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Climate Change: The Ultimate Challenge for Economics†

By William Nordhaus*

The science of economics covers a vast terrain, as is clear from the history of Nobel awards in this area. Among the many fields that have been recognized are portfolio theory to reduce investment risk, the discovery of linear programming algorithms to solve complex allocation problems, econometric methods as a way of systematically understanding history and behavior, economic growth theory, and general-equilibrium theory as the modern interpretation of the invisible hand of Adam Smith.

The award this year concerns another of the many fields of economics. It involves the spillovers or externalities of economic growth, focusing on the economics of technological change and the modeling of climate-change economics. These topics might at first view seem to live in separate universes. The truth is that they are manifestations of the same fundamental phenomenon, which is a global externality or global public good. Both involve science and technology, and both involve the inability of private markets to provide an efficient allocation of resources. They also draw on the fields mentioned above as integral parts of the theoretical apparatus needed to integrate economics, risk, technology, and climate change.

The two topics not only share a common intellectual heritage, but also are both of fundamental importance. Technological change raised humans out of Stone Age living standards. Climate change threatens, in the most extreme scenarios, to return us economically whence we came. Humans clearly have succeeded in harnessing new technologies. But humans are clearly failing, so far, to address climate change.

My colleague Paul Romer has made fundamental contributions to understanding the global externality of knowledge, and we learn of that key discovery in his essay. This essay addresses the climate-change externality—its sources, its potential impacts, and the policy tools that are available to stem the rising tides and damages that this externality will likely bring to humans and the natural world. It draws upon my writings in the area, most of which are cited in the references.

* Department of Economics, Yale University, PO Box 208268, New Haven, CT 06520 (email: william.nordhaus@yale.edu). The research underlying this essay has benefited from the contributions of innumerable teachers, collaborators, students, and institutions, many of whom are mentioned below. Because they are so numerous and their contributions are so deep, I will mention only one, who was a guiding mentor and contributor for many decades, Tjalling Koopmans. He represents the spirit of courageous innovation in many fields of economics and can stand in for the many others whose work fills the equations and pages of climate-change economics.

This article is a revised version of the lecture William Nordhaus delivered in Stockholm, Sweden, on December 8, 2018 when he received the Bank of Sweden Prize in Economic Sciences in memory of Alfred Nobel.

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I. Climate Change as a Global Public Good

I begin with the fundamental problem posed by climate change—that it is a public good or externality. Such activities are ones whose costs or benefits spill outside the market and are not captured in market prices. These include positive spillovers like new knowledge and negative spillovers like pollution.

The two key attributes of a public good are, first, that the cost of extending the output to an additional person is zero ("nonrivalry") and, second, that it is impossible to exclude individuals from enjoying it ("nonexcludability"). The theory of public goods was developed by Samuelson (1954), the first American Nobel laureate in economics, and it is fundamental to environmental economics today. Paul Romer applied these concepts to knowledge and invention in his path-breaking research.

The theory of public goods applies as well to climate change. Here, we are speaking of a negative externality or "public bad" in the form of greenhouse-gas (GHG) emissions rather than a public good of improved knowledge. Climate change is a particularly thorny externality because it is global. Global externalities, whose impacts are indivisibly spread around the entire world, are not new. In earlier centuries, countries faced religious conflicts, marauding armies, and the spread of infectious diseases such as the plague. In the modern world, the older global challenges have not disappeared, while new ones have arisen—including not only global warming but others such as the threat of nuclear proliferation, international financial crises, and the growing threat of cyberwarfare. Global externalities are different from local or national public goods because they resist the control of both markets and national governments, a point emphasized below.

Global warming is the most significant of all environmental externalities. It menaces our planet and looms over our future like a Colossus (see Figure 1 from Goya). It is particularly pernicious because it involves so many activities of daily life, affects the entire planet, does so for decades and even centuries, and, most of all, because none of us acting individually can do anything to slow the changes.

Further reflection will reveal that nations have had limited success with agreements to deal with global economic externalities. Two successful cases include handling international trade disputes (today primarily through the World Trade Organization) and the protocols to limit the use of ozone-killing chlorofluorocarbons (from the Montreal Protocol). The study of economic aspects of environmental treaties has been pioneered by Columbia University economist Scott Barrett (1994, 2003). He and other scholars believe these two treaties were successful because the benefits far outweighed the costs and because effective institutions were created to foster cooperation among nations.

Governance is a central issue in dealing with global externalities because effective management requires the concerted action of major countries. However, under current international law, there is no legal mechanism by which disinterested majorities of countries can require other nations to share in the responsibility for managing global externalities. Moreover, extralegal methods such as armed force are hardly recommended when the point is to persuade countries to behave cooperatively rather than free-riding.

It must be emphasized that global environmental concerns raise completely different governance issues from national environmental concerns. For national public

Figure 1. Climate Change as the Threatening Colossus

Source: Francisco de Goya, *El Coloso*, Museo Nacional del Prado

goods, the problems largely involve making the national political institutions responsive to the diffuse national public interest rather than concentrated national private interests—responsive to public health rather than private profits. For global public goods, the problems arise because individual nations enjoy only a small fraction of the benefits of their actions. In other words, even the most democratic of nations acting noncooperatively in its own interest would take minimal action because most of the benefits of cooperation spill out to other nations. It is only by designing, implementing, and enforcing *cooperative multinational policies* that nations can ensure effective climate-change policies.

A. *Integrated-Assessment Modeling*

Many areas of the natural and social sciences involve complex systems that link together multiple physical or intellectual sectors. This is particularly true for environmental problems, which have deep roots in the natural sciences but also require social and policy sciences to solve in an effective and efficient manner. A good example, which will be the subject of this essay, is climate-change science and policy, which involve a wide variety of disciplines such as atmospheric chemistry and climate science, ecology, economics, political science, game theory, and international law.

As understanding progresses across the different fronts, it is increasingly necessary to link disciplines together to develop effective understanding and efficient policies. Integrated assessment analysis and models play a key role here. Integrated assessment models (IAMs) can be defined as approaches that integrate knowledge from two or more domains into a single framework. These are often based on fundamental scientific theories, but in practice are increasingly computerized numerical dynamic models of varying levels of complexity (for a survey, see Nordhaus 2013b).

My own work on IAMs for climate change began with a simple energy/climate model in Nordhaus (1975, 1977). I discarded this for other approaches, such as an analytical model, a small macroeconomic model (Nordhaus and Yohe 1983), a static model with a damage function (Nordhaus 1990), and finally in Nordhaus (1992, 1994) hit upon a model that captured all the parts in the DICE model (Dynamic Integrated model of Climate and the Economy). The latest full version of the DICE model (DICE2016-R2) has much the same structure as the first version, but it has revised each of the major sectors in small or large ways. The evolution of the DICE model 1992–2016 is reviewed in Nordhaus (2018a).

Additionally, the DICE model has spawned several offspring. The RICE model is the regional version (first in Nordhaus and Yang 1996); the PRICE or probabilistic model incorporates uncertainty (Nordhaus and Popp 1997); R&DICE adds induced innovation, using the insights of Paul Romer's work on the economics of knowledge (Nordhaus 2010); and the C-DICE or coalition-DICE model simulates the endogenous formation of coalitions for global climate-change policy (Nordhaus 2015). The DICE model has also been widely used among researchers and students. The guiding philosophy is "open software," and the code has been available to others since the first model.

