%. Choosing an appropriate discount rate is essential in calculating the SCC, as it allows us to translate future environmental damages into their present value. If we choose a discount rate that is too low, then we will pay too much today for mitigation efforts. If we choose a discount rate that is too high, then we will impose higher costs on our children and grandchildren than we intend.

So, which is the right discount rate for regulations that reduce carbon emissions?

The answer from economics is straightforward—we are best off if we use an interest rate from an investment that pays off exactly when climate mitigation does. If the payoffs appear in boom years, like a diversified stock portfolio, we should use something like the average stock market return of 5.3%. But if the payoffs occur in lean years, like they do for US Treasury bonds, we should likely use a discount rate below 3%.

To understand why climate damages should have a low discount rate, let's consider US treasuries in more detail. Why does anyone hold Treasuries as an investment when its average return over the last 50 years is just 0.7 percent?[11] The answer is that, unlike many investments, the US government will still pay back the bond in bad times, and money received during a war or recession times is *more valuable* since we have less of it overall. In other words, society is willing to accept low *average* returns from investments that pay off in tough times when the value of additional income is especially high.

Following the same logic, the SCC merits a low discount rate if climate change includes the risk of recession-like or even war-like disruptions. When one considers the possibility of larger-than-expected temperature changes for a given change in emissions, sea level rise in short time periods, physical "tipping points", and human responses like mass migration, then the case for a low discount rate appears strong. This case is in many respects similar to purchasing life, fire, and other insurance policies that protect against major disruptive events.

The decline in global interest rates since the mid-1980s provides another reason to prefer low discount rates. Regulatory analysis since 2003 has often used a 3% discount rate because it was

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[10] U.S. Environmental Protection Agency Office of Air Quality Planning and Standards Health and Environmental Impact Division, *Regulatory Impact Analysis for the Proposed Emission Guidelines for Greenhouse Gas Emissions from Existing Electric Utility Generating Units; Revisions to Emission Guideline Implementing Regulations; Revisions to New Source Review Program* (August 2018).

[11] Real average annual return, 1968-2017. Annual 10-year Treasury returns and CPI inflation obtained from FRED, Federal Reserve Bank of St. Louis.

roughly equal to the real rate of return on long-term government debt at that time. However, forecasts from the Congressional Budget Office and the Blue Chip consensus imply that the real 10-year Treasury yield is now expected to be below 2 percent.[12] The broader point is that global interest rates have declined since the SCC was set and, even setting aside the risk characteristics of payoffs from climate mitigation investments, there is a solid case that the discount rates currently used to calculate the SCC may be too high.

Second, the new estimates only consider domestic benefits instead of global benefits. Although considering only the domestic impacts of climate change might appear to advance the interests of the US, my judgement is that it is likely to undermine US interests. This is because there is now a growing body of evidence that when the US accounts for the full global benefits of reducing our emissions, this incentivizes reciprocal climate policies in other countries, like China and India, that reduces their emissions which benefits the US.

An important example comes from five years ago. In June 2014 the US EPA proposed the Clean Power Plan: four months later, the US and China released a joint announcement on climate change, in which each country promised to further reduce emissions in order to "inject momentum into the global climate negotiations and inspire other countries to join in coming forward with ambitious actions".[13] Indeed, the Paris Climate Agreement followed where other countries made larger than expected pledged reductions.

Other periods are also instructive. The US failed to take action to reduce greenhouse gas emissions during the George W. Bush Administration and during these first three years of the Trump Administration. In both instances, these moves were justified by arguments that it made no sense for the US to cut emissions unilaterally and that other countries should cut first. Yet, both periods were characterized by little progress, and indeed many instances of backsliding, in reducing emissions globally.

I take away from these examples that the United States has a special role in global diplomacy in almost all issues, certainly including climate change, and that our leadership can produce demonstrable benefits for US citizens. Thus, my judgment is that the use of a SCC that only considers domestic benefits is very likely to deprive the United States of emissions reductions in the United States that would protect us from more virulent climate change. The importance of this dynamic is underscored by the fact that the US' share of global CO_2 emissions, depicted in Figure 1, is projected to remain at about 10% through the end of the century. Put plainly, a failure to account for global damages in the SCC is likely to be detrimental to our domestic interest.

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[12] Council of Economic Advisers, *Discounting for Public Policy: Theory and Recent Evidence on the Merits of Updating the Discount Rate* (2017).

