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The Nobel Memorial Prize for William D. Nordhaus*

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Abstract

William D. Nordhaus and Paul M. Romer received the 2018 Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel. This paper surveys Nordhaus' contributions on "integrating climate change into long-run macroeconomic analysis", for which he was recognized with this Prize.

Keywords: Carbon tax; climate change; climate clubs; DICE model; energy models; integrated assessment; social cost of carbon

JEL classification: *B*0; *O*4; *O*44; *Q*5; *Q*54

I. Introduction

William D. Nordhaus was awarded the 2018 Sveriges Riksbank Prize in Economic Sciences in Memory of Alfred Nobel "for integrating climate change into long-run macroeconomic analysis". The ubiquity of climate change in modern economic analyses might render it difficult to appreciate how truly ground-breaking this contribution has been. In the early 1970s, amidst heated public and academic debates about limits to growth from energy and resource scarcity, Nordhaus presciently flagged *climate change* as the more likely natural constraint on long-run growth (Nordhaus, 1974). He cautioned about melting polar ice caps as a consequence of misdirected economic growth almost 20 years before the United Nations released its first Intergovernmental Panel on Climate Change (IPCC) report in 1990 (Nordhaus and Tobin, 1972). Nordhaus immersed himself in the physical sciences literature and pioneered the first integration of a carbon cycle model into an economic linear programming model of global energy markets (Nordhaus, 1975a). He used this integrated model to produce the

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first ever estimates of global *carbon taxes* that could maximize economic welfare subject to constraints on greenhouse gas concentrations (Nordhaus, 1977). This work so clearly defined a new frontier that 1975 Nobel Laureate Tjalling Koopmans took time to describe the climate problem and Nordhaus' efforts in his own Nobel banquet toast at the time.[1] After Nordhaus' pioneering introduction in 1977, it would be years before other scholars began to study carbon taxes, and the term did not even appear again in the *American Economic Review* until 1991. Today, carbon pricing policies have been adopted by an estimated 46 countries and 24 subnational jurisdictions around the world (World Bank, 2018). As early as 1980, Nordhaus developed the first climate–economy optimizing integrated assessment model (IAM) by simultaneously incorporating the economy's greenhouse gas emissions, the carbon cycle, and a first aggregate climate change *damage function* into an economic growth model. Nordhaus (1980) introduced both a theoretical characterization and the first ever numerical estimates of *optimal* climate policy based on an integrated cost–benefit analysis. This fundamental innovation also came years before such frameworks became more widely studied, and other scholars built on Nordhaus' estimates from the beginning.[2] The 1980s saw significant advancements in scientific understanding of climate change and its potential impacts, and Nordhaus served on the frontlines of early syntheses of this work, for example, through his service on the National Academy of Sciences' Carbon Dioxide Assessment Committee. Building on this growing knowledge, Nordhaus continued to refine his climate–economy model (Nordhaus, 1991a), culminating in the introduction of the Dynamic Integrated model of Climate and the Economy (DICE; Nordhaus, 1992, 1993a,b, 1994a). Since its inception, DICE has served as a conceptual and modeling foundation for climate change economics and its policy applications. DICE is an unequivocal benchmark of the literature. Because of the model's transparency and Nordhaus' persistent efforts to make its code accessible and understandable to all, countless scholars have stood on the shoulders of DICE and its multi-regional variant RICE (Nordhaus and Yang, 1996; Nordhaus and Boyer, 2000) to analyze the climate implications of everything from scientific uncertainty to international technology spillovers. In the policy realm, DICE is one of three models that have been used by the US government to value the social cost of carbon (SCC; Greenstone *et al*., 2013). These

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[1] Koopmans received the prize jointly with Soviet scholar Leonid Kantorovich for their "contributions to the theory of optimum allocation of resources" (see https://www.nobelprize.org/prizes/economic-sciences/1975/koopmans/speech/).

[2] For example, Peck and Teisberg (1992) used the damage estimates in Nordhaus (1991a) to build another early optimizing integrated assessment model.

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SCC estimates have informed regulatory impact analyses of over 70 US federal rule-makings.[3] The US Courts have even overturned federal agency decisions for failing to incorporate these SCC estimates (Metcalf and Stock, 2017). Notwithstanding recent changes in US federal policy, these SCC estimates continue to inform decision-making across US states and other countries.[4]

Alfred Nobel established his namesake prize for "those who ... have conferred the greatest benefit to humankind".[5] Since diagnosing the lack of a carbon price as key potential source of conflict between economic growth and the environment in the 1970s, Nordhaus and his collaborators have integrated research from the physical, natural, and social sciences to give the world a flexible tool that can quantify such prices for a wide range of policy objectives. This work remains foundational for modern climate change economics, and carbon prices are now adopted by governments around the world to redirect the global economy towards a more sustainable long-term growth path. Without a doubt, this work exemplifies the spirit of Nobel's vision.

This body of work also represents science at its best: integrative across disciplines, visionary in scope yet incremental in progress, transparent, and producing knowledge for the benefit of humankind. Nordhaus has always emphasized the importance of the broader scientific community and the institutions that enable his (and all of our) work. He began his official 2018 Nobel Lecture in part by noting that:

> "I am here today [...] just one person representing what I think of as an invisible college of people around the world and over time, not just in economics but in many disciplines [...], dealing with this broad set of problems having to do not just

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[3] See Table A1 in the Appendix for a listing of federal rules, and also Nordhaus (2014) for a discussion.

[4] For example, both New York and Illinois have used this SCC estimate to set zero-emissions electricity subsidy rates; the New York State Energy Research and Development Authority (NYSERDA) Clean Energy Standard (https://www.nyserda.ny.gov/All-Programs/Programs/Clean-Energy-Standard and the Future Energy Jobs Bill, SB 2814, 220 ILCS 5/20-135). Canada has also adopted this SCC estimate (Policy on Cost–Benefit Analysis, Treasury Board of Canada Secretariat (see https://www.canada.ca/en/treasury-board-secretariat/services/federal-regulatory-management/guidelines-tools/policy-cost-benefit-analysis.html).

[5] While the Sveriges Riksbank Prize in Economic Sciences was not a part of Nobel's original will, the Royal Swedish Academy of Sciences "appoints the prize-winner(s) according to the same principles as for the Nobel Prizes" (see https://www.riksbank.se/en-gb/about-the-riksbank/the-tasks-of-the-riksbank/research/economics-prize/).

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> with climate change, but with the interaction of the economy with the natural world."[6,7]

This invisible college has a long tradition, going back to Sweden's first Nobel Laureate, Svante Arrhenius, who in 1896 made pioneering calculations on the relationship of atmospheric carbon dioxide concentrations and earth's heat retention.[8] Arrhenius' rule is still used today – and it was Nordhaus who introduced it into economic analysis.

This article surveys Nordhaus' contributions on integrating climate change in long-run macroeconomic analysis.[9] To begin, Section II reviews Nordhaus' identification of climate change and the lack of a carbon price as impediment to sustainable long-run growth. Then, Section III chronicles Nordhaus' first breakthrough on integrating the carbon cycle into economic modeling, based on his work at the International Institute for Applied Systems Analysis. Section IV describes Nordhaus' development of the first ever optimizing climate–economy IAM, which provided the first fully integrated cost–benefit assessment of climate policy. Section V presents the DICE framework. We describe the model and survey the foundational role it has played in the literature and policy realm to date. Finally, Section VI concludes by highlighting Nordhaus' influence on the levels of rigor and openness in academic and public debates, and towards a shared understanding of the issues.

II. A Prescient Diagnosis

> "In contemplating the future course of economic growth in the West, scientists are divided between one group crying 'wolf'

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[6] Transcribed from the Nobel Lecture video available from Nobel Media at https://www.nobelprize.org/prizes/economic-sciences/2018/nordhaus/lecture/.

[7] Nordhaus' influential first book on the DICE model (Nordhaus, 1994a) contained similar thanks to "the invisible but substantial contributions of a cadre of colleagues in this field who have contributed to the development of a field of the economics of global environmental issues."

[8] Arrhenius was awarded the Nobel Prize in Chemistry in 1903 for his work on electrolytic dissociation.

[9] Given this focus, we are thus unable to delve into Nordhaus' other major contributions, which span work on incorporating the environment into national accounts (Nordhaus and Tobin, 1972; National Research Council, 1999; Muller *et al.*, 2011), on endogenous technical change (e.g., Nordhaus, 1969), on developing a geographically based "G-Econ" database of gross value added for every one-degree longitude by one-degree latitude cell around the world (Nordhaus *et al.*, 2006), on "the political business cycle" (Nordhaus, 1975b; this is actually Nordhaus' most widely cited single paper as of February 2019), and on the measurement of income growth in the presence of technological change (e.g., Nordhaus, 1996). This latter study is especially famous for Nordhaus' collection of ancient lighting instruments used to construct a history of the true cost of lumen-hours from prehistoric fires to oil lamps to the present in an effort to test the ability of national accounts' price indices to adjust for technological progress.

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> and another which denies that species' existence." (Nordhaus, 1977)

The post-war economic boom of the 1950s and 1960s created a sharp divergence in perspectives on the future of economic growth. For economists, this period marked a shift towards expecting sustained growth as a norm. Growth "was simultaneously the hottest subject of economic theory and research [. . .] and a serious objective of the policies of governments" (Nordhaus and Tobin, 1972). For others, natural resource depletion became a paramount concern. In April 1970, an estimated 20 million Americans took to the streets to protest against environmental degradation.[10] Some scholars began to issue dire warnings about the planet's ability to sustain continued growth, as exemplified by prominent works such as Paul Ehrlich's neo-Malthusian *The Population Bomb* (Ehrlich, 1968) and the highly influential *Limits to Growth* report by Meadows *et al.* (1972). The authors warned that if present trends continue, the planet's limits to growth would be reached and "the most probable result will be a rather sudden and uncontrollable decline in both population and industrial capacity" (Meadows *et al.*, 1972). In sharp contrast, the emerging standards of neoclassical economic growth modeling did not even consider environmental processes.