The basic structure of the DICE model is shown in Figure 2. The figure displays the logical circular flow from emissions to climate to impacts then to policies and closing the circle back to emissions. The global warming problem starts at the upper left box, where economic growth and distorted price signals lead to rapidly rising emissions of CO_2 into the atmosphere. The arrow then moves to the box at the upper right, where the CO_2 concentrations and other forces lead to major changes in the climate system. The changing climate then produces impacts on human and natural systems in the box on the lower right. Finally, the box on the lower left shows societal responses to the threat of climate change.

The arrows in the figure represent the linkages between the different parts of the economy-climate-impacts-politics-economy nexus. However, the last two arrows are dashes with question marks. These links do not yet exist. There are no effective international agreements as of 2019 to limit the emissions of carbon dioxide (CO_2) and other greenhouse gases. If we continue along our current path of virtually no policies, then the dashed arrows will fade away, and the globe will continue on the dangerous path of unrestrained global warming.

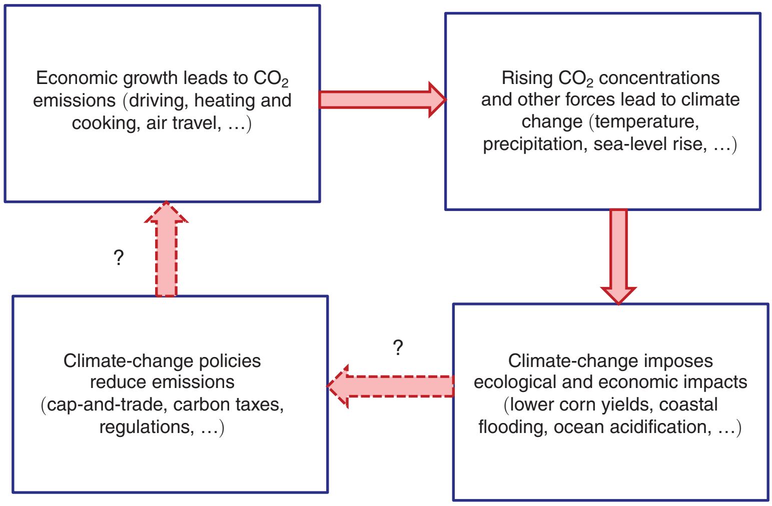

Figure 2. The Circular Flow of Global Warming Science, Impacts, and Policy

B. *Mathematical Representation*

My teacher, mentor, and coauthor Paul Samuelson—the first American Nobel laureate in economics—was responsible for the introduction of mathematics into economics. His view was that mathematics is necessary if we are to build coherent and consistent models of complex phenomena. That point was as much a part of my brain as the English language. Indeed, as J. W. Gibbs stated, "Mathematics is language."

So what is the DICE model in mathematics? Conceptually, it is a constrained nonlinear dynamic optimization model with an infinite horizon. More precisely, in slightly simplified form, we can write it as follows in two equations:

$$\max_{c(t)} W = \max_{c(t)} \left[\int_0^\infty U[c(t)]\, e^{-\rho t}\, dt \right] \tag{1}$$

subject to

$$c(t) = M\big(y(t); z(t); \alpha; \varepsilon(t)\big). \tag{2}$$

In the equations, $c(t)$ is consumption; $y(t)$ are other endogenous variables (such as global temperature); $z(t)$ are exogenous variables (such as population); α are parameters (such as climate sensitivity); ρ is the pure rate of time preference; and $\varepsilon(t)$ are random variables in the stochastic versions. This highly simplified representation shows an optimization of the path of consumption in (1) subject to a complex constraint in (2). The most challenging part of constructing the DICE model is to determine the structural constraints in (2). In the current version, there are about 20 equations necessary to represent the complex interactions shown in Figure 2.

C. *The Evolving Science of Climate Change*

Clearly, global warming is getting a lot of attention today. And just as clearly, people disagree about whether it is real, whether it is important, and what it means for human societies. What should the non-specialist conclude about this debate? If climate change is real, how much does it matter? Where should our concerns about global warming rank among the other issues we face, such as growing inequality and nuclear proliferation?

The short answer is that global warming is a major threat to humans and the natural world. I have used the metaphor that climate change is like a vast casino. By this, I mean that economic growth is producing unintended but dangerous changes in the climate and earth systems. These changes will lead to unforeseeable consequences. We are rolling the climatic dice, the outcome will produce surprises, and some of them are likely to be perilous. The message is that we need not roll the climatic dice—that there is time to turn around and walk back out of the casino.

The beginning of our understanding of the structure in Figure 2 lies in earth sciences. Climate science is an evolving field, but the essential elements have been developed by earth scientists over the last century and are well established. The most important and enduring source of global warming is the burning of fossil (or carbon-based) fuels such as coal, oil, and natural gas, which leads to emissions of carbon dioxide (CO_2). GHGs such as CO_2 accumulate in the atmosphere and stay there for a long time.

Higher atmospheric concentrations of GHGs lead to surface warming of the land and oceans. The initial warming effects are amplified through feedback effects in the atmosphere, oceans, and ice sheets. The resulting impacts include changes in temperatures as well as impacts on temperature extremes, precipitation patterns, storm location and frequency, snow packs, river runoff, water availability, and ice sheets. Each of these will have profound impacts on biological and human activities that are sensitive to the climate.

Past climates—varying from ice-free conditions to snowball earth—were driven by natural forces. Current climate change is increasingly caused by human activities such as emissions of greenhouse gases (GHGs). CO_2 concentrations in the atmosphere were 280 parts per million (ppm) in 1750 and reached more than 413 ppm in 2018. Models project that unless forceful steps are taken to reduce fossil fuel use, concentrations of CO_2 will reach 700–900 ppm by 2100. According to climate models, this will lead to a warming averaged over the globe in the range of 3°–5°C by 2100, with significant further warming after that. So unless there are efforts to curb or offset CO_2 emissions sharply, we can expect continued accumulations of CO_2 emissions in the atmosphere, and the resulting global warming with all its consequences.

One of the most exciting developments in the last half-century has been the development of deep paleoclimatic records on CO_2 concentrations as well as temperature proxies. Ice cores have provided some of the richest data. Figure 3 shows a reconstruction of global temperatures using Antarctica ice-core data for the last half-million years. The temperature at present is normalized at 0°C. The line with dots shooting up at the far right shows a projection of future temperature increases if there are no policies to slow climate change. If global warming