[13] The White House Office of the Press Secretary, *"*U.S.-China Joint Announcement on Climate Change*"* (November 2014).

II. Future Consequences of Federal Inaction

a. Climate Impact Lab Overview

In order to fully anticipate the consequences of federal inaction to climate change, it is imperative to estimate the risks of this inaction using rigorous, evidence-based models. In addition, these models and their resulting SCC estimates can help inform the nature of regulations aimed at reducing CO_2 emissions and market-based policies for combatting climate change, such as cap and trade systems or a carbon tax. As the National Academy of Sciences reported, these models should be updated over time to take into account new data and so that they remain tethered to the frontier of scientific and economic understanding.

In the absence of federal leadership here, the Climate Impact Lab (CIL), a multi-disciplinary, multi-institution research collaboration where I am co-director, has taken the Academy's challenge head-on. The CIL includes over 20 climate scientists, economists, data engineers, and other experts from institutions including the University of Chicago; the University of California, Berkeley; Rutgers University, New Brunswick; and the Rhodium Group. We aim to produce the world's first empirically derived estimate of the social cost of carbon. Combining an immense body of historical data on social, economic and climate indicators with climate models, we develop projections of the long-term effect of a "high emissions" climate change scenario[14] in five core sectors – mortality, labor productivity, coastal vulnerability, energy, and agriculture – in each of about 25,000 local regions spanning the globe. These sector-specific projections are then monetized and aggregated across all regions to determine the cost which emitting an additional ton of carbon imposes on future society and the economy.

A critical part of our work is ensuring that the SCC generally, and our research more specifically, is easily accessible to policymakers. This summer, we convened the first of a series of meetings and events geared toward state policymakers. Our goals were twofold: 1) to offer a factual overview of how the SCC was being applied at the state level across the country, offering an insight into the policy's wide range of potential uses; and 2), to begin to create a network of policymakers who could draw on each other's expertise as they worked to incorporate the SCC into laws in their own state capitals. This work is ongoing and will gather pace as the CIL's full findings take shape.

b. Key CIL Findings

CIL's core findings to date have been in the mortality sector. Climate change has a demonstrable impact on mortality rates, as extreme temperatures, both hot and cold, affect health outcomes such as heat stroke and cardiovascular disease. Using data from forty countries and statistical methods to account for the benefits and costs of adaptation, we estimate the full mortality risk due to climate change to be an additional 85 deaths per 100,000 in 2100.[15] This increase in the

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[14] All discussed CIL projections follow the RCP8.5, or "high emissions", scenario from the IPCC's 2014 "Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change". Cambridge, United Kingdom: Cambridge University Press.

[15] Carleton, et al. "Valuing the global mortality consequences of climate change accounting for adaptation costs and benefits." (2018).

global mortality rate is more than the mortality rate associated with all infectious diseases in 2018, as illustrated in Figure 2.

The analysis also reveals a very significant cost associated with the release of an additional metric ton of CO_2. Specifically, the elevated mortality risk equates to a monetary cost of $23.6 per metric ton of carbon emitted today when using the same assumptions that underlie the Obama SCC calculation. In other words, we estimate the *partial* social cost of carbon, accounting for costs to human mortality alone, to be at least $23.6 per ton. The Trump administration's current *full* SCC estimate, which includes costs projected among all sectors, is pegged at one to seven dollars,[16] while the Obama administration's was $50.6.[17]

Our research has therefore identified a partial SCC, derived solely from the impacts of temperature change on mortality, which is over three times larger than the Trump administration's full SCC and almost half of the Obama administration's full SCC. What's more, the Obama SCC pegged the mortality costs of an additional ton of CO_2 at less than $2, while our new and frontier approach puts the mortality costs of carbon emission at more than 10 times larger. This suggests that the Obama administration's methodology might substantially underestimate the full SCC.

The CIL's work on the other four sectors is in progress. Initial agricultural findings indicate that global grain yields may decline with climate change, and that adaptation to avoid further yield declines will be costly. Our coastal sector estimates predict sea level rises and changes to tropical cyclones which will cause substantial increases in economic risk to coastal regions in the US and elsewhere. The rising incidence of extreme heat will also cause substantial global losses in labor supply, with little evidence that outdoor workers have effective means of adapting to such conditions. Lastly, a forthcoming paper projects that climate change will lead to modest savings in global energy consumption, with savings in the decreased consumption of common heating fuels such as natural gas, coal, and oil more than offsetting increases in electricity consumption.