Nordhaus, at the time an Associate Professor of Economics at Yale University, took these concerns seriously, and began to bridge this chasm. Nordhaus had completed his undergraduate studies at Yale and earned his PhD at the Massachusetts Institute of Technology in 1967 under the guidance of Robert Solow (1987 Nobel Laureate and one of the founders of modern neoclassical growth theory), Edwin Kuh (an econometrician), and Paul Samuelson (1970 Nobel Laureate and one of the founders of modern economic analysis). From his dissertation, *Invention, Growth, and Welfare: A Theoretical Treatment of Technological Change* and subsequent work, Nordhaus was already confronting divergences between social and private returns to activities that affect economic growth.

In both the classic "Is Growth Obsolete?" (Nordhaus and Tobin, 1972), written with Yale colleague and 1981 Nobel Laureate James Tobin, and in "Resources as a Constraint on Growth" (Nordhaus, 1974), Nordhaus delivered several sharp insights on environmental limits to growth. On the one hand, for "appropriable resources" that the market already treated as economic goods (e.g., aluminum, coal, natural gas), Nordhaus (and Tobin) reviewed economic theory, empirical evidence, and data on resource endowments, consumption rates, and relative price trends with labor, and concluded that these resources did not appear poised to become a constraint

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[10] See "EPA History: Earth Day" on the Environmental Protection Agency's website, https://www.epa.gov/history/epa-history-earth-day.

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on growth in terms of availability, affordability, or efficiency.[11,12] On the other hand, they warned that "possible abuse of public natural resources is a much more serious problem". While Nordhaus and Tobin proposed a novel "measure of economic welfare" that included some adjustments for local air pollution disamenities, they noted that *global* environmental public goods are different. "Maybe we are pouring pollutants into the atmosphere at such a rate that we will melt the polar icecaps and flood all the world's seaports," they cautioned. Nordhaus (1974) provided a more explicit description of the greenhouse effect.[13] He introduced new findings from the physical sciences and effectively flagged climate change as the most serious potential sustainability problem resulting from unfettered growth and energy consumption.

Along with this diagnosis, Nordhaus and Tobin (1972) also immediately pointed towards a solution that could deliver both growth and environmental protection:

> "The mistake of the antigrowth men is to blame economic growth per se for the misdirection of economic growth. The misdirection is due to a defect of the pricing system – a serious but by no means irreparable defect [. . .].
>
> "There are [. . .] serious consequences of treating as free things which are not really free. [. . .] The producers of automobiles and of electricity should be given incentives to develop and to utilize 'cleaner' technologies. The consumers of automobiles and electricity should pay in higher prices for the pollution they cause, or for the higher costs of low-polluting processes. [. . .] At present, overproduction of these goods is uneconomically subsidized as truly as if the producers received cash subsidies from the Treasury.
>
> "Although general economic growth has intensified the problem, it seems to originate in particular technologies. The proper remedy is to correct the price system so as to discourage these technologies. Zero economic growth is a blunt instrument for cleaner air, prodigiously expensive and probably ineffectual."

While it was Pigou (1920) who introduced the idea of corrective taxes as a remedy for the divergence between the private and social

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[11] Of course, Nordhaus was careful to note that cartels render oil markets non-competitive. He deals with this issue formally in, for example, Nordhaus (1979).

[12] Leading formalizations of economic growth with scarce natural resources were later introduced by Dasgupta and Heal (1974), Solow (1974), and Stiglitz (1974).

[13] Examples of even earlier mentions of climate change in economics exist, such as Ayres and Kneese (1969) and Kneese (1971).

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costs of an activity, the application of this concept to the global climate presents a daunting challenge. In theory, a Pigouvian tax should reflect the value of marginal damages from an additional unit of pollution, evaluated at the socially optimal allocation. For pollutants that are local and dissipate quickly, social costs are typically data-intensive but conceptually straightforward to measure. For example, Pigou (1920) already cites a 1918 study by the Manchester Air Pollution Advisory Board, which surveyed households in both Manchester (polluted) and Harrogate (clean) about their laundry expenditures to estimate the washing externality costs of industrial smoke. Coupled with estimates of the marginal contribution to "smoke" concentrations from industrial activities, one could infer an approximate Pigouvian tax.

For climate externalities, the relevant calculations are exponentially more complex. First, each ton of carbon dioxide emitted today enters the global carbon cycle and has time-varying impacts on the climate for centuries to come. Second, the resulting marginal changes in the global climate affect the economy and human welfare in varying ways across sectors, countries, and time. Potential impacts range from changes in agricultural productivity to disease vectors, energy requirements, biodiversity losses, and potentially catastrophic climate destabilization, to name only a few. Producing a credible estimate of the resulting aggregate costs would thus require a rich body of literature about scientific impact that did not exist at the time when Nordhaus began to tackle this endeavor. The first step in this chain, however (i.e., the present and future impacts of energy consumption on the climate system) was already the subject of active research. Nordhaus and Tobin noted that "there is probably very little that economics alone can say" on the dangers of global environmental externalities. As a next step, collaboration with other disciplines would be essential for progress.

III. Integrating the Climate into Economics

> "The opportunity and need for fruitful collaboration between economists and physical scientists has never been greater." (Nordhaus and Tobin, 1972)

In 1974, Nordhaus traveled to Austria to visit the International Institute for Applied Systems Analysis (IIASA).[14] IIASA had been founded in 1972 as a collaborative effort between the United States, the Soviet Union, and

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[14] For further information about IIASA, see their website http://www.iiasa.ac.at/web/home/about/whatisiiasa/what_is_iiasa.html.

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several other countries in order to conduct "research into problems of a global nature that are too large or too complex to be solved by a single country or academic discipline". For example, IIASA's first major study, the Energy Project, embarked on a vast multidisciplinary investigation into the world's energy future (Häfele *et al.*, 1981). By 1975, IIASA already featured "a sparkling array of talent working on problems of energy, ecology, water resources, and methodology".[15] It was here that Nordhaus immersed himself in the physical and natural sciences research on carbon and the climate, learning from both colleagues and the literature (see Nordhaus, 2019). This new knowledge enabled him to produce the ground-breaking innovation of a first carbon-cycle economic IAM.

On the climate side, Nordhaus' approach built closely on the work of Lester Machta (1972), who had developed a matrix representation of the carbon cycle based on the movement of carbon between different reservoirs, such as the atmosphere and the ocean. Formally, in his 1975 IIASA working paper "Can We Control Carbon Dioxide?" (Nordhaus, 1975a), Nordhaus presented the following model based on this work. Let $M_i(t)$ denote the stock of carbon in reservoir i at time t, where $i = \{$Troposphere, Stratosphere, Upper oceans, Deep oceans, Short-term biosphere, Long-term biosphere, Marine biosphere$\}$, and let d_{ij} denote annual transfer coefficients from reservoir i to reservoir j. The carbon cycle can then be captured by

$$M_i(t) = \sum_{j=1}^{7} d_{ji} M_j(t-1). \tag{1}$$

In matrix form, equation (1) simply becomes $M(t) = D'M(t-1)$, where D denotes the Markov matrix of transfer coefficients d_{ij}. Critically, this representation enabled Nordhaus to incorporate the carbon cycle into linear programming models. Based on the contributions of 1975 Nobel Laureates Tjalling Koopmans and Leonid Kantorovich, this approach searches for the optimal allocation of resources in an economy subject to any relevant constraints, such as constraints on resource availability.

Thus, the fundamental innovation of Nordhaus (1975a) was to integrate equation (1) as a constraint into a dynamic energy market equilibrium model of the US and world economies, and to present the first estimates of optimal global energy allocations and pricing *subject to limitations on global greenhouse gas concentrations*. That is, Nordhaus used this integrated carbon cycle–economy model to study how energy inputs and prices should evolve across fuel types and sectors over time in order to maximize global

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[15] See the talk "The Founding of the Institute" given by Howard Raiffa at IIASA on 23 September 1992; the edited transcript is available on IIASA's website http://www.iiasa.ac.at/web/home/about/whatisiiasa/history/founding/the_founding_of_the_institute.html.

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welfare subjects to limits on climate change. As there were neither policy targets nor damage estimates available at the time, Nordhaus considered constraints designed to keep the climatic effects of carbon dioxide emissions "well within the normal range of long-term climatic variation". This type of analysis also remains the bedrock of policy applications of integrated assessment models to analyze how politically agreed upon climate targets, such as a limit to 2° C warming, can be achieved at the lowest economic cost. As a testament to Nordhaus' ability to capture the essence of complex processes even in parsimonious specifications, several of the model's predictions turned out to be strikingly accurate. For example, the model projected year 2000 tropospheric carbon dioxide concentrations in the absence of a global emissions control program to be 376 parts per million (ppm). In reality, they were 370 ppm in 2000, and reached 376 by 2003.[16]

Back in the United States, Nordhaus disseminated these findings along with a third trail-blazing contribution: *carbon taxes*. Nordhaus (1977) presented estimates of carbon tax schedules that could decentralize the efficient energy resource allocations from his model. This foundational contribution was again rooted in the linear programming approach, which enables researchers to calculate *shadow prices* that reflect the social costs of activities. While Nordhaus (1975a) had already presented estimates of shadow prices on carbon dioxide, Nordhaus (1977) labeled these explicitly as carbon taxes. These were the first ever quantitative estimates of carbon taxes as a tool to meet a policy objective, here to stabilize the global climate at least cost.[17]

Nordhaus continued to blaze the carbon tax analysis trail for several years (e.g., Nordhaus, 1979, 1980, 1982; Nordhaus and Yohe, 1983) before other scholars formally joined, with Edmonds and Reilly (1983) serving as an early example and others following in the later 1980s and early 1990s (e.g., Manne and Richels, 1990; see also Section IV). It should be noted that Nordhaus' carbon tax proposal was initially met with some fundamental skepticism (e.g., Hasson, 1980), as had been the case with early calls for pollution levies in other settings (Resources Editor, 2001). Thus, we should not take for granted the broad support that carbon pricing now enjoys, and we must credit Nordhaus for first introducing, quantifying, and championing this idea. Of course, we must also give credit to other scholars in the invisible college who had in parallel been advocating for pollution levies

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[16] See "Full Mauna Loa CO_2 record" on the National Oceanic and Atmospheric Administration (NOAA) website https://www.esrl.noaa.gov/gmd/ccgg/trends/full.html.