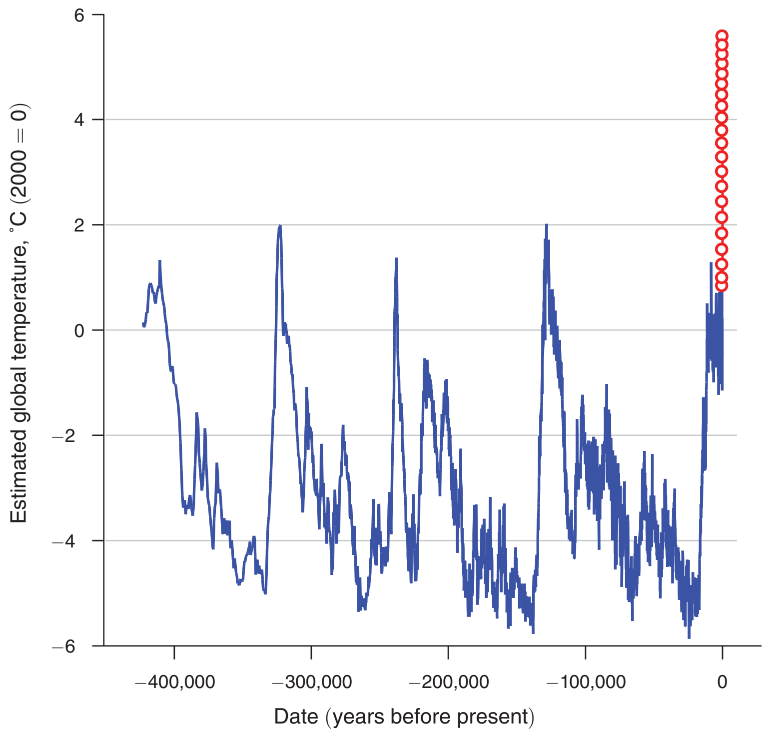

Figure 3. Estimated Global Temperature Variations for the Last 400,000 Years

Note: Based on Antarctic ice core (solid line) along with model projections for the next two centuries (circles).

Source: Nordhaus (2013a)

continues unchecked, future temperatures will soon surpass the historical maximum of the last half million years.

II. Slowing Climate Change

Scientists have focused on three potential strategies to slow climate change.

- Plan A is "abatement," or reducing emissions of CO_2 and other GHGs primarily by reducing combustion of carbon fuels.
- Plan B is "carbon removal," or removal of CO_2 from the emissions stream or from the atmosphere.
- Plan C is "geoengineering," or more precisely solar-radiation management, which would offset global warming by increasing the reflectivity of the earth.

I take this in reverse order. Plan C, geoengineering, makes the earth "whiter" or more reflective, so that less sunlight reaches the surface of the earth. This cooling effect can *on average* offset the warming that comes from the accumulation of CO_2 in the atmosphere. Perhaps the easiest to visualize is putting millions of little mirror-like particles into the stratosphere. For example, we might artificially increase sulfate aerosols in the stratosphere above background levels.

But geoengineering is dangerous. It is untested, will not offset climate change equally in all regions, will not deal with ocean carbonization, and will have major complications for international cooperation. To me, geoengineering resembles what doctors call "salvage therapy"—a potentially dangerous treatment to be used when all else fails. Doctors prescribe salvage therapy for people who are very ill and when less dangerous treatments are not available. No responsible doctor would prescribe salvage therapy for a patient who has just been diagnosed with the early stage of a treatable illness. Similarly, no responsible country should undertake geoengineering as the first line of defense against global warming.

Plan B, carbon removal, is in principle a highly attractive option. It is running combustion in reverse. While it is conceptually useful, we have no technologies that can remove 200 or 400 or 1,000 billion tons of CO_2 from the atmosphere at a reasonable cost. This might happen, but it has not happened yet, and it seems unwise to bank on it.

So that leaves Plan A, abatement, as the only realistic option to deal with climate change. Unfortunately, this approach is an expensive option. Energy modelers have made mountains of estimates of costs. Figure 4 provides a useful summary of the emissions reductions for different abatement strategies. These estimates come from a multi-model study that examines the costs of reducing emissions for different levels of reduction. The models differ on many dimensions such as resources, demand, growth, and the role of renewables. Moreover, these estimates assume efficient policies and harmonized prices, with 100 percent participation of countries. Realistic assumptions about policies and participation would raise the cost substantially, perhaps by a factor of two, depending on the details.

The figure shows the estimated costs for a 50 percent reduction and a 100 percent reduction. The average cost is slightly above 1 percent of output for a 50 percent reduction and 3.5 percent of output for zero emissions. It should be emphasized that the estimates for major reductions are highly speculative. Indeed, zero net emissions is unlikely to be feasible with today's technologies. However, the models give some sense of the range of costs for reducing emissions as estimated by today's energy models.

While some miraculous technological breakthroughs might conceivably arrive that can reduce abatement costs dramatically, experts do not see them arriving in the near future. New technologies—particularly for energy systems, which have massive financial and physical investments in capital such as power plants, structures, roads, airports, and factories—take many decades to develop, commercialize, and deploy.

The bottom line is that Plan A, to reduce emissions, is the only feasible and responsible policy. It is costly if we are to meet global temperature objectives. There are no realistic Plans B or C as of 2019.

A. *Damages or Impacts of Climate Change*

Estimating abatement costs is simple stuff compared to estimating damages or impacts of future climate change. Impacts might seem easier than the deep physics and chemistry of climate science because they are more familiar; the opposite is true. In reality, projecting impacts is the most difficult task and has the greatest uncertainties of all the processes associated with global warming.

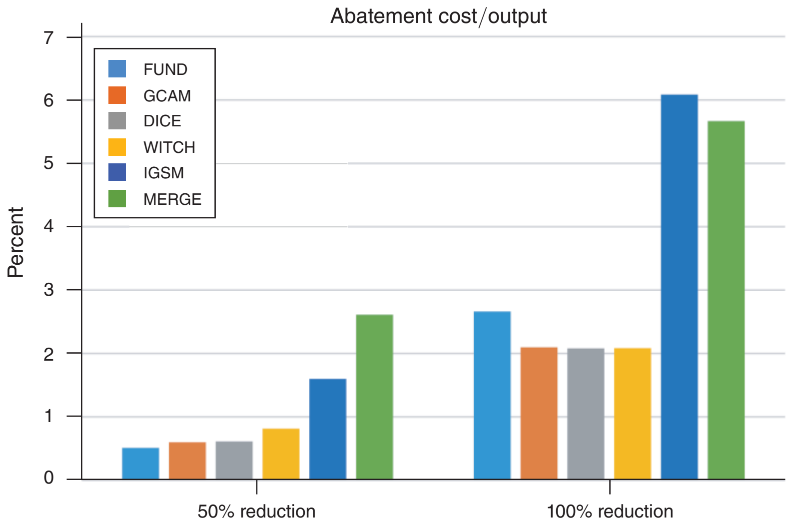

Figure 4. Abatement Costs, Six Studies

Notes: The six models as well as the methods are described in Gillingham et al. (2018). Note that the policies are harmonized across countries and assume efficient polices and 100 percent participation.

Some background here will be useful. Rising temperatures are not the major concern regarding the impacts of climate change. Rather, impacts focus the many associated effects on human and natural systems. A central concept in analyzing impacts is whether a system can be managed. Many sectors of high-income countries (such as laboratory clean rooms) are highly managed, and this feature will allow these sectors to adapt to climate change at relatively low cost for at least a few decades.

However, many human and natural systems are unmanaged or unmanageable and are highly vulnerable to climate-sensitive physical systems. The potential damages are likely to be most heavily concentrated in natural systems as well as in low-income and tropical regions such as tropical Africa, Latin America, coastal states, and the Indian subcontinent. Vulnerable systems include rain-fed agriculture, seasonal snow packs, coastal communities impacted by sea-level rise, river runoffs, forest erosion and fires, and natural ecosystems. There is potential for serious impacts in these areas.