By the end of 2020, we will calculate the full social cost of carbon by aggregating cost estimates across all sectors. The CIL's research translates the disparate types of impacts discussed above into one common metric - the dollar value that future populations and governments around the world would be willing to pay to avoid experiencing climate change. Subsequent research, to be completed by early 2021, will incorporate these results into a macroeconomic model designed to use information about the harm done by climate change to make recommendations about the best way for policy to respond.

c. Uncertainty

Standard economics suggests that the uncertainty about the costs of climate change strengthens, rather than weakens, the case for reducing emissions. Research in economics and casual

[16] Environmental Protection Agency Office of Air and Radiation, *Regulatory Impact Analysis for the Review of the Clean Power Plan: Proposal*. (October 2017).
[17] Interagency Working Group on Social Cost of Greenhouse Gases. "Technical Support Document: Technical Update of the Social Cost of Carbon for Regulatory Impact Analysis." Tech. rep., United States Government. (2016).

observation have long revealed that people exhibit a strong propensity toward risk-aversion - that is, people are willing to pay a premium to avoid uncertainty. This logic underlies the decisions people make in insurance markets. For instance, homeowners choose to purchase fire insurance despite the fact that it would be cheaper to self-insure over the long run; this is because they would rather face the certain payment of an insurance premium than an uncertain range of outcomes that includes their home burning down without compensation. A similar logic applies to climate change policy, because a number of factors mean that our estimates of the costs of climate change are uncertain and include very bad outcomes.

It is worth noting that the Obama administration's estimate of the SCC assumed that society is risk neutral, that is, we are not willing to pay a premium to avoid uncertainty. If the more realistic assumption that society is risk averse were introduced, then the estimated SCC would be higher, likely substantially so, than the $50 per metric ton of CO_2 discussed in the previous section. Similarly, there is a good case for scaling the damages from the CIL's research upwards to reflect the risk aversion that characterizes individuals' choices in their own lives.

d. Heterogeneity in the Distribution of Damages

The damages from climate change discussed above will be unevenly distributed among populations on both a global and national scale. The CIL's mortality projections, illustrated in Figure 2 and 3, demonstrate that globally the burden of increasing temperatures will most heavily fall on low-income regions. While Accra, Ghana will see an increase in the full mortality risk of 160 per 100,000 due to climate change in 2100, Oslo, Norway will experience a decline in the full mortality risk of 230 per 100,000 due to warmer winters. I say full mortality risk, because our projections reflect both changes in the number of deaths and the resources people devote to protect themselves against high and low temperatures. As a result, these disparities are driven not only by regional variation in temperature, but also by variation in resources available for adapting to changes in climate.

There will also be great variability in impacts across the United States. For example, an increase in the full mortality risk of 31 per 100,000 in Los Angeles stands in stark contrast to the reduction in the full mortality risk of 11 per 100,000 in McAllen, Texas. In short, climate change will leave some regions as winners and others as losers both around the globe and within the United States.

CIL projections of an uneven climate damage distribution within the US are not limited to mortality estimates. For instance, our energy sector finds that climate impacts vary considerably across locations. While northern latitudes will experience net savings due to reduced heating needs, increased cooling demand will lead to large increases in many areas of the tropics.

In other ongoing research on farming and climate risk within the United States, I find that rural areas will be hard-hit. My co-author and I estimate that with a high emissions scenario[18], rising temperatures will reduce 2050 corn acreage by 94% and soybean acreage by 98% when

[18] Following an RCP8.5 scenario. IPCC (2014). Mitigation of Climate Change: Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press.

compared to levels in 2002. The lost corn and soybean production will not be replaced by increased production of any crop currently grown in the US: as returns to agriculture decline in connection with climate change, farmers will seek to shift land use toward different crops and non-agricultural options. It will effectively bring an end to the more than 150-year tradition of farming as we know it in the US corn-belt that encompasses great swatches of Iowa, Nebraska, and Illinois.

Coastal communities will also suffer disproportionate damages due to climate change. In particular, sea level rise threatens to cause flooding and mass migration of individuals in coastal areas. Preliminary results from the CIL's coastal sector indicate that areas of Florida and New York are at the greatest risk of inundation; even among coastal communities, some will be far more severely impacted than others. It is clear, then, that the US political system will be placed under enormous stress, as it contends with not only the climate damages themselves, but also their distributional consequences. Determining which coastal areas we will prioritize protecting, for instance, seems to be an especially thorny issue.