[17] This statement reflects the best of our knowledge. We did not find any other prior references to carbon taxes or related phrases on JSTOR or on other scholarly archives. Google Scholar lists several carbon tax references with earlier dates, but we have found them to be (wildly) mis-labeled.

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as a cost-effective alternative to command-and-control regulations, such as for water pollution (e.g., Kneese and Bower, 1968; Kneese and Schultze, 1975).

Despite their ground-breaking nature, the carbon tax estimates in Nordhaus (1977) did not yet correspond to Pigouvian levies, as they reflected arbitrary rather than optimal emissions targets based on cost–benefit considerations. As noted by Nordhaus (1977): "The central question for economists, climatologists, and other scientists remains: How costly are the projected changes in (or the uncertainties about) the climate likely to be, and therefore to what level of control should we aspire?"

IV. Climate Change Impacts and Integrated Assessment

> "We now move from the *terra infirma* of climate change to the *terra incognita* of the social and economic impacts of climate change." (Nordhaus, 1991a)

While increased scientific attention towards greenhouse warming brought with it early calls for policy interventions (e.g., Woodwell et al., 1979), these continued to lack a cost–benefit foundation. In a 1980 Cowles Foundation working paper, Nordhaus proceeded to tackle this enormous challenge, and, in the process, made several fundamental contributions (Nordhaus, 1980).

First, Nordhaus presents a theoretical analysis of optimal growth and climate change. Though stylized so as to be accessible and "introduce to the natural scientist the analytical tools of the economist", this paper derives results that have remained central to economists' analyses of the climate problem. These include an analytical expression for the optimal carbon tax and a thorough treatment of how the pure rate of time preference, the intertemporal elasticity of substitution, and future output growth affect the social cost of carbon, bridging to the foundational work of Ramsey (1928) on the determinants of savings and interest rates.

Nordhaus' treatment distills the economic problem of climate management to its essence. On the one hand, current consumption $c(t)$ is an *increasing* function $f(.)$ of current fossil fuels usage and thus emissions $E(t)$. On the other hand, consumption (broadly defined to include, e.g., environmental amenities) can be harmed by the stock of accumulated atmospheric carbon $M(t)$ over pre-industrial levels via some relation $h(.)$. In its simplest form, a one-box representation, the law of motion for atmospheric carbon $M(t)$ can be boiled down to the fraction of carbon emissions entering the atmosphere β (i.e., remaining in the atmosphere net of immediate absorption by the biosphere) and the fraction δ leaving the atmosphere into an implicit sink, such as the deep oceans. In the simplest

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setting (without growth), the climate problem is thus to maximize the present value of utility $u(.)$ for current and future generations subject to its resource constraints and the laws of atmospheric carbon accumulation:

$$\begin{aligned} \max_{\{c(t)\}} W &= \int_0^\infty e^{-\rho t} \cdot u[c(t)]dt; && (2) \\ c(t) &= f[E(t)] - h[M(t)]; && (3) \\ \dot{M}(t) &= \beta E(t) - \delta M(t). && (4) \end{aligned}$$

Here, ρ denotes the pure rate of social time preference. The solution to this problem and the optimal carbon price $q(t)$ that can implement this allocation in the decentralized economy are then defined by the following condition:

$$\begin{aligned} \underbrace{f'[E(t)]}_{\substack{\text{Marginal}\\ \text{abatement cost}}} &= \int_0^\infty \underbrace{e^{-(\rho+\delta)v}\frac{u'[c(v)]}{u'[c(t)]}}_{\text{Present value of future consumption}} \cdot \underbrace{h'[M(v)]}_{\text{Future marginal damages}}\beta \; dv \\ &= \underbrace{q(t)}_{\text{Opt. carbon price}} . \qquad (5) \end{aligned}$$

Expression (5) illustrates the cost–benefit approach to climate policy. Emissions should be reduced up until the point where the marginal abatement cost (i.e., the amount of consumption society has to give up today to reduce emissions by one unit $f'[E(t)]$) equals the present value of marginal damages from emitting another ton, which corresponds to the marginal abatement benefit. Evaluated at the optimal allocation, this expression defines the optimal carbon pollution price $q(t)$. Intuitively, setting a carbon tax equal to $q(t)$ dollars per ton ensures that firms and consumers reduce their carbon emissions up until the point where their private marginal abatement costs equal $q(t)$, and thus the marginal abatement benefit.

Along with this transparent analytical illustration, Nordhaus introduced quantifications of the elements in equations (2)–(4) as a second key innovation. That is, rather than modeling the details of global energy markets as he had done in previous work, Nordhaus now used the results from those complex models to estimate a reduced-form abatement cost function $f'[E(t)]$ that would be intuitive to understand and use. Perhaps most significantly, Nordhaus introduced a first set of aggregate climate change impact functions $h'[M(t)]$. While the research available to inform this quantification was extremely limited at the time, the paper pioneered a way of thinking about the problem. Nordhaus' approach, now referred to as "enumerative", compiled available impact estimates across sectors, extrapolated them to unavailable countries and time periods, and aggregated them into a damage function $h'[M(t)]$ (see also Section V).

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Here, Nordhaus utilized some of the first impact estimates for agriculture, energy demand, health, and amenities as compiled by Ralph d'Arge for the World Meteorological Organization's First World Climate Conference in 1979 (d'Arge, 1979). Nordhaus also produced original estimates for sea level rise and its potential costs across different assumptions about critical uncertainties, such as the fate of the West Antarctic ice sheet and the pace of human adaptation. Throughout the paper, Nordhaus was careful to emphasize that these estimates were highly preliminary. Indeed, he only presented ranges of results "rather than give the spurious precision of a single figure".[18]

With these components, Nordhaus (1980) had built the first optimizing climate–economy IAM.[19] He translated the phenomenally complex problem of managing a dynamically changing global climate from growing greenhouse gas emissions into a transparent framework, distilling the core trade-offs into components that researchers would study and modify for decades to come (i.e., the "damage function", the "abatement cost function", discounting parameters, etc.). In short, Nordhaus turned Pigouvian theory into an actionable reality for the global climate.

Of course, the quantifications were still highly preliminary in 1980, and with the benefit of another decade of climate change research, Nordhaus (1991a) published an advanced iteration.[20] In this paper, Nordhaus presented a break-down of US gross domestic product (GDP) by sectoral vulnerability to climate change, and combined these figures with newer impact estimates to construct a revised damage function with a much narrower range of 0.25–2 percent of GDP-equivalent loss associated with 3° C warming. This "first serious and systematic effort to quantify economic damages from climate change" quickly became "a benchmark or reference point" to other studies (Toth, 1993). For example, Peck and Teisberg (1992) used Nordhaus' damage estimates to build an alternative optimizing IAM, the CETA model, which they subsequently used to analyze issues such as warming uncertainties and the value of information. Similarly, Manne and Richels (1995) build on the Nordhaus (1991a) damage estimates in deriving cost–benefit assessments for competing climate policies in their MERGE model. Others followed Nordhaus' enumerative approach to construct additional aggregate damage estimates (e.g., Cline, 1992a; Frankhauser, 1992). Of course, the most influential benchmark came with

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[18] The resulting range was wide indeed, suggested that a doubling of CO_2 concentrations could alter aggregate consumption by −12 to +5 percent.

[19] Of course, the results of this optimizing model represent a competitive equilibrium outcome, given appropriate prices and policies.

[20] A summary of the Cowles Foundation working paper (Nordhaus, 1980) was published in Nordhaus (1982).

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the first iteration of the DICE model (Nordhaus, 1992, 1993a,b, 1994a), which contained advanced damage estimates and has served as a basis for countless studies, as described below. Before proceeding, however, we note three points.

First, beyond his modeling work, Nordhaus has also contributed directly to the climate change impact estimation literature, employing diverse approaches ranging from expert elicitations (Nordhaus, 1994b) to the estimation of hurricane wind speed impact (Nordhaus, 2010b). Among the most influential is a paper written jointly with Robert Mendelsohn (a former Nordhaus student who also became a leader in environmental and climate economics) and Daigee Shaw (an environmental economist who had visited the Yale School of Forestry and Environmental Studies). Mendelsohn *et al*. (1994) developed a novel "Ricardian" approach to evaluating climate impacts on agriculture, which encapsulated two core insights. (i) While it was common to project yield losses for specific crops (e.g., corn) based on changes in ambient conditions, they noted that farmers could be expected to switch crops as the climate changes, mitigating income losses compared with what crop-specific damage assessments would suggest. (ii) The productivity value of climatic conditions should be capitalized into the prices of agricultural land. The Ricardian approach thus uses cross-sectional variation to infer the impacts of long-run climate on agricultural productivity. Though subject to intense debate to this day, the Ricardian approach has been extensively applied, and the study remains extremely influential.