Scientists are particularly concerned about "tipping points" in the earth's systems. These involve processes in which sudden or irreversible changes occur as systems cross thresholds. Many of these systems operate at such a large scale that they are effectively unmanageable by humans with existing technologies. Important global tipping points include the rapid melting of large ice sheets (such as Greenland or West Antarctic) and large-scale changes in ocean circulation such as the Gulf Stream. These tipping points are particularly dangerous because they are not easily reversed once they are triggered.

Impacts have been carefully studied in reports of the IPCC as well as by private scholars. The best evidence is that impacts of climate change will be nonlinear and cumulative. Early studies (EPA 1989) of the economics of different sectors indicated that the first 1° or 2°C of warming are unlikely to have major disruptive effects on agriculture and most other economic sectors, particularly if warming is gradual and farmers and other participants can adapt their technologies. More recent evidence, for example in the 2018 IPCC report on 1.5°C (IPCC 2014, 2018), suggests that even 2°C warming can be highly disruptive to human and particularly natural systems.

In the DICE model, the concept of damages includes non-market as well as market, and it has a correction for an insurance premium for high-consequence, low-probability events. In the 2016 model, damages are estimated to be 2 percent of output at a 3°C global warming and 8 percent of output with 6°C warming. But other summaries are all over the map. A recent meta-analysis by Howard and Sterner (2017) finds high estimates, with their preferred damage estimate being approximately 3.5 times the damages underlying the DICE model.

Even the concept of damages is contentious. One line of criticism is that they ignore catastrophic damages, which is wrong. Another line is that they do not include the possibility of "fat tails," which is more complicated because there is at this point no serious evidence of the presence of fat tails for the damage distribution.

A deeper critique is that damage functions monetize all human and non-human activities, which is correct. People might not object to monetizing the losses of wheat that are replaced by soybeans, or houses damaged by hurricanes. But they have firmer grounds for moral objections when studies put a price on human health impairments or monetize the submergence of entire island cultures. The economists' response is usually that we attempt to put all costs and benefits in a common metric so that we can balance the losses in one area with losses in others. We should be attentive to imputing appropriate prices, but it is better to include some values on health damages than to omit them from the analysis. As Keynes may have said, it is better to be vaguely right than precisely wrong.

B. *The Astounding Finding of Shadow Prices and the Social Cost of Carbon*

One of the deepest and most surprising findings of IAMs is the discovery of the "social cost of carbon." This insight comes from the marriage of optimization under constraints and the use of duality in linear programming.

Here is the basic intuition: The DICE model estimates the path of the economy that optimizes consumption, emissions, and climate change. (See equations (1) and (2).) These calculations take into account the production functions of the economy, the constraints of the carbon cycle, and the rest. One of the auxiliary byproducts of the calculations is an estimate of the impact on optimized consumption of an extra ton of emissions. For example, an extra ton of emissions might lower current consumption by $40, holding consumption in other periods constant but respecting all constraints.

I pause to note the source of this idea. Research of Kantorovich and Koopmans (for which they won the 1975 Nobel Prize) showed that the optimization of a linear programming problem produces both primal variables (here emissions) and dual variables or shadow prices (here the impact on the objective function of a unit change in emissions). The DICE model produces this shadow price as part of the solution—the shadow price is a mathematical variable associated with carbon emissions in an optimized framework. Later, this was interpreted as the carbon price or carbon tax associated with internalizing the carbon externality.

I remember puzzling over the dual variables on looking at the first printout of the model results in Nordhaus (1975). When that study saw the light of publication in 1977, the point was explicitly recognized as a fiscal question, with the interpretation of a carbon tax:

> *Because of the externalities, there are no market or political mechanisms which ensure that the appropriate level of control will be chosen. … To implement this efficient path implies that we are implicitly putting a positive price on emissions of carbon into the atmosphere, "carbon taxes," as a way of implementing the global policy on a decentralized level.*

This idea lay fallow for many years, then surfaced as a new concept, "the social cost of carbon."

Moving forward to today, the modeling landscape has changed dramatically. Progress in monitoring, fundamental science, economics, software, computation, and researchers' interests has produced dozens of groups around the world to weigh in with their different perspectives and approaches as well as alternative IAMs. This essay provides a tip of the hat to the extensive work of other researchers and then continues to focus on the most recent version of the DICE model.

C. *Objectives*

Looking back to the conceptual framework in Figure 2, it is useful to begin with the objectives of the framework: what is the goal of climate policy? A common approach today is to set climate objectives as hard targets based on climate history or ecological principles. Perhaps we should aim to limit the global temperature increase to 2°C, or even more ambitiously to 1.5°C.

However attractive a temperature target may be as an aspirational goal, the target approach is questionable because it ignores the costs of attaining the goals. If, for example, attaining the 1.5°C goal would require deep reductions in living standards in poor nations, then the policy would be the equivalent of burning down the village to save it. If attaining the low-temperature path turns out to be easy, then of course we should aim for it.

These points lead to an approach known as cost-benefit analysis, in which climate policy is set by balancing costs and benefits. Cost-benefit approaches pose deep problems just discussed because they require putting all changes, plus and minus, into a common metric. Moreover, many impacts are ones that may be difficult to measure, or ones that we may be reluctant to monetize. However, in the view of most economists, balancing of costs and benefits is the most satisfactory way to develop climate policy. Some of the issues of abatement costs and impacts were described above, and these are ones that would enter the model.

D. *An Overview of IAM Results*

One of the features of IAMs is that they can project trends, assess policies, and calculate costs and benefits. Perhaps the most important advantage of integrated models is that they are *internally consistent.* That is, they keep track of the different stocks and flows of all variables so that nothing gets lost. For example, carbon stocks tomorrow are carbon stocks today plus any flows from emissions.

Moreover, they can incorporate alternative assumptions. If someone doesn't like the output assumption, or the discounting, or wants to pursue a different policy, these differences can be incorporated while ensuring that all the other parts of the model are consistent with the changed assumption.

Here are some of the major findings from virtually all IAMs.

- One major finding of integrated assessment models is that policies to slow emissions should be introduced *as soon as possible*.
- A second finding is *uniformity of price*—that the most effective policies are ones that equalize the incremental or marginal costs of reducing emissions. Equivalently, in a market context, that means that the carbon prices should be equalized in every sector and in every country.
- Effective policies should have the highest possible *participation*; that is, the maximum number of countries and sectors should be on board as soon as possible. Free-riding should be discouraged.
- Finally, an effective policy is one that *ramps up over time*—both to give people time to adapt to a high-carbon-price world and to tighten the screws increasingly on carbon emissions.

Most experts agree on these central principles—universal participation, equalizing marginal costs or carbon prices in all uses in a given year, full participation, and increasing stringency over time. However, experts disagree on the stringency of policies. I return to this point in reviewing estimates of the social cost of carbon.