The uneven distribution of climate damages means that the very mitigation of climate change is a pursuit of environmental justice. A commitment to feasible solutions is the strongest defense we can offer to populations vulnerable to climate damages.

III. The Case for Market-Based Policy

The surest means to limiting climate damages is to reduce greenhouse gas emissions. This is not a small undertaking and its magnitude virtually requires that it be done cost-effectively. This means that the best policies will ruthlessly search out the least expensive reductions in greenhouse gas emissions both today and in the future. This section argues that the surest way to achieve this goal is to focus on the two market failures that define the climate change problem and therefore to price CO_2 emissions at their true societal cost, either through a carbon tax or a cap-and-trade, and to subsidize research, development, and demonstration of low carbon or carbon-reducing technologies.

a. Directly Set a Price on CO_2 Emissions to Obtain Inexpensive Emissions Reductions Today

The surest way to make progress in reducing CO_2 emissions inexpensively is to set an economy-wide price on CO_2 emissions, either through a tax or by instituting a cap-and-trade market. If set at the right level (e.g., the social cost of carbon), these pricing approaches solve the main problem: that currently people and firms do not take account of the damages that they cause when they engage in activities that involve the release of CO_2. The great appeal of this approach is that it unleashes market forces to uncover the least expensive ways to reduce emissions, thereby minimizing the costs to the economy, and does not require the government to identify which sector they will emerge from.

In economics, there is little controversy about the power of carbon pricing. However, the politics have not always favored such a simple and transparent approach to confronting the climate challenge. The result is that we have a hodge-podge of policies that target emissions in different sectors in different ways and with different degrees of intensity. The result has not always been good news. For example, in a pair of randomized control studies, my co-authors and I found that residential energy efficiency programs reduce CO_2 emissions at a cost of several hundred dollars per metric ton of CO_2 abated.[19,20] Further, a recent research paper by economists Kenneth Gillingham of Yale University and James Stock of Harvard University concludes "the range of costs of [US CO_2 mitigation policies] is extremely wide, from less than $10 per ton to over $1,000 per ton… most of the costs are relatively expensive, in the sense that they exceed [the 2017 US SCC]."[21] This wide variability and generally high costs per ton mean that we are getting smaller emissions reductions than is possible for any given level of spending on mitigation. Carbon pricing can ensure that we get a bigger bang in terms of emissions reductions for our buck.

I will conclude this subsection by noting that, given the scale of the emissions cuts that the science and economics suggest are warranted, the gains from relying on market-based approaches are likely to be quite substantial. In a period where too many American families have had stagnant incomes and there is an urgent need for resources to address other social challenges like education, health insurance, and entitlements, the case for carbon pricing is even stronger.

b. Invest in Research, Development, and Demonstration (RD&D) to Obtain Inexpensive Emissions Reductions Tomorrow

A carbon market is necessary, but it is not sufficient, because there is a second market failure that merits government attention. Specifically, the private sector on its own will not invest enough in RD&D because some of the benefits of these investments flow to their competitors. This leads them to focus their RD&D on "applied" projects, where the payoff only flows to them right away.

This "market failure" means that we have too little innovation in "basic" research projects that can benefit or even create an entire industry. This, too, is a market failure, and this is where the government can step in to fill the void by providing subsidies for RD&D. In doing so, the government can help unlock emissions reductions that are less expensive than they otherwise would be in the future.

Medicine provides a good parallel: the National Institutes of Health is funded at about $40 billion per year through the federal budget, constituting around 75% of global spending in basic medical science. Much of NIH research is concerned with understanding a disease rather than developing a particular drug. But that funding pays off: 15 of the 21 most important new drugs

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[19] Fowlie, Meredith, Michael Greenstone, and Catherine Wolfram. "Do energy efficiency investments deliver? Evidence from the weatherization assistance program." *The Quarterly Journal of Economics* 133, no. 3 (2018): 1597-1644.
[20] Allcott, Hunt, and Michael Greenstone. *Measuring the welfare effects of residential energy efficiency programs*. No. w23386. National Bureau of Economic Research, 2017.
[21] Gillingham, Kenneth, and James H. Stock. "The cost of reducing greenhouse gas emissions." *Journal of Economic Perspectives* 32, no. 4 (2018): 53-72.

between 1965 and 1992 were developed using NIH-funded research.[22] With a significant ramp-up of funding, the United States could achieve similar global leadership in energy innovation that would lower the cost of reducing CO_2 emissions and in doing so would increase emissions cuts.