Second, both scientific and policy attention towards climate change expanded rapidly during the 1980s. Nordhaus was involved in key work at this nexus. While there had already been high-level discussions of climate change in the US policy realm (e.g., Tukey *et al*., 1965), two influential reports released in 1979 brought the issue further into the limelight.[21] Spurred by these reports, the US Congress tasked the National Academy of Sciences with investigating the implications of fossil fuel combustion and carbon dioxide build-up in the atmosphere through the Energy Security Act of 1980 (Nierenberg *et al*., 2010).[22] Nordhaus served on the resulting Carbon Dioxide Assessment Committee. Their landmark report, released in 1983, provided comprehensive reviews on climate science and climate change impacts, including impacts on agriculture and water supplies. Nordhaus further presented two chapters detailing estimates of

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[21] One report was written by a group of eminent physicists of the JASON defense advisory panel (MacDonald *et al*., 1979). The other was an ad hoc study by the National Academy of Sciences (Charney *et al*., 1979).

[22] See "Getting to know Bill Nordhaus and Climate" by Jesse Ausubel, https://phe.rockefeller.edu/news/wp-content/uploads/2019/01/Nordhaus-and-Climate-Jesse-recollection3.pdf.

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future greenhouse gas emissions. One was based on a detailed review of the literature conducted with Jesse Ausubel, a fellow IIASA alumnus and a global leader in advancing climate research programs (Ausubel and Nordhaus, 1983). The second (Nordhaus and Yohe, 1983) was based on original modeling and data analysis joint with Gary Yohe, a former Nordhaus student who would also become a leader in the field, and later served as lead author at the IPCC. This forecasting work would also form the basis for the first DICE treatment of future population and productivity growth uncertainty.

Third, over the coming years, an increasing number of energy–economy and computational general equilibrium models began to account for greenhouse gas emissions (e.g., Edmonds and Reilly, 1983; Manne and Richels, 1990; Jorgensen and Wilcoxen, 1990); for reviews, see Nordhaus (1991b) and Gaskins and Weyant (1993). At this point, we shall also note the pioneering role that some of these modelers had played in first integrating energy systems into economic growth models, with Alan Manne (1977) serving as an early example (see also the discussion in Nordhaus, 2013). Now, these models typically included highly detailed representations of the energy sector and could be used to simulate, for example, the costs of greenhouse gas emissions reductions. Some environmental simulation models also began to consider socioeconomic climate change impacts, with Rotmans (1990) serving as an early example. While these were not cost–benefit integrated assessment models, it was not long until other researchers introduced such models, including many that remain influential today, such as PAGE (e.g., Hope *et al.*, 1993) and FUND (e.g., Tol, 1997; Anthoff and Tol, 2008); see early reviews by Kelly and Kolstad (1999b) and Weyant *et al.* (1996). Back then as now, these models often take a very different approach from Nordhaus as they are highly disaggregated and not based on macroeconomic growth models. That is, many early IAMs took economic growth as exogenous and did not model dynamic equilibrium.[23] While this set-up permits the simulation of emissions and impacts across a detailed set of sectors, it has the disadvantage of lowering the models' transparency and portability into other macroeconomic frameworks and settings. As explained by Nordhaus (2013a):

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[23] Of course, there were early exceptions. For example, Scheraga *et al.* (1993) incorporate several sectoral climate impacts (e.g., agricultural production cost increases) into the computational general equilibrium model of Jorgenson and Wilcoxen. The aforementioned CETA and MERGE models are also dynamic equilibrium frameworks. In later years, many more neoclassical growth model-based IAMs were developed, often building on DICE directly or indirectly, as discussed in Section V. See also later literature reviews such as Nordhaus (2013a), Weyant (2017), and Hassler *et al.* (2016).

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> "A useful analogy here is to the animal kingdom. Each model is like an animal that has its useful niche in the policy ecosystem. Small models can be fleet and can adapt easily to a changing environment, while large models take many years to mature but are able to handle much larger and more complex tasks. There is room for all in the world of climate change science."

In sum, while there was rapid entry of computational modelers into the energy–economy–climate nexus in the early 1990s, the need for a transparent growth-model based climate–economy–optimization model remained, leaving DICE to become a keystone species.

V. DICE

Model Overview

> " 'God does not play dice with the universe' was Albert Einstein's reaction to quantum mechanics. Yet mankind *is* playing dice with its natural environment." (Nordhaus, 1994a)

In 1992, Nordhaus published the first version of the influential DICE model. It is based on a standard neoclassical (Ramsey–Cass–Koopmans) growth model, but adds the three key ingredients of (i) endogenous greenhouse gas emissions from economic activity, (ii) a carbon cycle and climate system representation, and (iii) climate change impacts on the economy. The model arguably exemplifies Albert Einstein's principle that "[e]verything should be made as simple as possible, but not simpler".[24] At this point in time, Nordhaus already had 20 years of experience in working with energy–economy and energy–climate models, and he had been at the forefront of the literature as it developed. This experience enabled him to make very deliberate choices about the relevant levels of detail to include, which would prove to be of enduring value.

We now review the central equations of the DICE model. We focus on the 2008 version as a compromise between the earliest and latest versions; see Nordhaus (2018a) for a review of DICE model changes over time. First, aggregate global output $Q(t)$ is produced with a standard Cobb–Douglas technology using capital $K(t)$ and labor $L(t)$ inputs:

$$Q(t) = \Omega(t)[1 - \Lambda(t)]A(t)K(t)^{\gamma}L(t)^{1-\gamma}. \tag{6}$$

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[24] While this quote is commonly attributed to Einstein, it is not actually clear whether he said those words as such. A closely related confirmed quote reads more specifically that "[i]t can scarcely be denied that the supreme goal of all theory is to make the irreducible basic elements as simple and as few as possible without having to surrender the adequate representation of a single datum of experience" (Robinson, 2018).

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Available output further depends on total factor productivity $A(t)$, on climate change impacts via $\Omega(t)$, and on greenhouse gas abatement expenditures via $\Lambda(t)$, both described below. Net output $Q(t)$ can be used for consumption $C(t)$ or investment $I(t)$:

$$Q(t) = C(t) + I(t). \tag{7}$$

Capital accumulates based on investment and the prior capital stock net of depreciation δ_k:

$$K(t) = (1 - \delta_k)K(t - 1) + I(t - 1). \tag{8}$$

In lieu of the detailed energy sector modeling in Nordhaus' early work, economic activity in DICE is linked to industrial greenhouse gas emissions in a "reduced-form" way. On the one hand, there is a baseline emissions intensity $\sigma(t)$, which reflects the economy's current and expected future emissions per dollar of GDP in a business-as-usual scenario. This parameter can be calibrated to match competing predictions of future autonomous energy efficiency improvements. On the other hand, a fraction $\mu(t)$ of emissions can be abated through implicit investments in appropriate technologies. Net industrial emissions $E_{Ind}(t)$ are thus given by

$$E_{Ind}(t) = [1 - \mu(t)]\sigma(t)Q(t). \tag{9}$$

The limited nature of fossil fuel resource endowments is further captured with a constraint that cumulative carbon usage cannot exceed $CCum$:

$$CCum \geq \sum E_{Ind}(t). \tag{10}$$

Next, the total costs of emissions reductions $\mu(t)$ are specified as a fraction of aggregate output $\Lambda(t)$ via

$$\Lambda(t) = \pi(t) \cdot \theta_1(t)\mu(t)^{\theta_2}. \tag{11}$$

Intuitively, the higher the fraction of emissions avoided (e.g., $\mu(t) = 0.5$ implies an emissions reduction of 50 percent), the higher the fraction of GDP that must be spent on abatement, $\Lambda(t)$. The parameters $\theta_1(t)$ and θ_2 governing the shape of this function are estimated based on the results of detailed quantitative energy–economy models and on cost estimates for specific technologies. The variable $\pi(t)$ shifts abatement costs in the case of incomplete participation in global climate policy. Intuitively, the costs of reducing global emissions by a given amount are considerably higher if this abatement is undertaken by a few countries rather than spread across many nations. Letting $\varphi(t)$ denote the climate policy participation rate, $\pi(t)$ is thus specified as

$$\pi(t) = \varphi(t)^{1-\theta_2}. \tag{12}$$

Net industrial emissions $E_{Ind}(t)$ and exogenous land-based emissions $E_{Land}(t)$ then enter the carbon cycle through the atmosphere. The 2008 version of DICE tracks three carbon reservoirs: the atmosphere AT, the upper ocean and biosphere UP, and the lower ocean LO, with coefficient matrix ϕ governing transfer rates between reservoirs:

$$\begin{pmatrix} M_{AT}(t) \\ M_{UP}(t) \\ M_{LO}(t) \end{pmatrix} = \begin{pmatrix} \phi_{11} & \phi_{21} & 0 \\ \phi_{12} & \phi_{22} & \phi_{32} \\ 0 & \phi_{23} & \phi_{33} \end{pmatrix} \begin{pmatrix} M_{AT}(t-1) \\ M_{UP}(t-1) \\ M_{LO}(t-1) \end{pmatrix} + \begin{pmatrix} E_{Ind}(t) + E_{Land}(t) \\ 0 \\ 0 \end{pmatrix}. \tag{13}$$

One of the important innovations of the DICE model compared with Nordhaus' earlier work was that it featured not only the carbon cycle, but also the climate system. That is, the DICE model introduced a final link from atmospheric carbon concentrations to global temperature. Nordhaus' approach built closely on the Schneider–Thompson climate model (Schenider and Thompson, 1981), which represented temperature dynamics across layers such as the atmosphere and the ocean through a parsimonious set of equations. Formally, in DICE, increases in atmospheric carbon $M_{AT}(t)$ lead to an increase in the Earth's net radiative energy balance, or radiative forcing $F(t)$ (measured in watts per square meter), as first noted by Arrhenius (1896):

$$F(t) = \eta \left\{ \log_2 \left[\frac{M_{AT}(t)}{M_{AT}(1750)} \right] \right\} + F_{EX}(t). \tag{14}$$

