KAPSARC

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King Abdullah Petroleum Studies and Research Center

IEE JAPAN

The Institute of Energy Economics, Japan

# Towards More Pragmatic Global Climate Goals and Policies

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## About KAPSARC

The King Abdullah Petroleum Studies and Research Center (KAPSARC) is a non-profit global institution dedicated to independent research into energy economics, policy, technology and the environment, across all types of energy. KAPSARC's mandate is to advance the understanding of energy challenges and opportunities facing the world today and tomorrow, through unbiased, independent, and high-caliber research for the benefit of society. KAPSARC is located in Riyadh, Saudi Arabia.

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# Key Points

This paper presents an analysis of the climate and economic impacts of four different carbon emission scenarios. The scenarios include: a 'business as usual' reference scenario; a carbon emission mitigation scenario designed to meet the Paris Agreement goal of limiting average global temperature increases to no more than 2° Celsius (C) by 2100; and two scenarios that seek to optimize global welfare taking into account the total costs associated with carbon mitigation, adaptation and damage, one with more rapidly declining low-carbon or zero-carbon technology costs after 2050. Key insights include the following:

Under the optimal global welfare case with more rapidly declining technology costs after 2050, global average temperature increases peak at between 2.3°C and 2.7°C, which is above the level achieved under the 2°C by 2100 scenario.

However, the 2°C scenario, which relies exclusively on mitigation responses, requires very high carbon prices to achieve its goals; above $250/ton carbon dioxide equivalent ($CO_2e$) by 2050 and over $1,200/ton $CO_2e$ in 2100 (prices are in real 2014 U.S. dollars). This is reflected in a disproportionately high total economic cost between now and 2100, reaching around 4 percent of global gross domestic product (GDP) by 2090.

By comparison, carbon prices associated with the optimal global welfare cases are less than $50/ton $CO_2e$ by 2050, and between $175/ton $CO_2e$ (standard optimal case) and $300/ton $CO_2e$ (optimal case with more rapidly declining technology costs) in 2100. The total economic costs under the optimal global welfare scenarios never exceed 3 percent of global GDP, with the cost peaking at 2.6 percent of global GDP around 2130 under the optimal scenario, with more rapidly declining technology development costs after 2050.

This analysis suggests that a more pragmatic approach to tackling climate change (referred to as a practical approach hereafter) which balances mitigation, adaptation and damage is likely to minimize the overall cost to society. It also highlights the potential economic benefits associated with accelerating the development and deployment of cost effective low- and zero-carbon technologies. Governments have a crucial role to play to support effective research and development in this context. Scope remains to develop more practical and flexible approaches to climate policy that are clear, predictable and able to effectively evolve as the transition to a decarbonized global economy unfolds.

# Summary

The 2015 Paris Agreement represents an important step forward in global climate change agreements, by combining national goal-setting with a global framework to drive collective action. However, the sum of individual countries' nationally determined contributions falls far short of actions needed limit warming to 2°C, the goal agreed under the Agreement.

In this paper, we explore the climate and economic impact of four emissions pathways through 2200. We use the terms "emission pathways" or "emission paths" to refer to changes in the total volume of greenhouse gas (GHG) emissions over time under the modelled scenarios. Two of these pathways do not consider economic efficiency: a reference scenario without additional climate policy and a scenario that meets the 2°C by 2100 goal established in the Paris Agreement. Two further emissions pathways are the result of scenarios designed to minimize the economic impact of climate change, including mitigation, adaptation and residual damage costs. These two scenarios consider different rates of decline in GHG mitigation costs over time: one a constant rate of 0.5 percent and another with greater reduction in costs after 2050. For our analysis, we use the dynamic integrated climate economy (DICE) model developed by William Nordhaus of Yale University, with a global GHG mitigation cost curve developed by the Institute of Energy Economics, Japan (IEEJ).

The differences among these scenarios may offer insights for policymakers. The optimized case with greater cost reductions after 2050 results in a peak global average temperature increase of 2.3°C to 2.7°C, higher than the 2°C goal of the Paris Accord. However, the scenario that meets the Paris temperature goal incorporates disproportionately high economic cost up to 2100, with costs reaching nearly 4 percent of global GDP around 2090. By comparison, the more gradual emissions reduction paths associated with the optimal global welfare scenarios keep costs below 3 percent of GDP at all times. Furthermore, the optimized case with greater cost reductions after 2050 could achieve an outcome consistent with the 2°C scenario depending on the speed and degree of international collaboration.

Our modeling results demonstrate that balancing the mitigation, adaptation and residual damage costs is crucial to minimizing the overall cost of climate change to society. Although the agreed global goals may be challenging to reach, the mitigation commitments made in Paris do not come close and also do not meet our lower, economically efficient emissions paths. Reconciling the bottom-up approach of the Paris Agreement with the collective effort needed to effectively respond to climate change will be an ongoing challenge.

These results also emphasize the importance of continuing research and development in low-carbon and zero-carbon technologies. This represents a valuable hedge against uncertainty, as does carefully targeted financial support to move technologies from the demonstration to the commercial stage. Some action on climate change might be delayed until technologies become less expensive, but if the long-term costs associated with a changing climate are to be minimized, the substantial investment in research and development required to make this cost reduction possible should be made now.

Fundamental uncertainties make climate change policymaking highly problematic, while the transition to a low-carbon energy system will take decades to complete. Together these realities magnify the policymaking challenge facing governments. A

practical approach to climate change policymaking provides the flexibility to respond quickly and effectively to evolving scientific knowledge, technological developments, community aspirations and commercial innovations. It would also support a more consistent and predictable approach that would allow for incremental development of specific policy and regulatory responses over time while providing sufficient high-level policy clarity to build confidence and encourage investment. This is a crucial precondition for encouraging efficient and innovative responses to achieve a timely transition that helps to meet climate change goals at least cost. Well-functioning markets could be key enablers in this context.

The Paris Agreement anticipates revisions and refinements every five years, which provides much needed scope for incremental policy development at the national level. A practical approach to climate change policymaking would complement the Paris framework, allowing governments to capitalize on its flexibility by facilitating the use of more incremental and adaptable policy responses that better reflect local resource endowments and socio-economic circumstances.

# Introduction

The challenges associated with climate change policy are complex, interrelated, dynamic and only partly understood. This creates inherent uncertainty for policymakers around identifying and implementing appropriate policy responses. It also involves a real risk that unbalanced policies could have unintended consequences that may jeopardize achieving sustainable environmental and economic outcomes.

Reducing GHG emissions is an extreme version of a public good — no country can capture all the benefits of its own GHG reduction efforts, but all nations will be affected by the consequences. Thus, global efforts are needed to avoid the worst effects of climate change. Climate change raises great intellectual challenges — for scientists in understanding and modeling the complex interactions that rising GHG emissions can bring and for policymakers in balancing the trade-offs between emissions mitigation costs today and the potential for substantial, but uncertain, economic damage in the future.

Burning fossil fuels produces the greater part of the world's GHG emissions (Victor et al 2014). But fossil fuels power the world economy, meaning that efforts to reduce GHG emissions must focus on the world's economic engine. Never before have the world's nations needed to work together on a problem with roots so deeply ingrained into their economies and way of life. Climate change requires a very different level of effort from earlier global cooperation on issues such as ozone depletion, which only impacted a small portion of the economy and where substitute products were readily developed.

The sharing of responsibility for emissions reduction across developed and developing countries is a challenge, particularly felt in developing countries that are focused on bringing modern energy services and greater economic prosperity to their people. The potential damage resulting from a changing climate also varies greatly across geography, meaning that the local imperative for emissions reductions varies accordingly across the world.