The current state of US energy RD&D programs suggests there are opportunities to greatly expand federal investments to better meet the climate challenge. In 2018, federal RD&D spending on energy totaled $3.0 billion[23] – just one-third of the peak in energy RD&D during the 1980s. In increasing these totals, an especially promising area for further funding is the Department of Energy's Advanced Research Projects Agency (ARPA-E).[24] Modeled after the Defense Advanced Research Projects (DARPA) agency, which supported breakthroughs like GPS, ARPA-E has worked to develop new technologies that offer progress toward reducing dependence on imported energy, reducing emissions, and increasing energy efficiency. The 2019 budget allocated $366 million for the ARPA-E program, which is about 5% of the funding for the NIH and 1% of the funding for the National Science Foundation. As we get serious about reducing emissions, increased funding for agencies like ARPA-E remains critical to the United States' ability to address climate change with maximum economic benefit for US citizens.

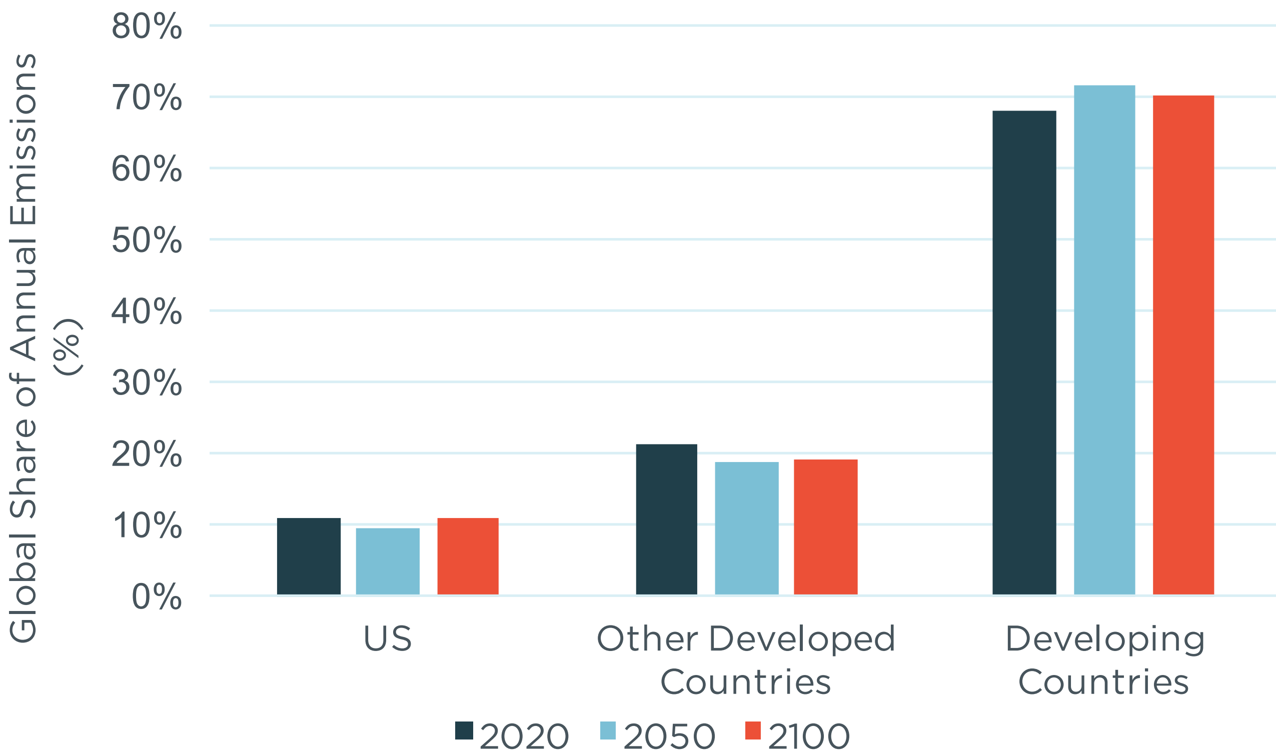
IV. Conclusions

Ultimately, society needs to balance the costs to our economy of mitigating climate change today with climate damages. The social cost of carbon, estimated using the best available evidence, is a key tool in this balancing act. My ongoing work with the Climate Impact Lab suggests that the social costs are large, both in dollars and in terms of human lives; and therefore that both the Obama and Trump administrations may have systematically undervalued the cost to society of CO_2 emissions.