Here, $F_{EX}(t)$ denotes exogenous forcings, such as from aerosols and certain chemicals (e.g., chlorofluorocarbons), and η is a parameter. Finally, increased forcings raise atmospheric temperatures $T_{AT}(t)$. DICE models this process along with ocean temperatures $T_{LO}(t)$ in order to capture heat exchange between the atmosphere and upper ocean and the deep ocean, and the resulting warming delays:

$$\begin{pmatrix} T_{AT}(t) \\ T_{LO}(t) \end{pmatrix} = \begin{pmatrix} (1 - \xi_1\xi_2 - \xi_1\xi_3) & \xi_1\xi_3 \\ (1-\xi_4) & \xi_4 \end{pmatrix} \begin{pmatrix} T_{AT}(t-1) \\ T_{LO}(t-1) \end{pmatrix} + \begin{pmatrix} \xi_1 F(t) \\ 0 \end{pmatrix}. \tag{15}$$

Here, ξ' are parameters governing heat transfer rates. Next, a critical element of integrated assessment is that atmospheric warming $T_{AT}(t)$ links back to the economy and human welfare via the impact function $\Omega(t)$,

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which is specified as

$$\Omega(t) = \frac{1}{1 + \pi_1 T_{AT}(t) + \pi_2 T_{AT}(t)^2}. \tag{16}$$

The quantification of the damage function has evolved considerably over the years as more research has become available. Consider agricultural impacts. Early estimates were only available for the United States. The synthesis by Nordhaus (1994a) suggested a benchmark estimate of around 5 percent of agricultural output lost from atmospheric CO_2 doubling. He extrapolated to other countries by econometrically estimating the association of per capita GDP and agricultural output shares, and by combining these estimates with future GDP growth projections for each country. In contrast, within a few years, agricultural impact estimates had become available for a wider range of countries and regions, permitting Nordhaus and Boyer (2000) to utilize local estimates in an updated damage function calibration. The latest iterations of DICE aggregate overall impact estimates statistically across a detailed review of the literature (Nordhaus, 2017; Nordhaus and Moffat, 2017). In DICE 2016, the income-equivalent[25] loss from a doubling in CO_2 concentrations corresponds to 2.1 percent of global GDP (Nordhaus, 2017). If this figure seems modest, it might be useful to remember that world GDP declined by "only" 1.73 percent during the Great Recession of 2009.[26]

The final element of DICE is its objective or social welfare function, which is specified as the present value of the population $L(t)$-weighted utility $U(.)$ over per capita consumption $c(t) \equiv C(t)/L(t)$:

$$\begin{aligned} W &\equiv \sum_t U[c(t), L(t)](1+\rho)^{-t} \\ &= \sum_t L(t) \left\{ \frac{[c(t)]^{1-\alpha} - 1}{1-\alpha} \right\} (1+\rho)^{-t}. \end{aligned} \tag{17}$$

Here, α captures the degree of curvature in the utility function, and ρ defines the pure rate of social time preference. Both are highly consequential parameters for climate policy as they reflect the rate at which society is willing to trade off consumption in the present versus the future and across generations with different levels of income. The DICE model calibrates these parameters to match empirically observed savings

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[25] One important point to note is that DICE seeks to include estimates of non-market costs and ecosystems losses in quantifications of equation (16), if largely by assumption due to the lack of quantitative evidence.

[26] Of course, the disruptive nature of these events is not comparable. The Great Recession involved a sudden year-on-year decline in GDP levels, whereas $\Omega(t)$ corresponds to a reduction in GDP-equivalent *relative to its potential* in the absence of climate change.

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and interest rates so as to reflect both society's revealed preferences and the opportunity cost of investing in climate abatement over alternative assets (e.g., health research, tech start-ups, etc.). As is well known, this approach is not without its critics (e.g., Stern, 2007), and DICE has also been used to study alternative approaches, as discussed below.

In full optimization mode, DICE then effectively maximizes equation (17) subject to constraints (6)–(16) by choice of capital investments $I(t)$ and abatement rates $\mu(t)$. The model can also be run in business-as-usual mode with no controls on carbon emissions ($\mu(t) = 0$), or in cost-effectiveness mode to identify the least-cost way of achieving an additionally specified policy goal, such as keeping temperature change below 2° C. As is standard, the resulting primal solution for the optimal allocation can be decentralized as a competitive equilibrium through appropriate choices of prices and policies. The *optimal carbon tax* at each point in time, then, is simply the *marginal abatement cost* evaluated at the desired abatement level $\mu^*(t)$ or, equivalently, the *social cost of carbon* as defined in equation (5).[27] Of course, the optimal allocation can also be decentralized by an appropriately designed emissions trading scheme. Beyond these basic runs, DICE can also be used to study a wide range of questions ranging from the welfare costs of delaying emissions reductions to the implications of clean energy innovations. As the benchmark results of DICE are both broadly familiar and best described by Nordhaus himself, we now turn the discussion towards extensions done by Nordhaus and others, and on the enormous influence of DICE in research and beyond. As noted by Dietz and Stern (2015): "To look only at Nordhaus's own studies with DICE is to understate its contribution hugely, because, by virtue of its simple and transparent unification of growth theory with climate science (not to mention Nordhaus's considerable efforts to make the model code publicly available), it has come to be very widely used by others."

Extensions and Influence

The unparalleled power of DICE as a basis for new research was apparent from the start. As its first iteration was published (Nordhaus, 1992), Kolstad (1993, 1994) had already built a model based on DICE to study uncertainty and learning about climate change (the "SLICE" model). Even Cline (1992b), who disagreed with aspects of Nordhaus' approach, used

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[27] To be clear, the optimal tax is not equal to the social cost of carbon if the latter is evaluated at a suboptimal allocation. In addition, marginal abatement costs as defined by equation (5) have an upper bound in DICE at $\mu = 100$ percent. At this point, the present value of marginal damages can diverge from the marginal abatement cost and, thus, the minimum tax required to implement the optimal allocation.

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the DICE model to formalize his arguments. Over the years, practically every element of DICE has been tested and extended by the literature, and countless studies have stood on its shoulders to investigate a kaleidoscope of questions. To give a sense of the richness of this influence, we now survey some examples.

Before proceeding, we stress that the following subsections highlight examples of the DICE model family in furthering the literature and do not constitute a general review. Even with this focus, there are thousands of studies citing and building on DICE. Apologies are thus extended to the many whose excellent work cannot be referenced here.

Uncertainty. While the DICE model is deterministic, it has enabled researchers to make significant progress towards understanding the vast and varied uncertainties that affect the climate problem. First, the comparatively small size of DICE permits extensive Monte Carlo analyses to assess the significance of uncertainty over each of its elements. Nordhaus (1994a) already devotes three out of eight book chapters to uncertainty. Nordhaus has continually produced dedicated analyses on this topic, including a probabilistic PRICE model extension (Nordhaus and Popp, 1997), updated uncertainty analyses with new DICE iterations (e.g., Nordhaus, 2008), and recently also a multimodel comparison together with five other IAMs (Gillingham *et al*., 2018).

On the one hand, these analyses illuminate the key sources of uncertainty afflicting our predictions of the future. For example, Gillingham *et al.* (2018) find that uncertainty over future economic growth is a significantly larger contributor to uncertainty over model outcomes than uncertainty over the equilibrium climate sensitivity or population growth. Another surprising result of this multimodel comparison is that parametric uncertainty dominates model uncertainty. That is, what we collectively do not know as a modeling community constitutes a larger source of uncertainty than the differences between our models.

On the other hand, these analyses have also illustrated the various channels through which uncertainty can affect climate policy design. For example, uncertainty about future climate change and damages renders stricter policy more desirable as insurance against worse outcomes (Nordhaus, 1994a). At the same time, if the states of the world where climate damages are unexpectedly high are also states of the world in which consumption levels are high (e.g., because of high future productivity growth), then this insurance value is diminished (Nordhaus, 2008).[28]

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[28] This question of the "climate beta" has received increasing attention in the literature. See, for example, Dietz *et al*. (2018) for a recent analysis building on DICE.

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Another consideration is the option value of waiting to learn more about climate change. Kelly and Kolstad (1999a) build on DICE to highlight this channel in a stochastic dynamic programming (SDP) extension with Bayesian learning over the climate's sensitivity to carbon dioxide, finding ambiguous net impacts on optimal policy. Several recent studies have developed SDP extensions of DICE, and have documented similarly nuanced results.[29] For example, Jensen and Traeger (2014) find that the impacts of output growth uncertainty on the optimal carbon price differ considerably depending on whether preferences are as in equation (17) or Epstein–Zin (Epstein and Zin, 1989; Weil, 1990). Crost and Traeger (2014) similarly find that the effects of damage function coefficient uncertainty can differ depending on whether the level or curvature of equation (16) is uncertain. DICE has also been used to study specific damage function uncertainties such as "tipping points" in the climate system. While Nordhaus (1980) already considered optimal climate policy with known tipping points, Lemoine and Traeger (2014) do so in a stochastic framework; see also the "DSICE" model analysis of Cai *et al*. (2018), which considers climate and economic uncertainty jointly.[30] Newer work has further considered richer sets of uncertainty. For example, Rudik (2019) introduces a DICE-based robust control framework that allows for consideration of structural damage function uncertainty and unknown model misspecification. Perhaps surprisingly, these are found to have only modest effects on optimal climate policy. Finally, other studies have used DICE to investigate more specific issues such as the consumption discounting implications of interest rate uncertainty (Newel and Pizer, 2003). In sum, while the literature does not yet provide harmonized answers to how different types of uncertainty should alter climate policy design (Lemoine

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[29] A fundamental trade-off between the Monte Carlo and SDP approaches is as follows. On the one hand, Monte Carlo analyses can simultaneously consider uncertainty over many if not all model parameters, whereas SDP frameworks have traditionally only been able to consider one or two sources of uncertainty at a time (see Lemoine and Rudik, 2017). On the other hand, SDP models formally capture decision-making under uncertainty, whereas Monte Carlo analyses do not (Crost and Traeger, 2013). Thus, several scholars have also innovated mixed approaches. For example, Nordhaus and Popp (1997) utilize results from a sophisticated Monte Carlo analysis to summarize uncertainty over all parameters into five "states of the world", which they then consider in an SDP (expected utility maximization) variant of DICE, the PRICE model. Another example, Pizer (1999), utilizes an analytical approximation to household decision-rules in order to consider a broader range of uncertainty in an SDP extension of DICE.