# An Evolving Approach to Global Goals: The Paris Agreement

The 21st Conference of the Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC), held in Paris in December 2015, marked a new beginning in global climate change negotiations. For the first time, negotiators recognized that individual nations must drive climate change policies; the top-down structure of the Kyoto Protocol had failed. Instead, the Paris Agreement recognizes that each nation has unique socioeconomic, resource, trade and development conditions. The Paris process combines bottom-up national policy setting with a global framework to drive collective action. In all, 195 countries signed up to the Paris Agreement, which entered into force on Nov. 1, 2016. A total of 148 countries had ratified the Agreement by June 2017 (UNFCCC 2017).

Nationally determined contributions (NDCs) are at the center of the Paris Agreement. These are the actions that each country proposes to take to slow and stop the rise in GHG concentrations in the atmosphere, by reducing GHG emissions and increasing sinks for GHGs. The Agreement commits all countries to reporting regularly on their GHG emissions and the progress they have made in implementing and achieving their NDCs, and to undergo international review of their progress. Additionally, all countries must submit new NDCs every five years, with the expectation that these will “represent a progression” beyond previous ones. However, the NDCs themselves are non-binding; countries are not obligated to reach the goals set in their respective NDCs (UNFCCC 2015).

The overall goal of the Paris Agreement is to limit global temperature rise to less than 2°C compared with preindustrial levels, and to “endeavor to limit" the temperature rise to 1.5°C. The 2°C temperature goal dates from the 2010 Copenhagen Agreement. It was chosen to avoid the worst impacts of climate change and to provide a simple single metric of climate health. However, it was not selected based on a rigorous analysis of costs and benefits (Victor and Kennel 2014; Randalls 2010; Jaeger and Jaeger 2010). Also, considerable uncertainty remains around how increasing concentrations of GHGs in the atmosphere affect global temperatures (IPCC 2014). We will return to this issue overleaf.

# Climate Goals and the Role of Pragmatism

The Paris Agreement focuses on the concentration of GHGs in the atmosphere, reducing GHG emissions and increasing sinks for GHGs. But mitigation is not mankind's only, or necessarily most cost-effective, response to climate change. Three types of costs can result from climate change and our response to it:

> Mitigation – Investments to reduce GHG emissions or remove GHGs from the atmosphere to prevent temperature rise. The most important mitigation activities are reducing emissions of carbon dioxide ($CO_2$) from the energy sector, since burning fossil fuels produces 60 percent of global GHG emissions (Victor et al 2014). Actions to reduce emissions of other GHGs and actions to remove $CO_2$ from the atmosphere, such as afforestation, are also included.

> Adaptation – Investments to prevent economic loss due to unmitigated future temperature rise. Such actions could include building dikes and levees in coastal areas, disease prevention efforts and agricultural research to reduce economic damages from a warming world.

> Damage – Economic loss that occurs despite mitigation and adaptation efforts, such as losses from flooding, net decreases in agricultural production, reduced biodiversity and an extended range of tropical diseases.

A practical approach to limiting the impact of climate change requires consideration of each of these potential responses and their costs. To maximize global welfare given the reality of climate change, policy responses should aim to minimize the sum over time of these three types of climate-related costs.

The 2°C goal, particularly if it is to be achieved by 2100, focuses on mitigation of climate change, with little consideration of the other two types of costs. At some very high levels of mitigation, however, it may be less expensive to adapt to the temperature change rather than to mitigate it through emissions reduction. Or the cost of mitigating or adapting to the temperature change may be greater than the economic damage that it causes. Focusing exclusively on mitigation without considering the other two types of cost can be harmful to overall economic growth and development. This paper considers the 2°C goal as mentioned above in light of current technology and our best understanding today of how GHG emissions will impact our climate and the economy. Ultimately, failure to consider all potential responses and their associated economic costs could jeopardize the emergence of a timely and cost-effective response to the critical threat of climate change.

Additionally, there is a time component involved in these trade-offs. Earlier mitigation actions result in greater cumulative emissions reductions, and thus more impact on limiting temperature rise. On the other hand, later mitigation efforts might be less expensive as technology improves and costs decline over time. A robust and practical climate approach must consider all potential actions and costs, including mankind's ability to adapt to the effects of climate change and the temporal trade-offs in terms of economic, social and environmental outcomes.

This paper explores practical long-term emissions paths that maximize societal welfare, taking into consideration the trade-offs between mitigation costs and the costs of temperature rise (adaptation and residual damage). We compare the environmental and economic outcomes of these practical paths with an emissions path that meets the current 2°C goal.

# Methodology – Modeling Practical Climate Goals

Modeling offers a tool to inform decision-making in the extremely complex realm of the interaction of climate change with human welfare. In particular, integrated assessment models combine physical and economic modeling to represent the impact of GHG emissions on human welfare. In this paper, we use the dynamic integrated model of climate and the economy, the DICE model, developed by William Nordhaus of Yale University. This combines a simplified climate model with a neoclassical economic growth model and is designed to evaluate alternate paths or policies in terms of social welfare. The model was most recently updated in 2013 (Nordhaus 2013).

The climate portion of the model relates $CO_2$ emissions to the carbon cycle, considering the distribution of emitted $CO_2$ in the atmosphere and shallow and deep ocean. The remaining $CO_2$ in the atmosphere then impacts the climate through ambient temperatures, ocean currents, sea level, etc. These overall climate changes impact ecosystems by changing agricultural yields, disease patterns and the distribution of species. Finally, these ecosystem changes affect economic growth. The DICE model contains simplified models of each of these impacts to relate changes in $CO_2$ emissions directly to economic impacts over the long term.

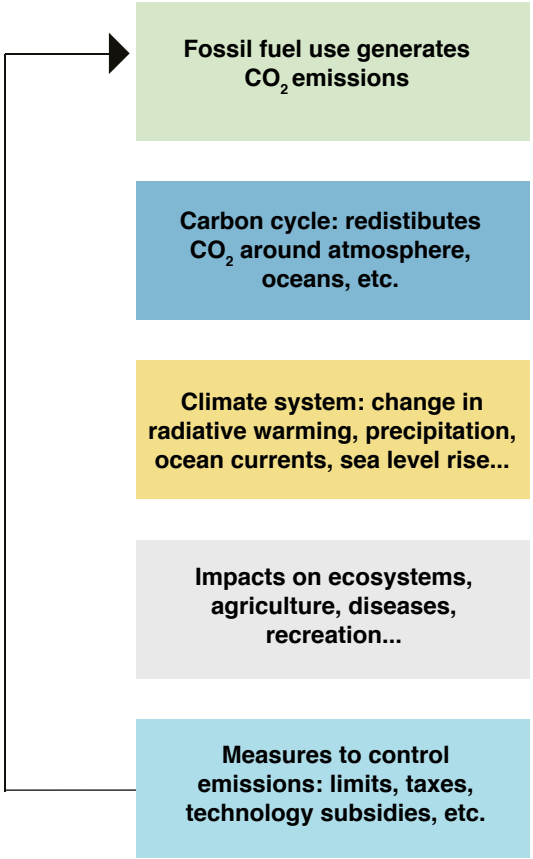



**Figure 1.** Schematic flow chart of DICE model (Source: Nordhaus 2013).

Source: KAPSARC.

The economic portion of the DICE model considers capital investments that reduce consumption today in order to increase future consumption. These include not only economic infrastructure such as roads and factories, but also investments to reduce GHG emissions. GHGs in the atmosphere can be seen as negative natural capital and investments to reduce GHG emissions as increasing natural capital. When economies devote current output to investments in emissions reduction, they reduce consumption today to increase natural capital and prevent an economic loss in the future (Nordhaus 2013).

The DICE model greatly simplifies the economic system by considering a single representative consumption variable. This variable is meant to include all forms of consumption — not only traditional goods and services, but also non market items such as leisure, health status and environmental services. Maximizing the net present value of this overall consumption variable over time is considered to maximize societal welfare. The model can be used to calculate emissions paths that maximize societal welfare overall, or to maximize welfare given specified policies or emissions paths that differ from the optimum.