Guided by the social cost of carbon, and in order to reduce current harmful emissions at the lowest cost, the US government can improve the lives of its citizens by enacting an economy-wide carbon price through a tax or cap-and-trade program. To unlock affordable *future* CO_2 emissions, the federal government has an appealing opportunity to significantly increase funding for energy research, development, and demonstration (RD&D). Through these two distinct policies, the United States can address climate change with minimum cost to current and future generations of Americans.

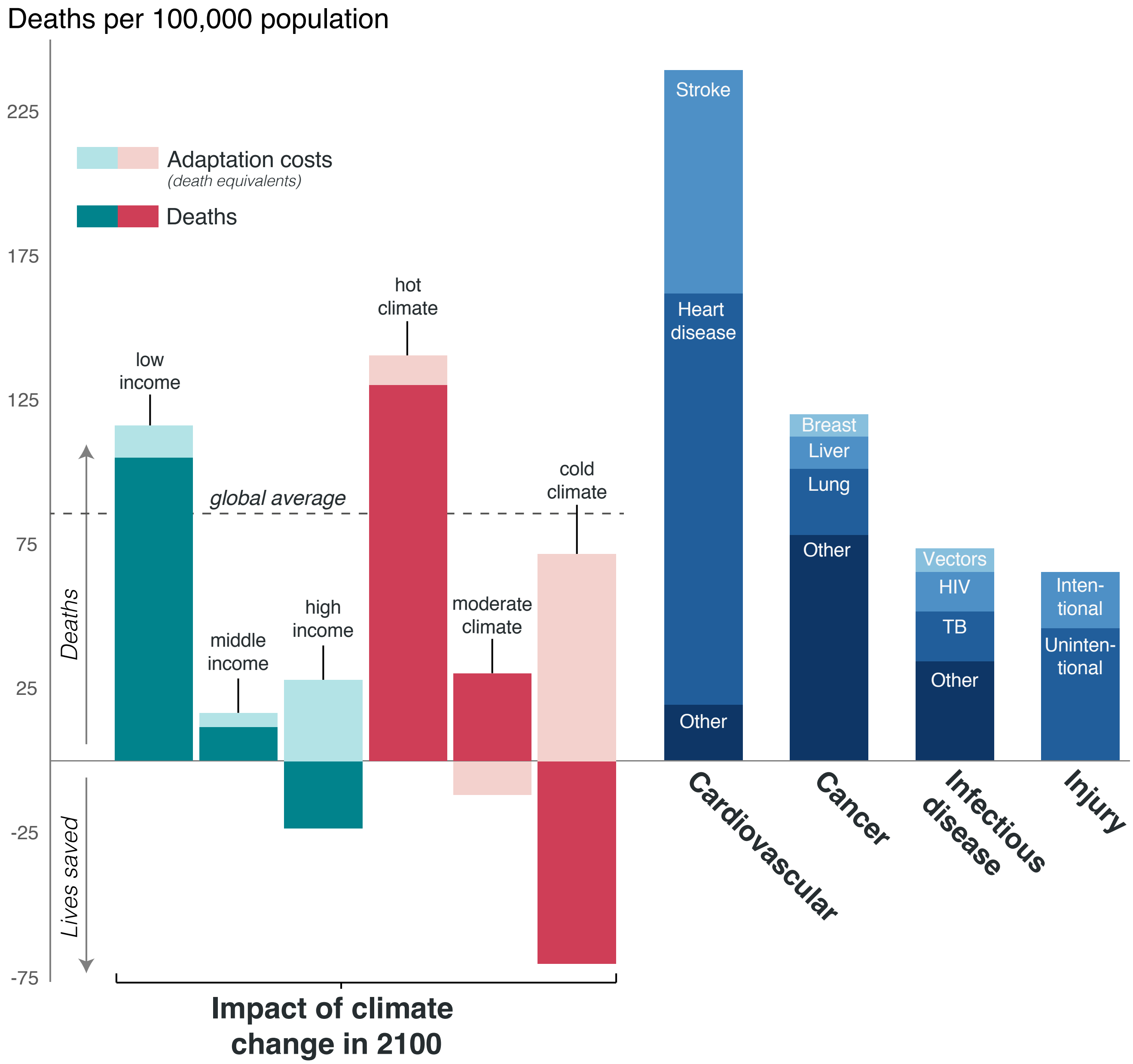
[22] National Science Foundation. "NSF History: Nifty Fifty."
[23] U.S. Office of Management and the Budget. *Historical Budget Tables* (FY 2020).
[24] Stine, Deborah D. "Advanced Research Projects Agency-Energy (ARPA-E): Background, Status, and Selected Issues for Congress." (2009).