[30] At the extreme, Weitzman (2009) and others have raised concerns over cost–benefit climate policy analyses not accounting for "fat tails". Recent work seeking to incorporate the possibility of extreme parameter realizations in DICE suggests that a combination of both extremely high temperature sensitivity and climate damage sensitivity in a no-policy scenario are required to produce catastrophic outcomes (e.g., Ackerman *et al*., 2010; Nordhaus, 2013a).

and Rudik, 2017), it does illustrate the power of DICE as a foundation for these important investigations.

Endogenous Technical Change. While the DICE model treats technological change as exogenous, it has enabled researchers to consider competing specifications of endogenous technological change (ETC), building also on the work of fellow 2018 Nobel Laureate Paul Romer. Two important advantages of DICE in this realm are that its tractability facilitates appropriately extensive sensitivity analyses given the high degree of uncertainty in quantifications of ETC, and that it allows for both cost-effectiveness and cost–benefit analysis of climate policy. Goulder and Mathai (2000) introduce two types of ETC (i.e., R&D investments and learning-by-doing) into a DICE-based framework. They find that the resulting policy implications might be large for cost-effective carbon taxes, but are modest for *optimal* climate policy. Intuitively, ETC might lower the carbon tax necessary to meet a given emissions reduction target, but it might also increase the optimal abatement level, thus having a smaller net effect on optimal carbon pricing. Nordhaus (2002) finds similar results in introducing the R&DICE model, which allows firms to lower the carbon intensity of production $\sigma(t)$ through R&D expenditures. While this form of ETC contributes to emissions reductions, its effects are quantitatively modest. At the same time, Nordhaus notes the importance of market failures due the divergence of private and social returns to research. Popp (2004) confirms these general findings in the ENTICE model, which also builds on DICE but incorporates ETC in a richer set of ways. David Popp, a former Nordhaus student, has become a leader in this field, contributing to both modeling and empirical advancements of ETC (e.g., Popp, 2002). Despite these consistent early results, many questions remain unanswered, and the nexus of ETC and climate policy remains a highly active area of research (see the review by Gillingham *et al*., 2008). Relevant to the present discussion, influential recent work such as that by Acemoglu *et al*. (2012) – which allows for directed technical change in both dirty and clean inputs, and finds a significant role for clean energy research subsidies – has continued to build on Nordhaus' work for core specifications and quantifications.

Spatial Heterogeneity. DICE is a global model that aggregates climate impacts, policies, and factors across countries. Though tractable, a global framework provides limited insights into regionally differentiated climate policies, such as the landmark Kyoto Protocol (in 1997), an international agreement of a select group of countries to reduce their greenhouse gas

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emissions. Nordhaus thus developed the RICE (Regional Integrated Model of Climate and the Economy) model, a multiregion version of DICE, in collaboration with his former student and climate change economist Zili Yang (Nordhaus and Yang, 1996). They used the model to compare climate outcomes and welfare across regions under business-as-usual, non-cooperative (Nash equilibrium), and idealized cooperative climate policy regimes. In updated versions, including joint work with Joseph Boyer (Nordhaus and Boyer, 2000), Nordhaus used variants of RICE to analyze international agreements such as the Kyoto Protocol (Nordhaus and Boyer, 1999) and the Copenhagen Accord (Nordhaus, 2010a). More recently, Nordhaus built on RICE to develop an international coalition-building model and to introduce the concept of "climate clubs", as described below (Nordhaus, 2015).

Despite its richness, the RICE model is again sufficiently transparent and accessible that it has been used extensively by others. Scholars have utilized RICE to analyze climate policy implications of issues such as inter-regional inequality aversion (Anthoff and Emmerling, 2019), age-specific demographics (Fenichel *et al.*, 2017), and technological change with spillovers (e.g., the FEEM–RICE model by Bosetti *et al.*, 2006; Buonanno *et al.*, 2003). Hassler and Krusell (2012) extend RICE in a decentralized equilibrium setting and study carbon leakage in oil markets from regional climate policies. Leading new work by Krusell and Smith (2018) formalizes the heterogeneous agent representation and considers a much finer degree of spatial disaggregation than RICE, but also builds on Nordhaus' work in its general approach and in relying on the G-Econ spatial economic database (Nordhaus *et al.*, 2006).

One particularly innovative new development based on RICE is Nordhaus' analysis of "climate clubs". While serving as President of the American Economic Association, Nordhaus began his 2015 presidential address by noting that international free-riding remains the most vexing and unresolved aspect of climate change. As a potential mechanism to overcome this classic public goods problem, Nordhaus proposed a "climate club", which would consist of two parts: (i) an agreement by a group of countries to undertake emissions reductions through a harmonized carbon price, and (ii) a penalty jointly levied upon non-participating countries in the form of a small uniform percentage tariff.[31] In order to investigate the viability of such a scheme, Nordhaus developed the Coalition-DICE (C-DICE) model,

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[31] Some prior literature and policy discussions have considered "carbon tariffs" based on the carbon content of imported goods. In theory, such a duty would level the playing field and alleviate trade disadvantages for countries adopting carbon pricing. However, Nordhaus (2015) notes that "studies of carbon duties indicate they are complicated to design, have limited coverage, and do little to induce participation".

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which is based on RICE and designed to analyze coalition stability with such trade levies. The results are remarkable: all regions would find it advantageous to join a climate club with a harmonized carbon price of $25 per ton CO_2 given non-participation penalties as low as a 3 percent tariff. The net economic benefits associated with climate clubs are enormous, potentially of the order of hundreds of billions of dollars.

While some might be quick to question the legal and political viability of such tariffs, it should be noted that many policies of today would have been unthinkable in the not-too-distant past. "What is toxic or opposed in one generation gradually becomes accepted in the next. Social security took a long time. It was opposed for many, many decades but since Reagan it has been widely accepted," Nordhaus commented in a recent interview.[32]

Broader Literature. The broader literature builds on Nordhaus' work in myriad ways across multiple fields and generations. On the one hand, there is a wealth of literature directly extending DICE, with applications spanning topics as diverse as overlapping generations (e.g., Howarth, 1998; Leach, 2009), limited substitutability between environmental and market goods (Sterner and Persson, 2008), carbon tax interactions with fiscal policy (Barrage, 2019), disagreement about discount rates (Heal and Millner, 2014), and climate policy design from the perspective of policy-makers who are agnostic about climate science (Rezai and van der Ploeg, 2019). On the other hand, Nordhaus' work has informed the development of other IAMs, which have, in turn, spawned further academic offspring. For example, the analytically tractable decentralized equilibrium climate–economy model of Golosov *et al.* (2014) builds on DICE in numerous ways, and has itself become highly influential as a basis for other studies. Finally, macroeconomics as a field has come to recognize the importance of climatic and environmental processes. Growth scholars ranging from Acemoglu *et al.* (2012) to Brock *et al.* (2014) and Desmet and Rossi-Hansberg (2015) have followed Nordhaus in integrating climate change into their growth models. Indeed, "Environmental Macroeconomics" now features as a chapter in the *Handbook of Macroeconomics*, based on the foundations of Nordhaus' work (Hassler *et al.*, 2016). In sum, whether directly or indirectly, a prodigious body of literature thus ultimately stands on Nordhaus' shoulders.[33]

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[32] See the article "After Nobel in Economics, William Nordhaus Talks About Who's Getting His Pollution-Tax Ideas Right" by Coral Davenport, in the *New York Times*, 13 October 2018 (https://www.nytimes.com/2018/10/13/climate/nordhaus-carbon-tax-interview.html).

[33] Of course, we must also acknowledge the vast number of IAMs that have been independently developed by research teams around the world over the past years; see, for example, newer reviews by Nordhaus (2013a), Weyant (2017), and Clarke *et al.* (2009).

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Policy Impacts

Taking a step back, we recall that Nordhaus initially diagnosed the lack of a carbon price as an impediment to sustainable long-run growth. He worked for decades to produce a transparent, credible, and widely applied framework that could quantify this missing carbon price (i.e., the SCC estimates). As of 2018, an estimated 46 countries and 24 subnational jurisdictions have levied a price on carbon emissions (World Bank, 2018), and 17 out of 23 OECD countries recently reported using SCC values in public cost–benefit analyses (Smith and Braathen, 2015). Even beyond the idea of carbon pricing, Nordhaus' work is too influential as a fundamental way of thinking about the climate problem to trace out his policy impacts comprehensively. As is well known – including from other work by Nordhaus and his fellow 2018 Nobel Laureate Paul Romer – the social returns to research and new ideas greatly exceed the credit that innovators privately receive.

For a recent example of this continued general influence, consider the European Union's debate about whether and how to adjust its greenhouse gas emissions trading scheme in the wake of the 2009 financial crisis. The European Economic and Social Committee (EESC) eventually issued the following official opinion:[34]

> "There is a broad consensus that setting an appropriate, generally accepted price on carbon is key to a successful climate change policy (William D. Nordhaus, Economic Issues in a Designing a Global Agreement on Global Warming). If the price of carbon is not set appropriately and is not generally accepted, it cannot have an incentivising effect. [. . .] Therefore the EESC calls on the European Commission to present options to strengthen the EU ETS, and consistent measures in the non-ETS sectors."

Beyond this broad influence of Nordhaus' ideas, his specific research findings have also contributed to international climate policy compendia such as the UK Stern Review on the Economics of Climate Change (Stern, 2007) and the Intergovernmental Panel on Climate Change's Assessment Reports (IPCC, 2001, 2007, 2014).