Integrated climate models such as the DICE model must be run over extremely long timeframes to capture the long-term impacts of climate change and produce meaningful results. In this paper, we present results from the DICE model through 2200. Modeling impacts so far into the future introduces great uncertainty, but shorter timeframes do not fully capture the impacts of GHG emissions decisions.

# Assumptions and Uncertainties

The modeling process relating GHG emissions to economic welfare involves many uncertainties. This optimization relies on a number of assumptions, some scientific and some more philosophical in nature.

## How will population, GDP and baseline $CO_2$ emissions evolve over time?

We use United Nations World Population Prospects (medium variant) through 2100 (United Nations 2015). After 2100, we assume that the population growth rate declines in line with the trend through 2100. Population growth slows from its current rate of 1.2 percent per year to 0.5 percent in 2050, 0.1 percent per year in 2100, and 0.01 percent per year in 2200. World population reaches 9.7 billion in 2050, 11.2 billion in 2100 and 11.7 billion in 2200.

Global GDP is calculated using a simple production function

$$GDP(t)= A(t)K(t)^{\alpha}P(t)^{1-\alpha} \quad (1)$$

where A is total factor productivity, K is total accumulated capital, P is population and α is the capital share of output and capital accumulation (assumed as 0.3 in the DICE model). Total factor productivity is assumed to grow over time because of improving technology, but the growth rate declines over time.

The model uses a carbon intensity method, $CO_2$ emissions divided by real GDP, to generate baseline (or unmitigated) $CO_2$ emissions. Through 2050, we assume that $CO_2$ emissions before abatement increase in line with the Asia/World Energy Outlook from the Institute of Energy Economics, Japan (IEEJ). Carbon intensity declines by 48 percent from 2014 to 2050, an annual decline rate of 1.8 percent. This decline takes into account technology and efficiency improvements that occur outside of any GHG emissions reductions efforts. After 2050, carbon intensity continues to decrease, but at an ever slower rate. The decline rate decreases by 0.1 percent annually, consistent with the DICE model.

The model does not consider global energy demand or how energy demand is distributed. Therefore, this analysis gives no insight into energy use per capita or eliminating the challenge of energy poverty. The emissions pathways the model generates are global, and any number of ways to distribute the emissions and the related energy use could be envisaged.

## How sensitive is the climate to increases in GHG concentration?

The equilibrium climate sensitivity (ECS) is defined as the equilibrium global mean temperature that results from a doubling of atmospheric $CO_2$ concentration. The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report estimates that the ECS has a likely range of 1.5°C to 4.5°C, with a slight decrease in the lower bound from earlier IPCC estimates (IPCC 2014). The rate of increase in average global temperature has slowed since the early 2000s, contributing to a downward revision in the estimate (Johansson et al 2015).

The wide range in the ECS has fundamental implications for the nature and magnitude of policy responses. We consider central values of 2.5°C and 3°C in our analysis. The implications of uncertainty in the ECS are further discussed in our Conclusion.

## What are the cost curves for mitigation, abatement, and damage?

Our modeling approach includes a realistic assessment of mitigation costs, based on the IEEJ global emissions mitigation cost curve. This estimates the full range of current GHG mitigation costs, from low to very high levels of mitigation. Cost data for GHG emissions reduction technologies come from a variety of sources, including the Organization for Economic Cooperation and Development (OECD); the Japanese Ministry of Economy, Trade and Industry (METI); and Lawrence Berkeley National Laboratory.

The IEEJ used the MARKAL (MARKet ALlocation) model to construct its global emission mitigation cost curve from the raw technology cost data. This is a linear programming model that constructs a least-cost energy system given economic and technical scenarios and constraints. It describes the energy system on the supply side with technologies that collect energy sources to transform them into final energy, and on the demand side with technologies that consume final energy to produce energy services (Matsuo et al 2012). The model can estimate the least-cost energy system to meet energy demand given a constraint on GHG emissions. It is run for a range of levels of GHG emissions reduction, from 0 percent to 100 percent, to construct the cost curve for GHG emissions mitigation.

Costs are low at the beginning of the cost curve, since low levels of mitigation can be achieved through low cost or even economically beneficial actions, such as improving energy efficiency and fuel switching. Costs rise along the curve at higher levels of GHG mitigation, when more expensive technologies like carbon capture and storage are required to meet more stringent emissions reduction levels.

We use the MARKAL model to construct today's mitigation cost curve, then make assumptions as to how the curve changes over time. Mitigation costs are expected to fall over time, as existing low-carbon technologies decline in price and new, more cost-effective technologies are introduced. We make two assumptions about how the mitigation costs decline in the future. One case assumes that the mitigation cost curve declines at 0.5 percent per year through 2200. The second assumes that the decline in mitigation costs accelerates after 2050 at higher levels of emissions reduction, flattening the cost curve over time and reducing the 'cost wall' for deep emissions reductions. As a result, from 2050 through 2200, we have assumed that costs decline by 0.5 percent per year for emissions reductions of less than 50 percent, but for emissions reductions above 50 percent, we have assumed that costs decline at 1.5 percent per year over the period.

The adaptation and damage cost curves are highly uncertain and are subject to ongoing research. The DICE model calculates the optimal mitigation curve, with the effect of the remaining emissions being subject to adaptation or becoming residual damage. The damage function in the DICE model has been calibrated for temperature changes between 0°C and 3°C. Estimates of damage have not been calculated for temperature increases greater than 3°C. The model does not include sharp thresholds or tipping points for economic damage resulting from climate change and does not allow damage to exceed 100 percent of economic output (Nordhaus 2013).

The model does not differentiate between adaptation and damage costs. Climate change policy at the national level must consider how much to spend on adaptation, but these decisions will be based on local conditions and are beyond the scope of this work.

## How can current and future costs and benefits be balanced?

The discount rate is used to calculate the present value of future costs and benefits. In our analysis, this declines over time from 5 percent in 2010 to 4 percent in 2050 and 3.5 percent in 2100. Lower discount rates generally correspond to lower rates of economic growth and this model assumes that economic growth slows somewhat over time.

Since investments to reduce GHG emissions now provide the benefit of avoided economic damages many years into the future, the choice of discount rate makes a big difference in determining what investments are considered economic. A global debate has emerged around the appropriate discount rate, with disagreement over how to properly balance present costs against benefits to future generations. Unlike the other crucial factors, where the debate is largely scientific, debate about the discount rate has some philosophical aspects.

### The discount rate debate

Despite the debate around an appropriate discount rate for long-term climate change modeling, economists generally agree on the theory behind its calculation. The Ramsey equation to determine the appropriate discount rate for intertemporal investments has two terms. The first represents the relative importance of the welfare of future generations and the second considers the fact that future generations are likely to be wealthier than today's population.

The 'social discount rate' $r$ can be formulated as follows (Ramsey's formula):

$$r=\rho+\eta g$$

$\rho$: Pure rate of time preference

This is the relative weight of the welfare of different generations over time. This term is in units of an interest rate, but is intended to discount the actual welfare of future generations, rather than the value of goods or currency (Nordhaus 2008).

$\eta$: Elasticity of marginal utility with respect to consumption

$g$: Growth rate of per capita consumption

This term represents the change in marginal utility of consumption over time. As future generations become wealthier than those today, a unit of additional consumption will bring about less improvement in welfare than a unit of additional consumption today.