E. *Results from the DICE Model*

I next turn to the results of the DICE model to provide more granularity to the analysis, relying on the DICE-2016R3 model. These simulations estimated the temperature trajectories for six sets of cases: no policy, a cost-benefit optimum with standard damages and an alternative set of damages, and three temperature-limiting strategies where the limit is 2°C. The temperature limits are a hard cap of 2°C and two paths where temperature is limited over a 100-year and a 200-year averaging period. Figure 5 shows the associated temperature trajectories.[1]

The base path (which is essentially the path the globe is following) continues to have rising temperature, passing 4°C by 2100. In the DICE model, it is essentially infeasible to attain the stringent temperature target of 1.5°C, and the 2°C path requires negative emissions in the near term. Another finding, much more controversial, is that the cost-benefit optimum rises to over 3°C in 2100—much higher than the international policy targets. Even with the much more pessimistic alternative damage function, the temperature path rises to 3°C in 2100.

[1] The DICE model used for this essay is a slight variant of the DICE-2016R2 model referred to in Nordhaus (2018b). The changes are as follows: the model allows for negative emissions. The emissions control rate can increase by at most 20 percent per five-year period. The economic data are moved to 2018 prices by reflating by 20 percent from 2010 US international dollars. The alternative damage function has a damage coefficient 3.5 times the standard function (from Howard and Sterner 2017), while retaining the quadratic function.

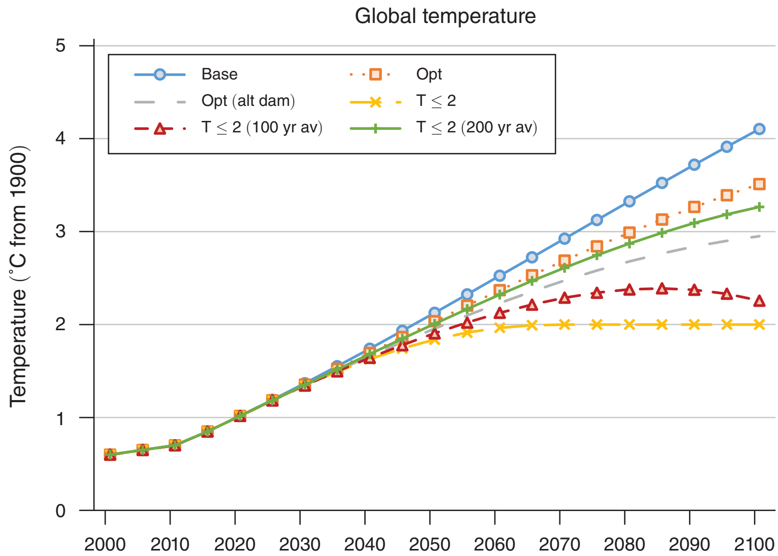

Figure 5. Temperature Trajectories for Different Objectives

An interesting new approach (added for this essay) is a policy that targets *average* temperature rather than *peak* temperature. For example, temperature might be limited to an average of 2°C for each 100-year period starting in 2015 (that is, 2015 to 2114), then for the 100-year period starting in 2020, and so forth. As Figure 5 shows, the standard cost-benefit optimum is close to the path where the 200-year average is limited to 2°C. So to the extent that the damages are a function of the average temperature increase (say for melting of ice sheets or ocean warming), the average-temperature standard would be appropriate, but the appropriate averaging period will differ for different systems and is yet another area ripe for research.

F. *Carbon Pricing*

Economics points to one inconvenient truth about climate-change policy: for any policy to be effective, it must raise the market price of CO_2 and other GHG emissions. Putting a price on emissions corrects for the underpricing of the externality in the marketplace. Prices can be raised by putting a regulatory limit on the amount of allowable emissions and allowing trading ("cap-and-trade"), or by levying a tax on carbon emissions (a "carbon tax").

Raising the price on carbon will achieve four goals. First, it will provide signals to consumers about which goods and services are carbon-intensive and should therefore be used more sparingly. Second, it will provide signals to producers about which inputs are carbon-intensive (such as coal and oil) and which are low-carbon (such as natural gas or wind power), thereby inducing firms to move to low-carbon technologies. Third, it will give market incentives for inventors, innovators, and investment bankers to invent, fund, develop, and commercialize new low-carbon products and processes. Finally, a carbon price will economize on the information required to undertake all these tasks.

G. *The Social Cost of Carbon*

As mentioned above, one of the most amazing results of IAMs is the ability to calculate the optimal carbon price. This is now called the "social cost of carbon" or SCC. This concept represents the economic cost caused by an additional ton of carbon dioxide emissions (or more succinctly carbon) or its equivalent. In a more precise definition, it is the change in the discounted value of consumption denominated in terms of current consumption per unit of additional current emissions. In an optimized climate policy (abstracting away from various distortions), the social cost of carbon will equal the carbon price or the carbon tax.

Estimates of the SCC are a critical ingredient in climate-change policy. They provide policymakers a target to aim for if they are seeking an economically efficient policy for carbon pricing. They would be an anchor for internationally harmonized carbon prices such as those in the climate club discussed below. Another application is for rulemaking when countries do not have comprehensive policies covering all GHGs.

Estimates of the SCC differ across models and vintages (see Nordhaus 2014, 2017). Table 1 shows calculations for the most recent published version of the DICE model, DICE-2016R3. The optimal carbon price is estimated to be \$36/ton CO_2 in the standard model. However, the SCC varies greatly depending upon the policy target. For both damage functions and less ambitious temperature targets, the SCC is in the \$43–\$108 per ton range for 2020. For targets of 2°C and below with short averaging periods, the SCC is in the \$158–\$279 per ton range for 2020.

Studies indicate that the SCC is highly uncertain. The MUP study (Gillingham et al. 2018) and Nordhaus (2018b) indicate that the one-sigma uncertainty for the SCC is roughly as large as the median value. The SCC is so uncertain because of the cascading uncertainties from economic growth, emissions intensities, and damage functions.

H. *The Conundrum of Discounting*

Controversies involving the discount rate have been central to global-warming models and policy for many years. The economic theory of discounting, which for many years was an obscure topic in public finance and project analysis, assumes great prominence in climate-change IAMs because of the long delays between investments in abatement and returns in averted damages. However, notwithstanding the extensive discussions, discounting is just as contentious today as it was at the dawn of the studies in this area.

Discounting involves two related and often confused concepts. One is the idea of a *discount rate on goods*, which is a market-based concept that measures the relative price of goods at different points of time. The second important discount concept involves the relative weight of the economic welfare of different households or generations over time and is called the *generational discount rate*. It is calculated in percent per unit time, like an interest rate, but refers to the discount in future welfare, not in future goods or dollars.

While the concept of discounting raises broad philosophical and ethical questions, most analyses of the discounting issue in the economic and IAM literatures use the "Ramsey approach," drawn from the Ramsey-Koopmans-Cass model of

Table 1—Social Cost of Carbon Alternative Concepts, DICE 2016-R3 Model (2018$)

	Social cost of carbon 2018$ per ton of CO_2			
	2015	2020	2050	2100
Base	37	45	108	304
Optimal	36	43	105	295
Optimal (alt dam)	91	108	249	584
$T \leq 2.5$ (200yr)	41	49	123	379
$T \leq 2.0$ (200yr)	49	59	153	511
$T \leq 1.5$ (200yr)	69	84	226	776
$T \leq 2.5$ (100yr)	76	93	260	755
$T \leq 2.0$ (100yr)	130	158	413	1,013
$T \leq 1.5$ (100yr)	236	279	682	1,191
$T \leq 2.5$	95	118	361	477
$T \leq 2.0$	225	275	749	459
$T \leq 1.5$	NF	NF	NF	NF

Notes: Base = no controls. *Optimal* = cost-benefit maximum with base and alternative damage function. $T \leq 2.5$ (200yr) = temperature limited 2.5°C for a 200-year average (and the parallel notation for different temperature limits and averaging periods). $T \leq 2.5$ is temperature limited to 2.5°C as a hard constraint. In the table, "NF" indicates not feasible.

optimal economic growth (Ramsey 1928, Koopmans 1963, Cass 1965). This is precisely the model of growth underlying the DICE model.