Most directly, the US Government has used DICE to value the social cost of carbon for regulatory impact analysis. After the US Supreme Court ruled in 2007 that carbon dioxide and other greenhouse gases should be regulated as "air pollutants" under the US Clean Air Act, there was no

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[34] Opinion of the European Economic and Social Committee on "The impact of the crisis on the ability of European firms to undertake pro-climate investments", 2012/C 24/02.

established figure for how to value these emissions in regulatory impact analyses (Nordhaus, 2014). Several rule-makings in 2009 relied on a review by Tol (2005), which already included several SCC estimates by Nordhaus and co-authors (listed in the Appendix). In 2010, an Interagency Working Group (IWG) was formed to produce a harmonized set of SCC estimates for use by the US federal government (Greenstone *et al*., 2013). Their analysis used DICE along with two other IAMs: the PAGE model by Hope (2006) and Hope *et al*. (1993), and the FUND model by Tol (1997) and Anthoff and Tol (2008, 2014). By our accounting, these and the survey-based SCC estimates have been used in regulatory impact analyses for over 70 US final rule-makings to date (listed in the Appendix). While the Trump Administration has disbanded the IWG (Executive Order 13793, 2018), its SCC estimates are still used to inform climate policy design.[35] First, several US states have used the IWG SCC estimates. For example, the public utility commissions of several states, such as those of Colorado and Minnesota, have adopted IWG SCC figures in their proceedings and resource planning (Paul *et al*., 2017). California's Air Resources Board is using the IWG SCC figures in its climate policy planning, and both Illinois and New York have used the IWG SCC figures in setting subsidy rates for zero-emissions electricity. Second, other countries such as Canada have adopted modified versions of the IWG SCC figures for regulatory impact analysis.[36] Finally, several federal US carbon tax policy proposals introduced in Congress have been based on the IWG SCC figures, highlighting their continued policy relevance going forward.[37]

VI. Conclusion

> "We need to approach the issues with a cool head and a warm heart. And with respect for sound logic and good science." (Nordhaus, 2012a)

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[35] One contentious issue is whether the United States should consider only domestic or global impacts of its regulations. The IWG had focused on the global SCC, whereas the Trump Administration has posited an alternative value for the domestic SCC in its regulatory impact assessments (see the Regulatory Impact Analysis for Review of the Clean Power Plan: Proposal, US Environmental Protection Agency, October 2017).

[36] For example, the Policy on Cost–Benefit Analysis, Treasury Board of Canada Secretariat, Government of Canada (2018). For a survey of other countries' uses of SCC values in cost–benefit analysis, see Smith and Braathen (2015).

[37] The American Opportunity Carbon Fee Act (S.2368) is directly motivated by the IWG estimates (Whitehouse, 2017). Other recent proposals consider carbon prices in the relevant \$15 to \$50 range (Ye, 2018).

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In 2019, the world finds itself at a divisive moment. In the United States, President Trump has denounced climate change as “a hoax”, while Democrats in Congress are pushing for a “Green New Deal” of aggressive measures striving to eliminate greenhouse gas emissions within a decade. At first glance, one may wonder how much has really changed since Nordhaus’ 1977 description of debates about the environment and the economy as “divided between one group crying ‘wolf’ and another which denies that species’ existence”. Beneath the surface, however, there have been tectonic shifts of progress emanating from the scientific community. Here, we conclude by reviewing Nordhaus’ contributions to elevating scholarly and public debates to higher levels of rigor and openness, and to fostering a shared understanding of the issues.

First, since Nordhaus introduced the idea of carbon taxes in 1977, economists from across the political spectrum have come to support carbon pricing with unique levels of agreement and enthusiasm. A bipartisan group of over 3,500 economists recently issued a formal statement in support of carbon pricing in the United States, including numerous former Chairs of the US Federal Reserve and of the Council of Economic Advisers.[38]

Second, while significant disagreements remain among economists about the appropriate level for such prices and the social cost of carbon, Nordhaus has led the literature by example through in-depth engagements with alternative points of view. Consider, for example, the critique of utility discounting of future generations as unethical by Stern (2007) – that is, ρ in equation (17) – or the “Dismal Theorem” critique by Weitzman (2009) that “fat-tailed” risks render the climate problem unsuitable for cost–benefit analysis. Nordhaus not only wrote dedicated analyses carefully responding to these ideas (Nordhaus, 2007, 2009), but he has also maintained an academic dialogue with them throughout his subsequent work.[39] In his official Nobel Lecture, Nordhaus added: “A special word of thanks to my critics, because those are the people you learn from the most.”[40]

At its core, this serious engagement with new ideas, findings, and opposing points of view reflects Nordhaus’ core desire to *get things right*, earning him a reputation for being “careful and apolitical” (Gillingham,

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[38] See the Economists’ Statement on Carbon Dividends, available on the Climate Leadership Council website, https://www.clcouncil.org/economists-statement/.

[39] For example, Nordhaus routinely reports “Stern Review discounting” scenarios along with standard DICE model results (e.g., Nordhaus, 2017), and has devoted entire book chapters to scholarly engagement with Stern’s perspective (e.g., Nordhaus, 2008). Nordhaus has also repeatedly returned to the question of “fat tails” in his analyses of uncertainty and climate change, such as by studying under which parametric and policy scenarios catastrophic risks might arise (e.g., Nordhaus, 2013a; Gillingham *et al.*, 2018).

[40] Transcribed from the Nobel Lecture video available from Nobel Media at https://www.nobelprize.org/prizes/economic-sciences/2018/nordhaus/lecture/.

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2018). A third contribution in this regard is that Nordhaus has continually pushed the literature towards transparency and critical self-assessments. In recent work, he shines a light both on the prediction errors in his own past work (Nordhaus, 2018a), and on thorny questions about computational complexity and errors in the broader literature (Nordhaus, 2012b). In Gillingham *et al.* (2018), Nordhaus joins forces with several IAM modeling groups in order to push the frontier on multimodel comparisons so as to illuminate key uncertainties afflicting our projections of the future.

Fourth, Nordhaus has also led by example in engaging with climate change skeptics. Responding to a *Wall Street Journal* editorial entitled "No Need to Panic About Global Warming", Nordhaus wrote a pointed, fact-based response, "Why the Global Warming Skeptics Are Wrong" (Nordhaus, 2012a), which quickly became a sensation in itself. One of the misleading claims by the skeptics pertained to Nordhaus' work and the costs of delaying climate policy for 50 years. In response, Nordhaus created a dedicated Excel version of the RICE model and posted it to his website with instructions for anyone to run the model and see for themselves.[41] This episode again demonstrates the power of Nordhaus' transparent approach as a teaching tool, and universities from around the world have incorporated Nordhaus' work into their curricula.[42] Nordhaus' response further illustrates his desire to be open, fact-based, and rigorous. "The history of science tells us that we need to be alert to the possibility of allowing a false consensus," he wrote in Nordhaus (2013b). "The correct response to critics is to look carefully at their arguments and determine whether they do indeed undermine standard theories. Scientists and economists need to confront contrary arguments with the same vigor with which they argue for the validity of their own approaches."

Finally, it should be clear at this point that Nordhaus has led the way in building bridges between the natural and economic sciences. The Nobel Prize announcement commended that he "significantly broadened the scope of economic analysis by constructing models that explain how the market economy interacts with nature" (Royal Swedish Academy of Sciences, 2018). Importantly, however, Nordhaus has continued to lead in this engagement, noting that the "findings [of our models] must be qualified and constantly updated because of the uncertainties involved at all stages"

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[41] Though no longer available on Nordhaus' website, the Internet Archive (Wayback Machine) snapshot of his website from 21 July 2012 features the link to the RICE, "Model available for NYRB readers (March 2012)", as can be seen at https://web.archive.org/web/20120721224053/http://www.econ.yale.edu/~nordhaus/homepage/RICEmodels.htm.

[42] For example, Nordhaus' response to the skeptics' editorial can be found on syllabi ranging from MBA courses (Slaughter, 2014) to undergraduate courses on climate change economics (e.g., Bosetti, 2018) and MPA courses at policy schools (e.g., Pizer, 2018).

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(Nordhaus, 2013b). To this end, for example, the latest version of DICE incorporates a novel representation of Greenland ice sheet dynamics that can account for hysteretic or irreversible effects of a rise in sea level (Nordhaus, 2018b).

As noted at the beginning of this article, the rich and ever-expanding literature on the economics of climate change and sustainable growth now feature many studies that incorporate climatic processes into economic analyses. At this point, however, the ubiquity of this approach shall leave no doubt about the enormity of its contribution, which we owe to the curiosity, brilliance, and scholarship of William D. Nordhaus.

Appendix

Table A1 lists the US Federal (Final) Rules using SCC estimates either from the Interagency Working Group (which uses DICE as one of three models to estimate the SCC) or based on a survey by Tol (2005), which also included several DICE- and RICE-based estimates. The list was compiled by searching the Federal Register website for final rules referencing the "social cost of carbon", and manually sorting through the results to confirm the relevant SCC was used (as opposed to, for example, merely mentioned in a comment).