One possible approach takes the view that the choice of discount rate should be based entirely on normative 'ethical' considerations, with no need to consider observed discount rates or estimates of the opportunity cost of capital. This sets the value of ρ very close to zero, accounting only for the possibility that some exogenous event will wipe out the human race. In other words, it considers future generations of equal value to those today. The Stern Review, which adopted a discount rate of 1.4 percent, takes this normative approach. Stern argued that observed rates of return or costs of capital do not consider a number of factors that are crucial to the economics of climate change, including externalities, missing markets, unrepresented consumers and imperfect information (Stern 2008).

The other approach asserts that the discount rate must be based on observed behavior as reflected in market interest rates, without making moral judgments about the desirability of the distribution of incomes over time. This approach includes consideration of the returns on alternative investments as the benchmarks for investments in climate, and tweaks the value of ρ and η so that the resulting discount rate fits into the prevailing interest rate paradigm. William Nordhaus has been a leading champion of this approach (Nordhaus 2007). Our analysis follows this approach, selecting values of $\rho=1.5$ and $\eta=1.45$ to get discount rates from 5 percent to 3 percent, declining as economic growth rates fall over time (Nordhaus 2013).

The overall challenge in deciding on an appropriate discount rate comes down to whether it should be based on observable interest rates or on normative considerations. At the root of this controversy is the nature of the variable being optimized for society — the overall social welfare (Goulder and Williams 2012). Consumption is a measurable quantity that is a means to an end — what economists call utility. Social welfare, however, is a broader concept that brings to bear non quantifiable factors in addition to classical economic utility. The economic models used to evaluate policies generally conflate pure economic factors – consumption, utility – with impossible to measure aspects of social welfare to simplify the analysis. Thus, the variable being optimized is a mix of empirical and normative considerations, and both empirical and normative considerations are likely important in determining an 'appropriate' discount rate. The conflation of utility and social welfare is necessary to the modeling process, so the debate about discounting is likely to continue.

Additionally, studies show that lower discount rates are appropriate if large uncertainties are expected in the future (Gollier 2012). A declining discount rate also makes sense when considering events very far into the future (Weitzman 1998). Both of these factors may apply to climate change and further exploration of the effect of the discount rate is a potential avenue for future work.

# Modeling Results

We use the DICE model to evaluate four different emissions pathways. The reference case considers past trends in emissions and current policies without additional GHG emissions mitigation activities. The 50 percent reduction by 2050 case was selected to model a global average temperature increase of no more than 2°C, consistent with the current goals of the UNFCCC.

The two 'optimal' cases model global $CO_2$ emissions pathways that optimize global welfare given the overall cost of climate change to society — the sum of mitigation costs and the residual costs of adaptation and damage. These two cases differ in how technology costs decline over time. As described earlier, the optimal path assumes that the cost curve for emissions mitigation declines at a constant 0.5 percent per year. The cost-reduction case assumes that costs decline more rapidly after 2050, as research into less carbon-intensive technology pays off.

Figure 2 shows these four potential paths for $CO_2$ emissions through 2200.

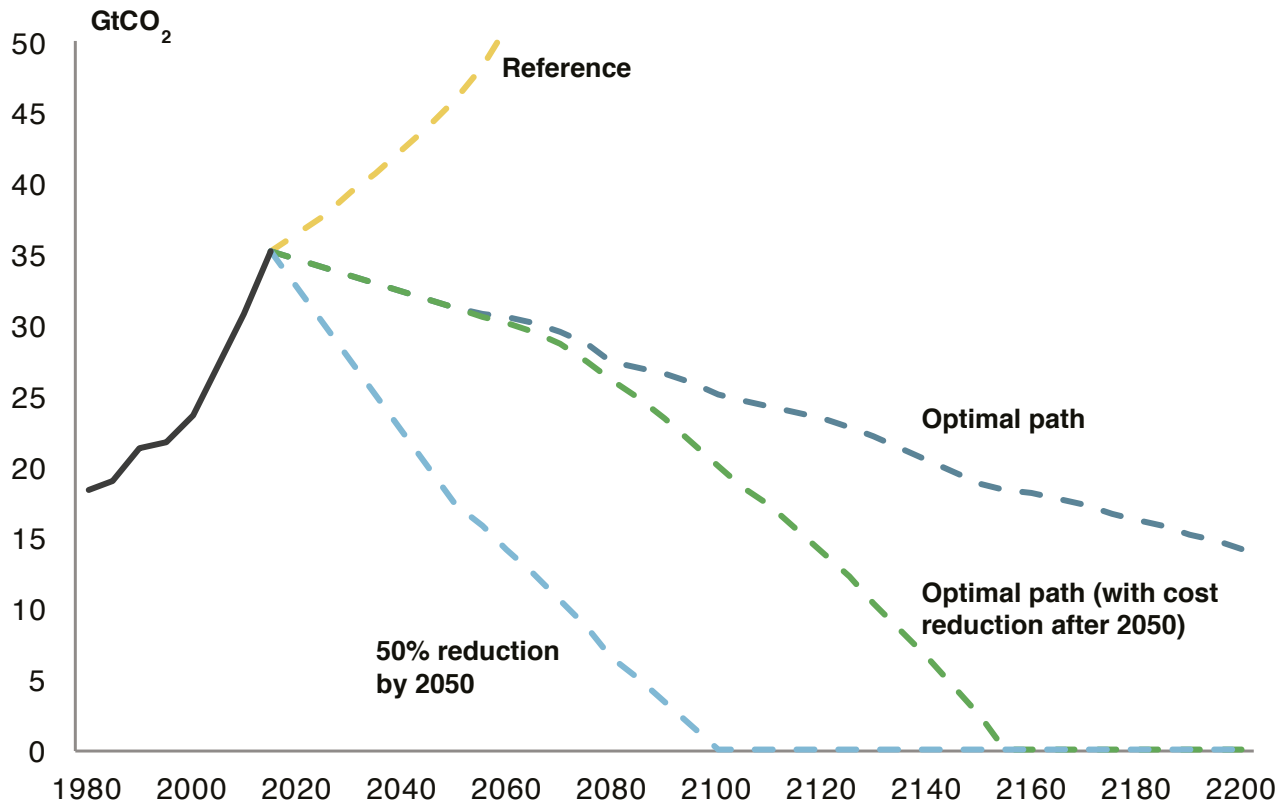



**Figure 2.** $CO_2$ emissions pathways.

Source: KAPSARC.

The 50 percent reduction by 2050 case reaches zero emissions just after 2100, while the optimal path with additional cost reduction after 2050 reaches zero approximately 50 years later. Without an accelerated rate of cost reduction after 2050, the optimal path does not reach zero emissions during the modeled timeframe.

Figure 3 shows the atmospheric $CO_2$ concentration over time for each emissions pathway. The optimal path levels off at around 570 parts per million (ppm), but does not peak during the modeled period. For the optimal path with cost reduction after 2050, $CO_2$ concentration peaks at 525 ppm just after 2100. For the path that includes 50 percent reduction in emissions by 2050, $CO_2$ concentration peaks at 450 ppm around 2060.