There are two ways of using the Ramsey equation as a framework for discounting in global warming or other long-run questions. One is the *prescriptive view*, in which analysts argue for the ethically just goods discount rate. This is the approach taken in Cline (1992) and the *Stern Review* (2006). This approach generally yields a low goods discount rate, around 1 percent per year.

A second approach is the *descriptive approach*, advocated by Robert Lind in Lind et al. (2013), and in Nordhaus (1994), and which is the approach in the DICE/RICE models. This approach assumes that investments to slow climate change must compete with investments in other areas. The benchmark should therefore reflect the opportunity cost of investment. The descriptive approach yields a market rate of return in the neighborhood of 5 percent per year when risks are appropriately included.

I will not reprise the debate on discounting here. It is just as unsettled as it was when first raised three decades ago. Instead, I will present the results of modeling with alternative rates on the social cost of carbon. This shows how alternative discount rates affect decisions *today.* Table 2 shows the impact of discounting for alternative constant discount rates between 0.1 percent and 5 percent per year. Once discount rates are set below 3 percent per year, the impact on decisions becomes dramatically larger. This shows that discounting is perhaps the most important conceptual issue facing current climate policy.

III. From National to International Policies

The natural question is, "How are we doing? What is the current market price of carbon? Is it near the DICE model finding of \$36/ton? Or near the temperature-limiting level of \$100–\$250 per ton?"

TABLE 2—DISCOUNTING AND THE SOCIAL COST OF CARBON

Discount rate (%)	Social cost of carbon 2018\$ per ton of CO_2 2015	2020	2050	2100
0.1	970	966	917	665
1.0	497	515	614	657
2.0	219	236	349	544
3.0	93	104	179	361
4.0	44	49	93	207
5.0	23	27	55	126
DICE-opt	36	43	105	295

The answer is that the world is nowhere near the lowest of these figures. The actual global carbon price is at most one-tenth of that. Carbon prices in the United States and most other countries are virtually zero, so there is a huge gap between reality and global aspirations. Whether we adopt the economists' approach of cost-benefit analysis, or the Paris Accord's target of 2°C, we must be realistic and realize that the world is not close to attaining those goals. Effective policies have not been introduced, either in any major country or for the world as a whole.

A. *The Syndrome of Free-Riding*

Why have *global* policies on climate change been so ineffective compared to many other *national* policies (for pollution, public health, and water quality as examples)? Why have landmark agreements such as the Kyoto Protocol and the Paris Accord failed to make a dent on emissions trends? The reason is free-riding. This is the tendency for countries to seek their own national interests.

When a country says not only "America First" but "Only America Counts," that displays the syndrome. When actions do not spill over the border, countries are well governed when they put their citizens' interests first rather than promoting narrow interests who lobby for protectionist tariffs or lax environmental regulations.

However, nationalist or *noncooperative* policies that seek to maximize the interests of a single country at the expense of other countries—sometimes called "beggar-thy-neighbor policies"—are a poor way to resolve global problems. Noncooperative nationalist policies in the area of tariffs, ocean fisheries, war, and climate change lead to outcomes where nations are worse off.

Some contests are zero-sum games, as when nations compete in the Olympics. Others are negative-sum games, as when nations go to war. However, many global issues are cooperative games, where the sum of nations' incomes or welfare is improved if countries step away from nationalistic policies and take cooperative policies. The most important example of cooperation is treaties and alliances that have led to the sharp decline in the lethality of battle deaths in recent years. Another important example is the emergence of low-tariff regimes in most countries. By reducing barriers to trade, all nations have seen an improvement in their living standards.

However, alongside the successful outcomes lie a string of failures. Nations have failed to stop nuclear proliferation, overfishing in the oceans, littering of space, and transnational cybercrime. In many of these failures, we see the syndrome of free-riding. When there are international efforts to resolve a global problem, some nations inevitably contribute very little. For example, the North Atlantic Treaty Organization (NATO) defends its members against attacks. Countries agree to participate in the costs. However, the United States in 2018 spent 70 percent of the total defense spending. Many countries spend only a tiny fraction of their GDP on defense, Luxembourg being the extreme case, spending only 0.5 percent of GDP on defense. Countries that do not participate in a multiparty agreement on public goods get a free ride on the costly investments of other countries.

Free-riding is a major hurdle in the solution of global externalities, and it lies at the heart of the failure to deal with climate change. No single country has an incentive to cut its emissions sharply. Suppose that when country A spends \$100 on abatement, global damages decline by \$200. However, country A might get only \$20 of the benefits, so it would tend to decline the responsibility. Hence, if there is an agreement, nations have a strong incentive not to participate. If they do participate, there is a further incentive to miss ambitious objectives. The outcome is a *noncooperative free-riding equilibrium* in which few countries undertake strong climate-change policies—a situation that closely resembles the current international policy environment.

The message is, nations speak loudly but carry no stick at all.

In the case of climate change, there are additional factors that impede a strong agreement. There is a tendency for the current generation to ride free by pushing the costs of dealing with climate change onto future generations. Generational free-riding occurs because most of the benefits of costly emissions reductions today would accrue many decades in the future.

The double free-riding difficulties are aggravated by interest groups that muddy the water by providing misleading analyses of climate science and economic costs. Contrarians highlight anomalies and unresolved scientific questions while ignoring the strong evidence supporting the underlying science and current projections of climate change.

The obstacles to effective policies have been particularly high in the United States, where the ideological opposition has hardened even as the scientific concerns have become increasingly grave. The abyss of contrariness was perhaps the statement by Donald Trump, who tweeted, “The concept of global warming was created by and for the Chinese in order to make US manufacturing non-competitive.” Contrary to this fantasy, it is generally thought that the modern science of climate change was discovered by the Nobel-prize-winning Swedish chemist Svante Arrhenius in 1896 during the late stages of the Qing dynasty.

IV. A Short History of International Climate Agreements

The risks of climate change were recognized in the United Nations Framework Convention on Climate Change, ratified in 1994. That treaty stated, “The ultimate objective… is to achieve… stabilization of greenhouse-gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.”

The first step to implement the Framework Convention was taken in the Kyoto Protocol in 1997. High-income countries agreed to limit their emissions to 5 percent below 1990 levels for the 2008–2012 budget period. Under the protocol, important institutional features were established, such as reporting requirements. The protocol also introduced a method for calculating the relative importance of different greenhouse gases. Its most important innovation was an international cap-and-trade system of emissions trading as a means of coordinating policies among countries.

The Kyoto Protocol was an ambitious attempt to construct an international architecture to harmonize the policies of different countries. But countries did not find it economically advantageous to make the necessary emissions reductions. The United States withdrew very early. The Protocol did not attract any new participants from middle-income and developing countries. As a result, there was significant attrition in the coverage of emissions under the Kyoto Protocol.