Figure 1: Annual Greenhouse Emissions by Region



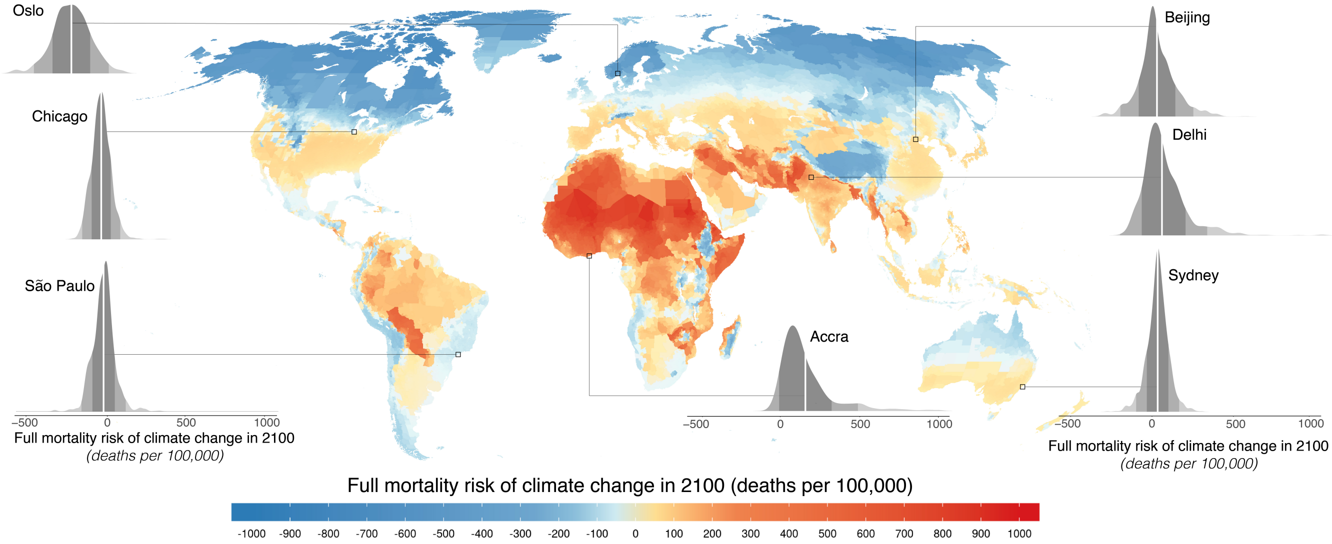
Notes: Greenhouse gas emission projections are sourced from the Climate Interactive C-Roads Model.

Figure 2: Climate Impacts on Mortality Rival Leading Causes of Death



Notes: Impacts of climate change (teal and coral) are calculated for the year 2100 under RCP8.5 and SSP3 and include changes in death rates (solid colors) and changes in adaptation costs, measured in death equivalents (light shading). Income and average climate groups are separated by tercile of the 2015 global distribution across all 24,378 impact regions. Blue bars on the right indicate average mortality rates globally in 2018, with values from WHO (2018).

Figure 3: The Mortality Risk of Future Climate Change



Notes: The map indicates the full mortality risk of climate change, measured in units of deaths per 100,000 population, in the year 2100. Estimates come from a model accounting for both the costs and the benefits of adaptation, and the map shows the climate model weighted mean estimate across Monte Carlo simulations conducted on 33 climate models; density plots for select regions indicate the full distribution of estimated impacts across all Monte Carlo simulations. In each density plot, solid white lines indicate the mean estimate shown on the map, while shading indicates one, two, and three standard deviations from the mean. All values shown refer to the RCP8.5 emissions scenario and the SSP3 socioeconomic scenario.