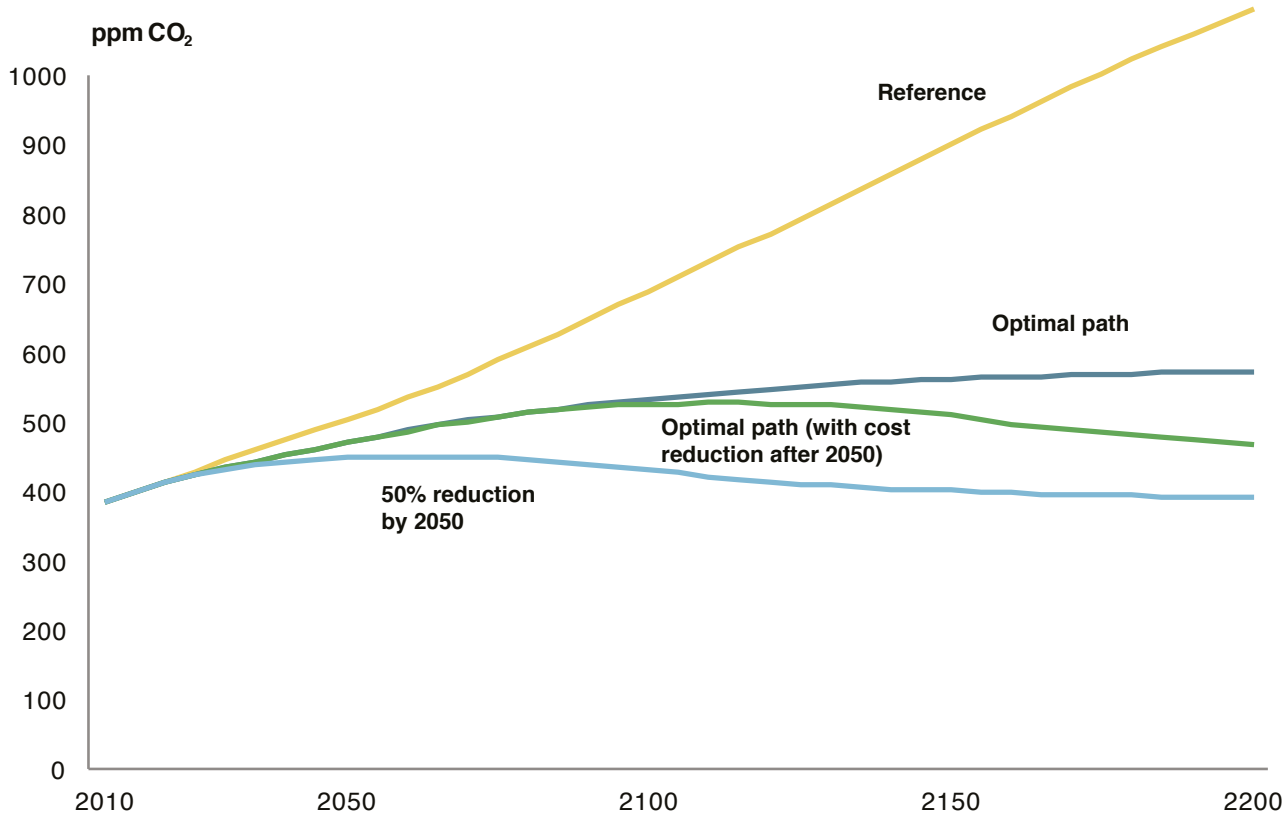



**Figure 3.** Atmospheric $CO_2$ concentration.
Source: KAPSARC.

Figure 4 shows the carbon price associated with each of the emissions reductions pathways. This price could represent the allowance price in a cap and trade system or a unified global carbon price consistent with achieving that path's emissions reductions. Since the reference case does not include new policies to reduce GHG emissions, there is no carbon price in this case.

Very high carbon prices are required to achieve a 50 percent reduction in GHG emissions by 2050. The price reaches more than $250 per ton of $CO_2$ by 2050 and tops out at more than $1,200 per ton of $CO_2$ in 2100. (All carbon prices in this section are in real 2014 U.S. dollars.) This high carbon price coincides with emissions reaching zero and is needed to bring about that very high level of mitigation.

Carbon prices are much lower in the optimal cases. The price is less than $50 per ton of $CO_2$ in 2050 for both optimal paths. Prices begin to diverge for the optimal cases after 2050 as the cost reductions add up over time in the reduced cost case.

In these optimal cases, the carbon price is also equal to the social cost of carbon, an estimate of the marginal damage caused by an increment of $CO_2$ emissions, or, conversely, the marginal benefit of reducing an increment of $CO_2$ emissions at that time. For comparison, the U.S. government estimates the 2050 social cost of carbon at a 3 percent discount rate at $79 per ton (converted from $69/ton in 2007 U.S. dollars in original source, U.S. Government Interagency Working Group 2015). The social cost of carbon increases over time because future emissions are expected to produce larger incremental damages, as physical and economic systems become more stressed over time in response to greater climatic change (U.S. Government Interagency Working Group 2015).

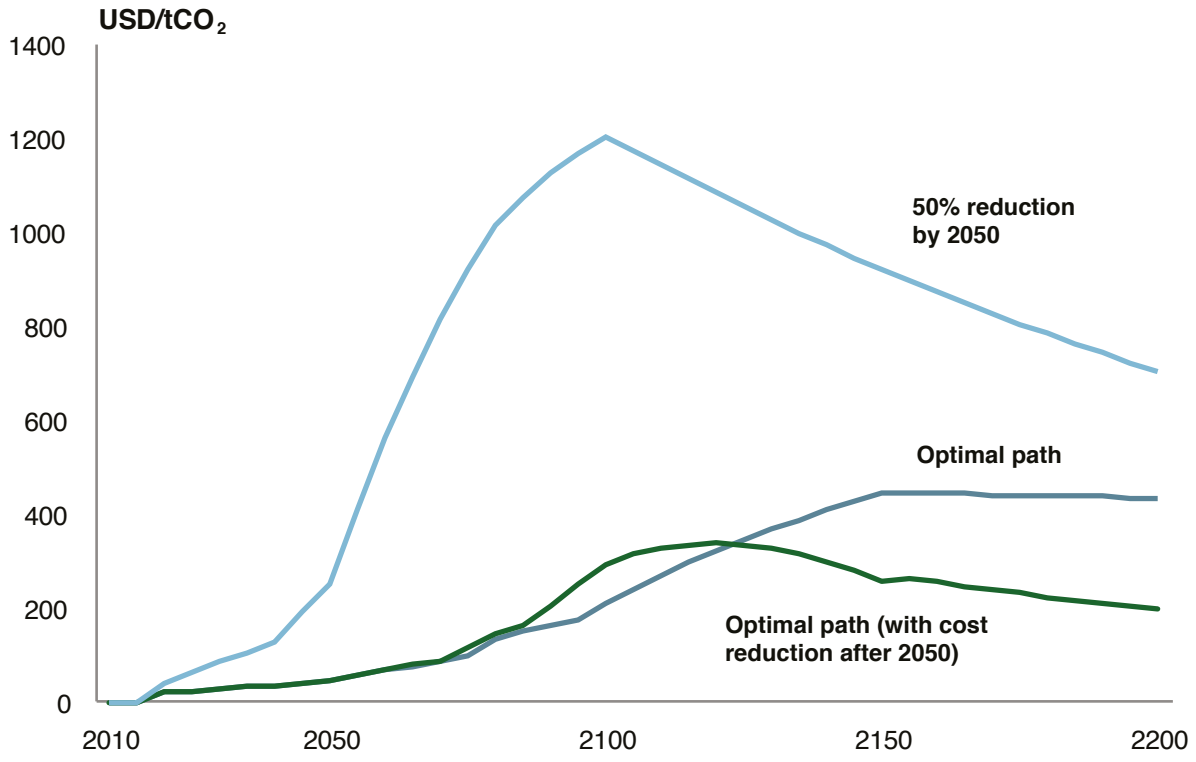



**Figure 4.** Carbon price.

Source: KAPSARC.

## U.S. government's social cost of carbon estimate

To provide consistency in how different parts of the U.S. government consider $CO_2$ emissions in their regulatory rulemaking, the U.S. government convened the Interagency Working Group on the Social Cost of Carbon. The most recent update of this work occurred in 2013 (Pizer et al 2014). The group's work uses three different integrated assessment models: the DICE model used in this work and the FUND and PAGE models.