Also, emissions grew more rapidly in noncovered countries, particularly developing countries like China. The protocol as first designed would have covered two-thirds of global emissions in 1990, but the actual scope in 2012 was barely one-fifth of world emissions. It died a quiet death, mourned by few, on December 31, 2012. Kyoto was a club that no country cared to join.

The Kyoto Protocol was followed by the Paris Accord of 2015. This agreement led to a target for climate policy to limit climate change to 2°C above pre-industrial levels. The Paris Agreement requires all countries to make their best efforts through "nationally determined contributions."

For example, China announced that it would reduce its 2030 carbon intensity by 60–65 percent compared to 2005 levels. This would amount to an annual decrease of 1.7–2.0 percent per year. The United States under the Obama administration committed to reduce its greenhouse gas emissions by 26-28 percent below the 2005 level in 2025. The Trump administration announced that the United States will withdraw from the agreement, although that would not occur until November 2020.

An important point is that the Paris Accord is *uncoordinated* and *voluntary.* It is uncoordinated in the sense that its policies, if undertaken, would not limit climate change to the target 2°C. Moreover, while countries agree to make best efforts, there are no penalties if they withdraw or fail to meet their obligations. The world is therefore just where it stood in 1994, recognizing the dangers of climate change without effective policies to stop it.

A. *The Effectiveness of Climate Policies*

After a quarter-century of international agreements, we can step back to measure the effectiveness of past international agreements. This might be through analyses of participation, coverage, targets, and timetables. But the real answer lies in the results. The best single measure of trends is the "carbon intensity" of production (which was the Chinese target mentioned above). This measures the trend in the ratio of CO_2 emissions to output. For example, in 2010, the United States emitted 5.7 billion tons of CO_2, and its real GDP was $14.8 trillion, which equals a carbon intensity of 0.386 tons of CO_2 per $1,000 of GDP. By 2015, carbon intensity declined to 0.328, for an average rate of decarbonization of 3.1 percent per year.

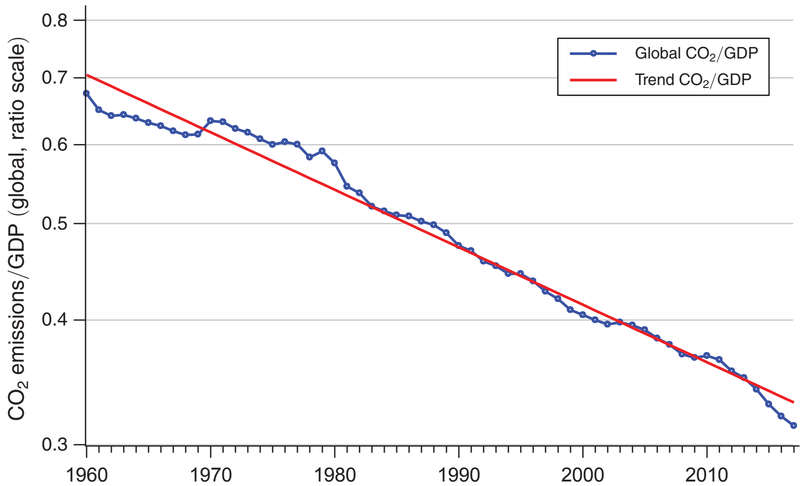

Figure 6. Trend in Global Decarbonization, 1980–2017

If policies were effective, then the trend in carbon intensity should have declined sharply after, say, the Framework Convention or the Kyoto Protocol or the Paris Accord. Figure 6 shows the global CO_2/output ratio from 1980 to 2017 along with a trend curve. The global average intensity has declined at 1.6 percent per year over the period, with a higher rate since 2010.

However, a closer look indicates that most of the improvement in the rate of decarbonization comes from China. Table 3 shows the rate of decarbonization for the world, for China, and for the world less China. Focus on the last column, the world less China. This shows that the rate of decarbonization is virtually identical before and after 2000. The three landmark years (1994 for the Framework Convention, 1997 for Kyoto, and 2015 for Paris) show no breaks in the ex-China trend. While we cannot say why the trend has proven so persistent, the trend definitely suggests that climate policies have not tilted the emissions curve down.

One reason why the emissions trend has been so persistent is that the commitments are so modest. Let's look at the commitments of the United States and China relative to trend. For all the celebrations, China's commitment is actually less than its recent trend. China would reach its target before 2030 at the current trend of decarbonization of 5 percent per year. So China need only continue its current path. For the United States, the goal is slightly more ambitious. The rate of decarbonization in the United States has been 2.8 percent per year for the last decade, while the target would imply a rate of 3.4 percent per year.

A more important question is how the current rate of decarbonization would compare with trajectories that would attain the aspirational temperature targets. Table 4 shows the rate of growth of emission for the first decade of controls for alternative policies using the DICE model. The baseline is a continuation of current trends, with rising emissions. The other seven objectives require sharply declining emissions over the next decade.

Table 3—Decarbonization of the Global Economy, Regions and Periods

Period	World (%)	China (%)	World less China (%)
1980–1990	−1.8	−3.8	−2.0
1990–2000	−1.5	−5.2	−1.5
2000–2010	−0.9	−1.0	−1.8
2010–2017	−2.3	−4.8	−2.0
1980–2017	−1.6	−3.6	−1.8

Table 4—Emissions Change, Alternative Policies

Scenario	Annual average emission change (%), 2015–2025
Base	2.0
Optimal	−1.5
T ≤ 2 (200 yr)	−2.4
Optimal (alt dam)	−2.6
T ≤ 1.5 (200 yr)	−2.6
T ≤ 2 (100 yr)	−2.6
T ≤ 2 (no av)	−2.7
T ≤ 1.5 (100 yr)	−2.7

Notes: The table shows the annual rate of global emissions in different scenarios. Note that the policies require a sharp decline in emissions over the next decade. For definitions of scenarios, see Table 1.

The lesson here is that policies taken to date fall far short of what is necessary to slow climate change sufficiently to meet international goals.

B. *Climate Clubs to Overcome Free-Riding*

In light of the failure of past agreements, it is easy to conclude that international cooperation is doomed to failure. This is the wrong conclusion. In spite of the obstacles of potential free-riding, nations have in fact overcome many transnational conflicts and spillovers through international agreements. Countries enter into agreements because joint action can take into account the spillover effects among the participants. These agreements are a kind of "club of nations" that will be described below.

Although most of us belong to clubs, we seldom consider their structure. A club is a voluntary group deriving mutual benefits from sharing the costs of producing a shared good or service. The gains from a successful club are sufficiently large that members will pay dues and adhere to club rules to gain the benefits of membership.

The major conditions for a successful club include the following: that there is a public-good-type resource that can be shared (whether the benefits from a military alliance or the enjoyment of low-cost goods from around the world); that the cooperative arrangement, including the costs or dues, is beneficial for each of the members; that non-members can be excluded or penalized at relatively low cost to members; and that the membership is stable in the sense that no one wants to leave.