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Table A1. *US Federal Final Rules using the SCC in impact analysis*

Rule title	Agency	Date
Energy Conservation Program: Energy Conservation Standards for Walk-In Cooler and Freezer Refrigeration Systems	DOE	10/07/2017
Energy Conservation Program: Energy Conservation Standards for Residential Central Air Conditioners and Heat Pumps	DOE	26/05/2017
Energy Conservation Program: Energy Conservation Standards for Dedicated-Purpose Pool Pumps	DOE	26/05/2017
Energy Conservation Program: Energy Conservation Standards for Miscellaneous Refrigeration Products	DOE	26/05/2017
Energy Conservation Program: Energy Conservation Standards for Ceiling Fans	DOE	19/01/2017
Energy Conservation Program: Energy Conservation Standards for Dedicated-Purpose Pool Pumps	DOE	18/01/2017
Energy Conservation Program: Energy Conservation Standards for Residential Central Air Conditioners and Heat Pumps	DOE	06/01/2017
Stream Protection Rule	DOI; OSMRE	20/12/2016
Roadless Area Conservation; National Forest System Lands in Colorado	USDA; FS	19/12/2016
Energy Conservation Program: Energy Conservation Standards for Residential Dishwashers	DOE	13/12/2016
Minimum Training Requirements for Entry-Level Commercial Motor Vehicle Operators	DOT; FMCSA	08/12/2016
Energy Conservation Program: Energy Conservation Standards for Miscellaneous Refrigeration Products	DOE	28/10/2016
Cross-State Air Pollution Rule Update for the 2008 Ozone NAAQS	EPA	26/10/2016
Emission Guidelines and Compliance Times for Municipal Solid Waste Landfills	EPA	29/08/2016
Standards of Performance for Municipal Solid Waste Landfills	EPA	29/08/2016
Energy Conservation Program: Energy Conservation Standards for Battery Chargers	DOE	13/06/2016
Energy Conservation Program: Energy Conservation Standards for Dehumidifiers	DOE	13/06/2016
Energy Conservation Program: Energy Conservation Standards for Commercial Prerinse Spray Valves	DOE	27/01/2016
Energy Conservation Program: Energy Conservation Standards for Pumps	DOE	26/01/2016
Energy Conservation Program: Energy Conservation Standards for Residential Boilers	DOE	15/01/2016
Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards for Small, Large, and Very Large Air-Cooled Commercial Package Air Conditioning and Heating Equipment and Commercial Warm Air Furnaces	DOE	15/01/2016

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Table A1. *Continued*

Rule title	Agency	Date
Energy Conservation Program: Energy Conservation Standards for Refrigerated Bottled or Canned Beverage Vending Machines	DOE	08/01/2016
Energy Conservation Program: Energy Conservation Standards for Ceiling Fan Light Kits	DOE	06/01/2016
Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category	EPA	03/11/2015
Carbon Pollution Emission Guidelines for Existing Stationary Sources: Electric Utility Generating Units	EPA	23/10/2015
Standards of Performance for Greenhouse Gas Emissions From New, Modified, and Reconstructed Stationary Sources: Electric Utility Generating Units	EPA	23/10/2015
Energy Conservation Program: Energy Conservation Standards for Single Package Vertical Air Conditioners and Single Package Vertical Heat Pumps	DOE	23/09/2015
Energy Conservation Program: Energy Conservation Standards for Packaged Terminal Air Conditioners and Packaged Terminal Heat Pumps	DOE	21/07/2015
Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards and Test Procedures for Commercial Heating, Air-Conditioning, and Water-Heating Equipment	DOE	17/07/2015
Final Affordability Determination-Energy Efficiency Standards	USDA; HUDD	06/05/2015
Energy Conservation Program: Energy Conservation Standards for Automatic Commercial Ice Makers	DOE	28/01/2015
Energy Conservation Program: Energy Conservation Standards for General Service Fluorescent Lamps and Incandescent Reflector Lamps	DOE	26/01/2015
Energy Conservation Program: Energy Conservation Standards for Commercial Clothes Washers	DOE	15/12/2014
National Pollutant Discharge Elimination System-Final Regulations To Establish Requirements for Cooling Water Intake Structures at Existing Facilities and Amend Requirements at Phase I Facilities	EPA	15/08/2014
Energy Conservation Program for Consumer Products: Energy Conservation Standards for Residential Furnace Fans	DOE	03/07/2014
Energy Conservation Program: Energy Conservation Standards for Walk-In Coolers and Freezers	DOE	03/06/2014
Energy Conservation Program: Energy Conservation Standards for Commercial and Industrial Electric Motors	DOE	29/05/2014
Energy Conservation Program: Energy Conservation Standards for Commercial Refrigeration Equipment	DOE	28/03/2014

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Table A1. *Continued*

Rule title	Agency	Date
Energy Conservation Program: Energy Conservation Standards for External Power Supplies	DOE	10/02/2014
Energy Conservation Program: Energy Conservation Standards for Metal Halide Lamp Fixtures	DOE	10/02/2014
Energy Conservation Program: Energy Conservation Standards for Standby Mode and Off Mode for Microwave Ovens	DOE	17/06/2013
Energy Conservation Program: Energy Conservation Standards for Distribution Transformers	DOE	18/04/2013
National Emission Standards for Hazardous Air Pollutants for Major Sources: Industrial, Commercial, and Institutional Boilers and Process Heaters	EPA	31/01/2013
2017 and Later Model Year Light-Duty Vehicle Greenhouse Gas Emissions and Corporate Average Fuel Economy Standards	EPA; DOT; NHTSA	15/10/2012
Energy Conservation Program: Energy Conservation Standards for Dishwashers	DOE	01/10/2012
Standards of Performance for Petroleum Refineries; Standards of Performance for Petroleum Refineries for Which Construction, Reconstruction, or Modification Commenced After May 14, 2007	EPA	12/09/2012
Oil and Natural Gas Sector: New Source Performance Standards and National Emission Standards for Hazardous Air Pollutants Reviews	EPA	16/08/2012
Energy Conservation Program: Energy Conservation Standards for Residential Clothes Washers	DOE	31/05/2012
Energy Conservation Program: Energy Conservation Standards for Residential Dishwashers	DOE	30/05/2012
Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards and Test Procedures for Commercial Heating, Air-Conditioning, and Water-Heating Equipment	DOE	16/05/2012
National Emission Standards for Hazardous Air Pollutants From Coal- and Oil-Fired Electric Utility Steam Generating Units and Standards of Performance for Fossil-Fuel-Fired Electric Utility, Industrial-Commercial-Institutional, and Small Industrial-Commercial-Institutional Steam Generating Units	EPA	16/02/2012
Energy Conservation Program: Energy Conservation Standards for Fluorescent Lamp Ballasts	DOE	14/11/2011
Greenhouse Gas Emissions Standards and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles	EPA; DOT; NHTSA	15/09/2011
Energy Conservation Program: Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers	DOE	15/09/2011

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Table A1. *Continued*

Rule title	Agency	Date
Federal Implementation Plans: Interstate Transport of Fine Particulate Matter and Ozone and Correction of SIP Approvals	EPA	08/08/2011
Energy Conservation Program: Energy Conservation Standards for Residential Furnaces and Residential Central Air Conditioners and Heat Pumps	DOE	27/06/2011
Energy Conservation Program: Energy Conservation Standards for Residential Clothes Dryers and Room Air Conditioners	DOE	21/04/2011
National Emission Standards for Hazardous Air Pollutants for Area Sources: Industrial, Commercial, and Institutional Boilers	EPA	21/03/2011
National Emission Standards for Hazardous Air Pollutants for Major Sources: Industrial, Commercial, and Institutional Boilers and Process Heaters	EPA	21/03/2011
Standards of Performance for New Stationary Sources and Emission Guidelines for Existing Sources: Commercial and Industrial Solid Waste Incineration Units	EPA	21/03/2011
Light-Duty Vehicle Greenhouse Gas Emission Standards and Corporate Average Fuel Economy Standards; Final Rule	EPA; DOT; NHTSA	07/05/2010
Energy Conservation Program: Energy Conservation Standards for Residential Water Heaters, Direct Heating Equipment, and Pool Heaters	DOE	16/04/2010
Regulation of Fuels and Fuel Additives: Changes to Renewable Fuel Standard Program	EPA	26/03/2010
Energy Conservation Program: Energy Conservation Standards for Small Electric Motors	DOE	09/03/2010
Energy Conservation Program: Energy Conservation Standards for Certain Consumer Products (Dishwashers, Dehumidifiers, Microwave Ovens, and Electric and Gas Kitchen Ranges and Ovens) and for Certain Commercial and Industrial Equipment (Commercial Clothes Washers)	DOE	08/01/2010

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Table A1. *Continued*

Rule title	Agency	Date
*Energy Conservation Program: Energy Conservation Standards for Refrigerated Bottled or Canned Beverage Vending Machines	DOE	31/08/2009
*Energy Conservation Program for Certain Industrial Equipment: Energy Conservation Standards and Test Procedures for Commercial Heating, Air-Conditioning, and Water-Heating Equipment	DOE	22/07/2009
*Energy Conservation Program: Energy Conservation Standards and Test Procedures for General Service Fluorescent Lamps and Incandescent Reflector Lamps	DOE	14/07/2009
*Energy Conservation Program: Energy Conservation Standards for Certain Consumer Products (Dishwashers, Dehumidifiers, Microwave Ovens, and Electric and Gas Kitchen Ranges and Ovens) and for Certain Commercial and Industrial Equipment (Commercial Clothes Washers)	DOE	08/04/2009
*Average Fuel Economy Standards Passenger Cars and Light Trucks Model Year 2011	DOT; NHTSA	30/03/2009
*Energy Conservation Program for Commercial and Industrial Equipment: Energy Conservation Standards for Commercial Ice-Cream Freezers; Self-Contained Commercial Refrigerators, Commercial Freezers, and Commercial Refrigerator-Freezers Without Doors; and Remote Condensing Commercial Refrigerators, Commercial Freezers, and Commercial Refrigerator-Freezers	DOE	09/01/2009

Source: Federal Register Search.

Notes: The table lists US Federal (Final) Rules using IWG SCC estimates in cost–benefit assessments. An asterisk indicates Tol (2005) survey-based SCC. The acronyms used are as follows: DOE, Department of Energy; EPA, Environmental Protection Agency; DOI, Department of Interior; OSMRE, Office of Surface Mining Reclamation and Enforcement; USDA, Department of Agriculture; FS, Forest Service; DOT, Department of Transportation; FMCSA, Federal Motor Carrier Safety Administration; HUDD, Housing and Urban Development Department; NHTSA, National Highway Traffic Safety Administration.

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