The group presents its results for the social cost of carbon in terms of three different discount rates: 2.5 percent, 3.0 percent and 5.0 percent. In addition, the 95th percentile of the estimates for the 3.0 percent discount rate represents the higher than expected economic impacts from climate change. Estimates are given in five-year increments through 2050. The figure below demonstrates the range of uncertainty in values of the social cost of carbon, along with how important the choice of discount rate is to the calculated value. Moving from a discount rate of 5.0 percent to 3.0 percent more than triples the average value of the social cost of carbon in 2020.

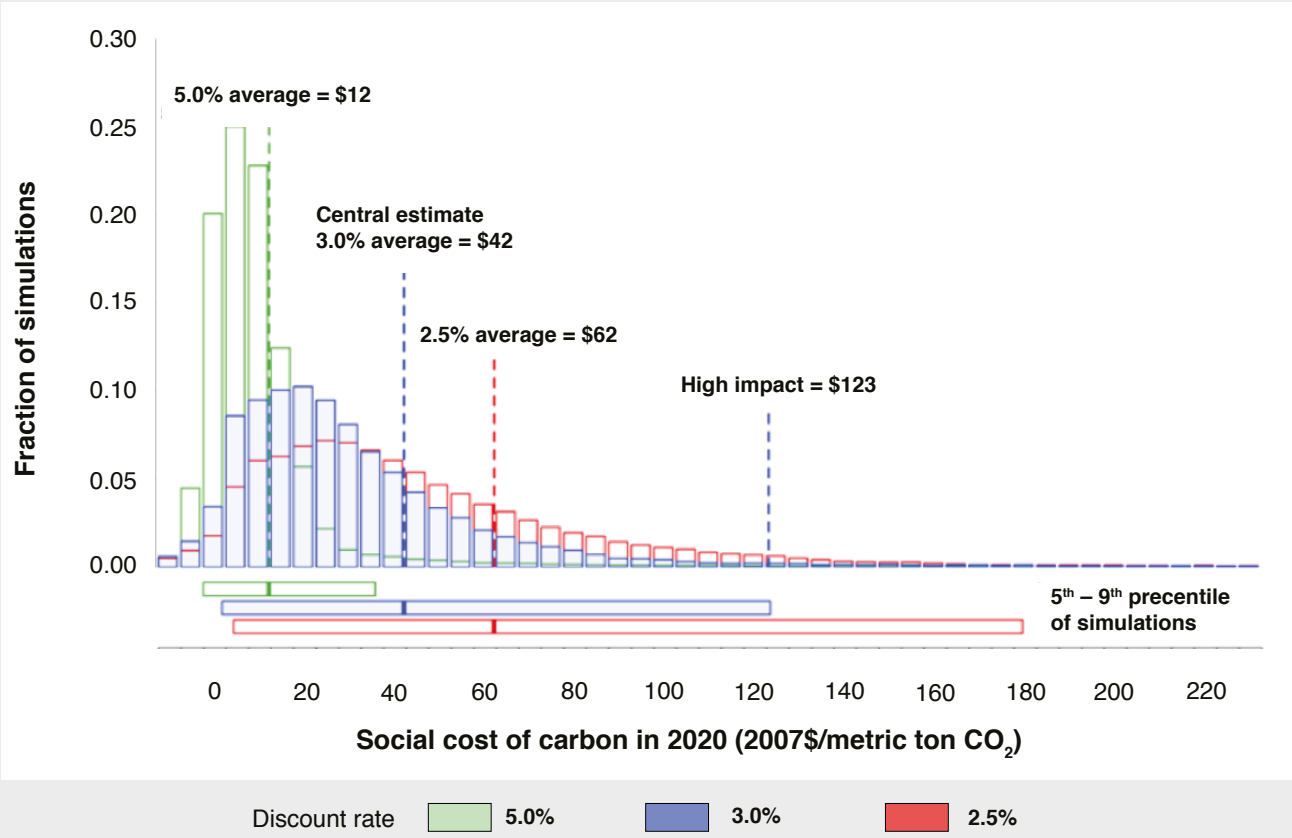



**Figure ES-1.** Frequency distribution of SC-$CO_2$ estimates for 2020[3].

Source: U.S. Government Interagency Working Group 2013.

Figure 5 shows the average global temperature rise since the early 19th century for ECS estimates of 2.5°C and 3°C for each scenario. The higher level of climate sensitivity is the more conservative assumption.

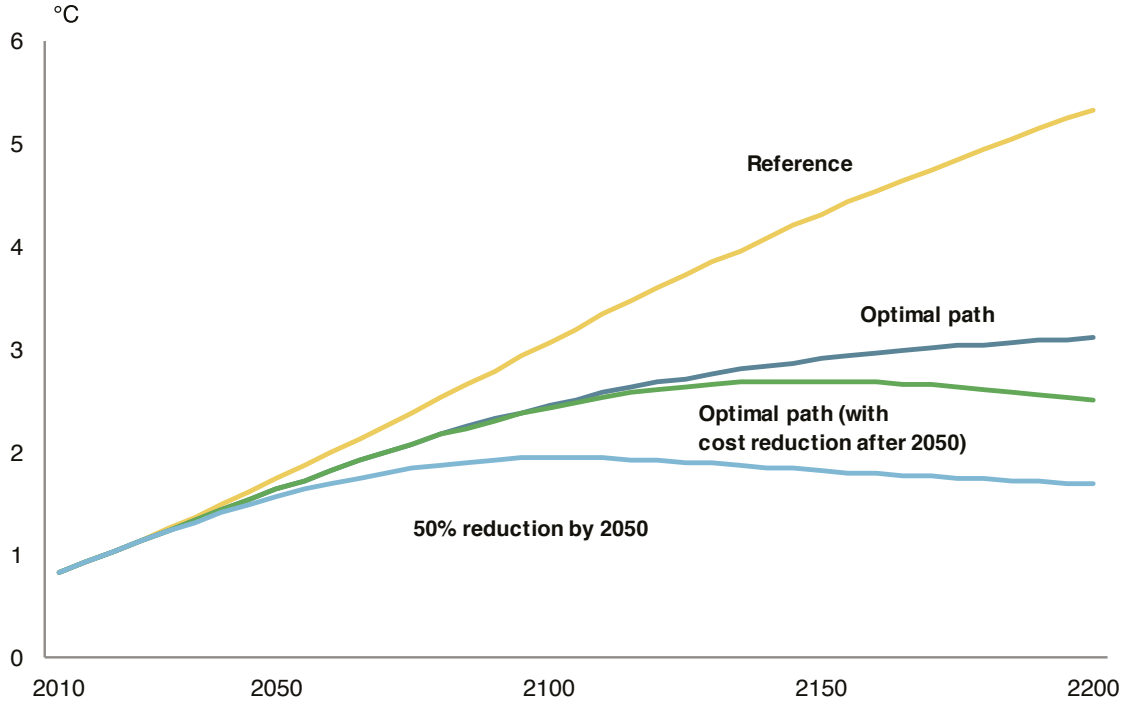
In the 3°C ECS case, the optimal path reaches 3.1°C of temperature increase above preindustrial levels by 2200. Although temperature increase is flattening somewhat, it does not peak during the modeled period. For the optimal path with cost reduction after 2050, the global temperature increase levels off at 2.7°C around 2120 and declines slightly thereafter.

If we could accelerate technological innovation, getting back to the 2°C track would not be impossible. For the path that includes a 50 percent reduction in emissions by 2050, the global temperature increase peaks at 1.9°C around 2100 and declines thereafter.