So what is the idea of a climate club? The notion is that *nations can overcome the syndrome of free-riding in international climate agreements if they adopt the club model rather than voluntary arrangements.* A climate club is an agreement by participating countries to undertake harmonized emissions reductions, but the central new feature is that nations would be penalized if they did not meet their obligations. The club proposed here centers on an "international target carbon price" that is the focal provision of the agreement. For example, countries might agree that each country will implement policies that produce a minimum domestic carbon price of \$25 per ton of CO_2.

One important feature of the carbon club is that it organizes policies around a target carbon price rather than emissions reductions (emissions limits being the approach of the Paris Accord and the Kyoto Protocol). One reason for focusing on prices rather than quantities is the structure of the costs and benefits. But the more important and unusual one involves the dimensionality of the two approaches for bargaining.

This point has been explored in depth by Harvard economist Martin Weitzman (2017). He has shown that it would be both less distortionary and easier to negotiate a single carbon price than to set multiple quantity limits. The intuition is straightforward, even though the proof is difficult. In voting on a price, countries can simply negotiate for one that is near their top choice. So the United States might vote for any price less than \$40 a ton assuming that all other countries participated. For every price, each country would have a "yes, no" choice. Perhaps the price that got 50 percent or 75 percent of the votes would win.

With quantities, the voting is much more complicated. There is not only a global total but also a set of national caps. So the United States would be inclined to vote for a low global total and a high national cap on emissions. Each country would do the same. The result is that there would be no dominant policy, and the choices would cycle around. This difference between a single variable (the harmonized price) and many variables (the number of country caps) is a central reason why quantity restrictions have proven fruitless. The cycling with multidimensional policies is an updated version of Kenneth Arrow's voting paradox.

A key component of the club mechanism—and the major difference from all current proposals—is that nonparticipants are penalized. While many different penalties might be considered, the simplest and most effective would be uniform percentage tariffs on the imports of nonparticipants into the club region. With penalty tariffs on nonparticipants, the climate club creates a strategic situation in which countries acting in their self-interest will choose to enter the club and undertake ambitious emissions reductions because of the structure of the incentives.

Both theory and history suggest that some form of sanction on nonparticipants is required to induce countries to participate in agreements with local costs but diffuse benefits. A sanction is a governmental withdrawal, or threat of withdrawal, of customary trade or financial relationships. A key aspect of the climate-club sanctions analyzed here is that they benefit those who impose sanctions and harm those who are sanctioned.

There is a small theoretical literature analyzing the effectiveness of climate clubs and comparing them to agreements without sanctions. The results suggest that a well-designed club using trade sanctions would provide well-aligned incentives for countries to join a club that requires strong abatement.

Figure 7 illustrates the basic findings from my study on climate clubs in Nordhaus (2015). It shows the global average carbon price for different target prices (on the bottom) and tariff rates (shown as the bars, left to right from 0 percent to 10 percent).

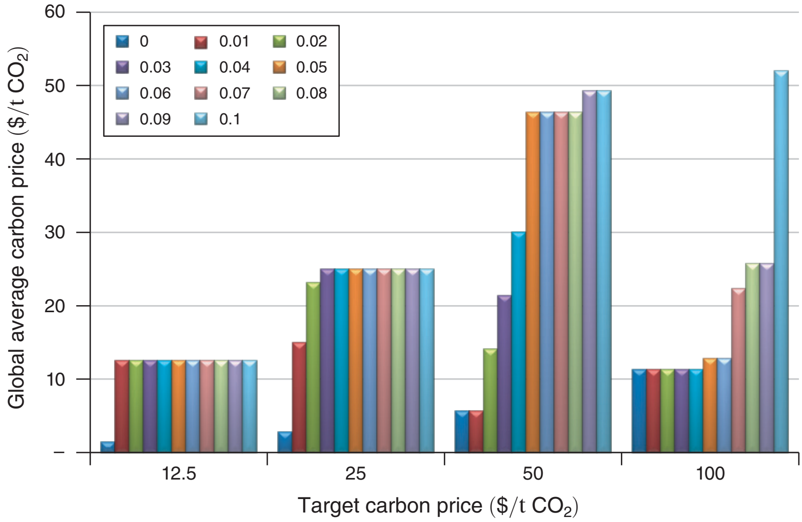

Figure 7. Actual Global Carbon Price as a Function of the Target Price and the Penalty Tariff Rates

A careful look shows that with a tariff rate (or penalty) of zero, the global carbon price is low. This is the current situation. For low carbon prices, it is easy to induce participation and obtain higher global carbon prices with low tariffs. However, as the price rises above $50 per ton, it becomes very difficult to get full participation because the costs of abatement are more than the costs of the tariffs. Of the cases examined, a $50 target carbon price induces the highest actual global price for most tariff rates.

The climate club shown in Figure 7 is just the sketch of the basic point about the necessity of some kind of club, or penalty for nonparticipation, in a global agreement. It predicts—alas, in a way that seems empirically verified—that voluntary international climate agreements will accomplish little, and definitely will not meet the ambitious objectives of the Paris Accord.

The international community is a long way from adopting a climate club or an analogous arrangement that will slow the ominous march of climate change (as seen in the figures above and elsewhere). Obstacles include ignorance, the distortions of democracy by anti-environmental interests and political contributions, free-riding among those looking to the interests of their country, and short-sightedness among those who discount the interests of the future. Global warming is a trillion-dollar problem requiring a trillion-dollar solution, and the battle for hearts, minds, and votes will be fierce.

C. *Four Steps for Today*

If climate change is the ultimate challenge, what steps can individuals and countries take today? There is no simple answer to this complex phenomenon, but here are four specific goals to focus on.

First, people around the world need to understand and accept the gravity of the impacts of global warming on the human and natural world. Scientists must continue intensive research on every aspect from science and ecology to economics and international relations. Those who understand the issue must speak up and debate contrarians who spread false and tendentious reasoning. People should be alert to the claims of contrarians who find some negative results or list reasons to wait for decades to take the appropriate steps.

Second, nations must establish policies that raise the price of CO_2 and other greenhouse-gas emissions. While such steps meet resistance (who wants to take foul-tasting medicines?), they are essential elements for curbing emissions, promoting low-carbon technologies, and inoculating our globe against the threat of unchecked warming.

Moreover, we need to ensure that actions are global and not just national or local. While politics may be local, and the opposition to strong steps to slow warming comes from nationalistic attitudes, slowing climate change requires coordinated global action. The best hope for effective coordination is a climate club, which is a coalition of nations that commit to strong steps to reduce emissions along with mechanisms to penalize countries who do not participate. While this is a radical proposal that breaks with the approach of past climate agreements, no other blueprint on the public agenda holds the promise of strong international action.

Finally, it is clear that rapid technological change in the energy sector is central to the transition to a low-carbon economy. Current low-carbon technologies cannot substitute for fossil fuels without a substantial economic penalty on carbon emissions. Developing economical low-carbon technologies will lower the cost of achieving our climate goals. Moreover, if other policies fail, low-carbon technologies are the last refuge—short of the salvage therapy of geoengineering—for achieving our climate goals or limiting the damage. Therefore, governments must support and the private sector must intensively pursue low-carbon, zero-carbon, and even negative-carbon technologies.

Therefore, knowledge, proper pricing, coordinated action, and new technologies—these are the steps that are necessary if we are to tame this Colossus that threatens our world.

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