An ECS of 2.5°C is a more optimistic assumption that lowers the temperature profile for each emissions path. The optimal case reaches a temperature increase of 2.6°C in 2200 and the optimal path with cost reductions after 2050 reaches a peak temperature increase of 2.3°C. Getting back to the 2°C track would then be easier. The 50 percent emissions by 2050 case peaks at a temperature increase of 1.7°C

Figure 6 shows the overall economic cost of climate change — the sum of mitigation costs, adaptation costs and economic damage — in terms of their impact on global GDP each year. These graphs make clear the cost of reducing emissions by 50 percent by 2050 to achieve the UNFCCC's 2°C goal. For a climate sensitivity of 3°C, the economic cost of climate change tops out around 2090 at nearly 4 percent of global GDP. The economic cost of these emissions reductions rises steeply; they decline rapidly after their 2090 peak. By contrast, the optimal emissions paths represent a more measured approach to climate costs, ramping up more slowly over time and peaking at lower cost levels. The optimal path reaches 2.9 percent of GDP in 2200 and the path that assumes cost reductions after 2050 peaks at 2.6 percent of GDP around 2130.

The more optimistic assumption of a 2.5°C climate sensitivity results in similar conclusions, but with lower overall costs due to the smaller temperature rise. Achieving a 50 percent reduction in emissions by 2050 results in peak overall cost of 3.6 percent of GDP around 2090. The optimal path reaches 2.2 percent of GDP in 2200 and the path that assumes cost reductions after 2050 peaks at 2.1 percent of GDP.



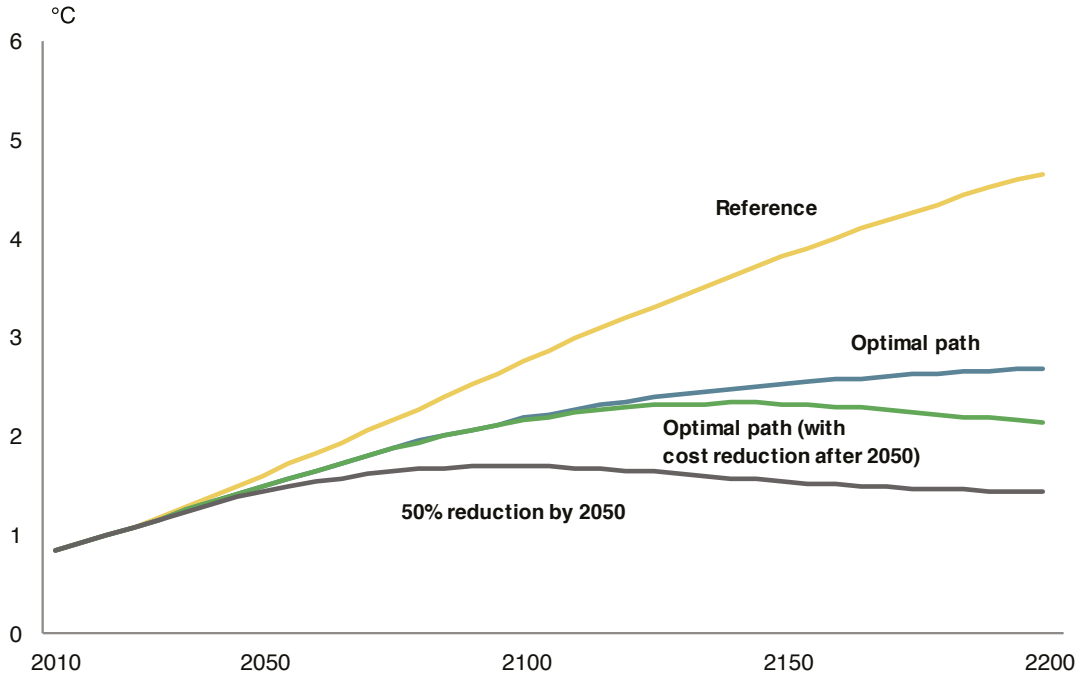
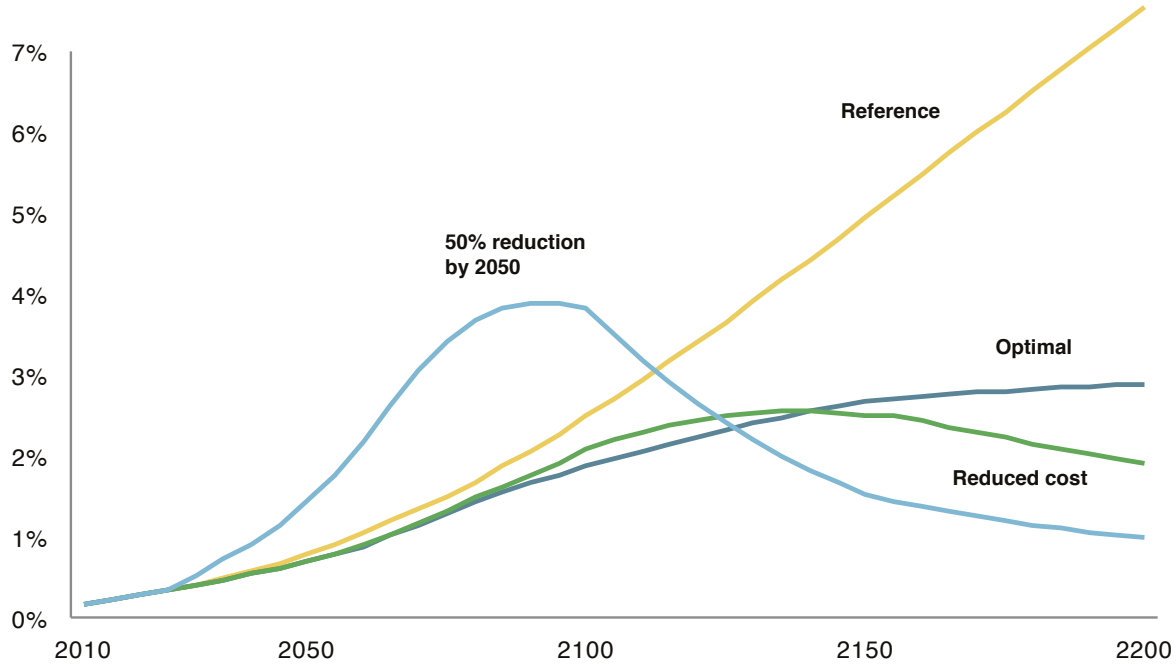




**Figure 5.** Average global temperature rise.

Source: KAPSARC.



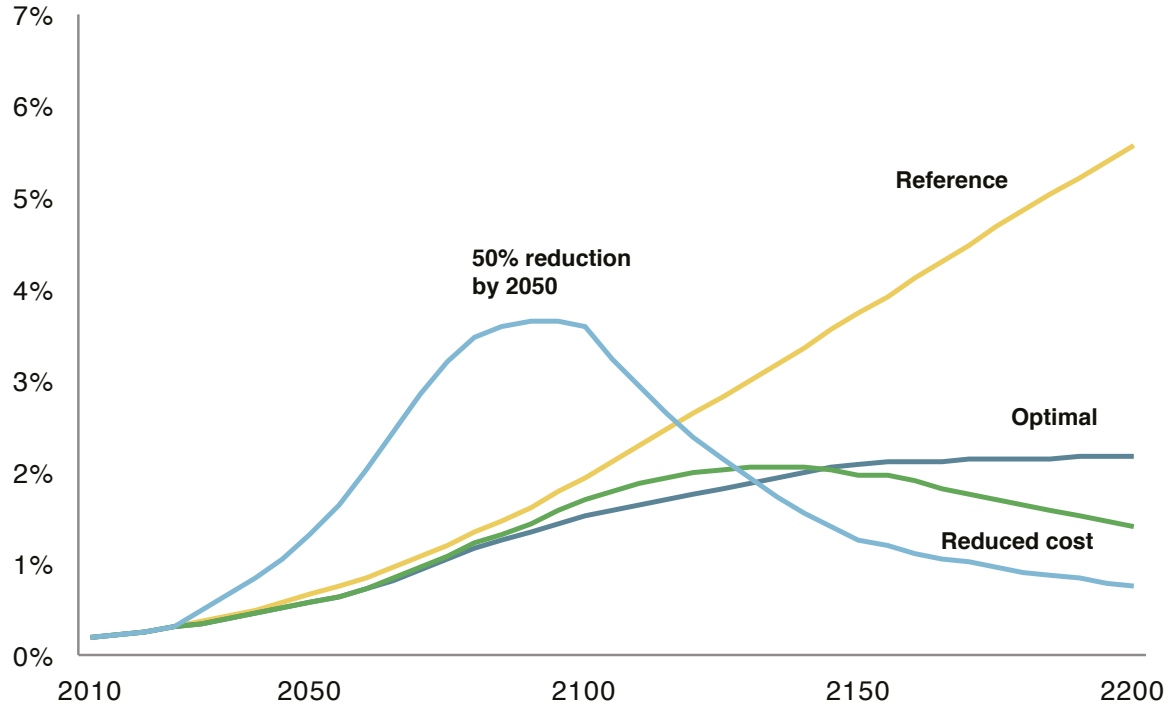




**Figure 6.** Economic cost of climate change, in percentage of GDP.

Source: KAPSARC.

# Some Policy-Relevant Insights

The conclusions from our analysis may offer insights for policy decision-making.

## Incorporating all climate costs is key to efficient outcomes

Considering the total cost of climate change — including mitigation, adaptation and residual damage — is crucial to understanding and minimizing the overall economic impact of climate change and the cost of associated policy responses on society. Overemphasizing mitigation at the expense of adaptation can result in higher overall costs. At very high levels of GHG emissions mitigation, our cost curves suggest that adapting to or accepting the resulting economic damage may be much less expensive options. With the overall cost to society in mind, particularly given the inherent uncertainties associated with climate science and the related economic impacts of climate change, the case for a 50 percent reduction in emissions by 2050 may be hard for policymakers to justify. Our economic analysis suggests that reducing emissions so quickly could be inefficient and very costly.

On the other hand, we find that the NDCs submitted in Paris do not include enough emissions reductions to reach the efficient paths we have described. Estimating an overall amount of emissions reductions from the NDCs is challenging given their different structures, baselines and levels of specificity. But the NDCs appear to promise less than 4 percent emission reduction from business as usual by 2030, which represents an absolute increase in emissions over that timeframe. By contrast, the efficient paths we calculated include absolute emissions reductions of about 13 percent over the same timeframe.

The Paris Agreement includes a process for countries to revisit their NDCs every five years. Although a 50 percent reduction by 2050 may appear unrealistic for many countries, most still need to step up their efforts to achieve an economically efficient and socially acceptable outcome. The five-year review process presents an opportunity for countries to propose more ambitious efforts to reduce their emissions, but many have a long way to go. Reconciling the bottom-up approach of the Paris Agreement with the collective effort needed to effectively respond to climate change will be an ongoing challenge.

## Technology research and development must be policy priorities

This analysis demonstrates the importance of ongoing research and development in minimizing the economic and social impacts of climate change. If the cost of emissions mitigations technology declines more rapidly after 2050, we estimate that the world would achieve much better outcomes, in terms of smaller temperature rise and lower economic cost. It may even be possible to achieve an emission outcome consistent with the 2°C goal depending on the nature of technological developments under the optimum scenario. So with this scenario we do not necessarily have to give up on achieving an emissions outcome consistent with the 2°C goal. This conclusion assumes progress in basic scientific research and technologies that are far from commercialization today, potentially including advanced nuclear reactors, nuclear fusion, carbon free hydrogen production and carbon sequestration and use.

In addition, a 0.5 percent annual decrease in the cost of emission mitigation technology is a baseline assumption in the optimal case, even without

additional reductions post 2050. If the world cannot sustain this level of technology improvement, the economic damage will be greater than described in our results for the optimal path.

Governments and international collaboration have important roles to play in basic scientific research. Businesses will underinvest in technology, or not invest at all, without clear commercialization prospects. Commercial investment in new energy research can be particularly challenging. Thus, there is a need for governments and research institutions to pick up the slack in basic research, given the societal importance of low-carbon energy technologies. According to the Third Hartwell Report – a 2010 paper published by the London School of Economics jointly with Oxford University – which calls for a new viewpoint on climate policy:

> **"To the extent that taxpayer consumer funds are used to fund technological initiatives, it should be used not to support individual companies or technologies, but rather to support key strategic technological platforms such as technology-agnostic test-beds, basic science and R&D activity, demonstration support, and competitive, innovation-focused deployment regimes." (Prins et al, 2013).**

Nevertheless, many government programs today focus more on clean energy implementation than on basic research. Perhaps the time has come to reconsider the balance of public investment among research and development, demonstration and deployment. Government programs, such as loan guarantees or public private partnerships could be used to help bring new energy innovations to full commercial scale.

Programs to support low-carbon technologies in the marketplace must be carefully designed to support market development without creating rent-seeking behavior and inefficient deployment. Deployment of still maturing energy technologies in the marketplace should be undertaken as a means to increase knowledge and spur further invention and innovation, not as an end in itself (Prins et al 2013). A strong push to bring technologies into the marketplace before they are ready can lock in less efficient and more expensive technology and squeeze out new innovations (Jenkins et al 2012). Policies to push the deployment of low-carbon technologies have also weakened consumer support for a low-carbon transition in some countries because of a backlash against their high costs.

## Generational cost sharing must be carefully considered

Our analysis shows that the pathway that calls for 50 percent reduction in GHG emissions by 2050 disproportionately loads the costs of climate change onto the generation alive between 2050 and 2100. Modeled costs fall dramatically after that time, as the investment to reduce carbon emissions has largely been made.

By contrast, the optimal paths described in this study spread the economic cost of climate change more evenly across generations. They are less expensive overall than the 50 percent reduction path and also avoid the challenge of paying the costs of climate change upfront, especially given that future generations are likely to be wealthier than those alive today, a fact that is taken into account in the selection of the discount rate. (See text box, The Discount Rate Debate, for further explanation.)

## Crucial uncertainties demand flexible and adaptable policy responses

Many uncertainties remain in climate change science and modeling, affecting both physical and economic outcomes. The sensitivity of the climate to rising $CO_2$ concentrations is a crucial uncertainty in the physical world, with enormous implications for economic outcomes and policy responses. If the actual sensitivity of the climate is at the high end of the IPCC range, economic damage would be larger than estimated here, which would justify greater emphasis on mitigation. The converse, however, is also true.

Nonetheless, as the Third Hartwell paper points out, “We can never know enough to conclude that research and data gathering should cease and policy-making begin.” (Prins et al 2013).

Climate change policymaking must confront the challenges of uncertainty. The flexible nature of the Paris Agreement is suited to coping with uncertainty, since the process anticipates revisions and refinements every five years and allows countries to take into account their changing economic and social conditions.

A practical approach involves making the best decisions possible using today’s science and considering today’s costs without swinging too far in either direction — locking in overly expensive technologies to reduce GHG emissions on one side or ignoring the risks and waiting for better information on the other. Ongoing research into low-carbon technologies is a valuable hedge in this world of uncertainty, as is support to move technologies from the demonstration to the commercial stage. The transition to a low-carbon energy system will take generations, with time for adjustments in either direction as the scientific information and commercially viable technological options become clearer.

On the economic side, the emissions abatement cost curve is an important source of uncertainty. We assume steady improvement over time in our modeling process, but improvement is likely to occur in step changes, as invention and innovation lead to the deployment of more efficient and cost-effective technologies. This is reflected in the optimal case with greater reduction in the cost of zero-carbon technologies after 2050. Policy changes are also likely to occur as step changes in response, as low-carbon and zero-carbon technologies mature.

# Conclusion

Our research aims to identify the global emissions paths that minimize the overall global cost of climate change to the economy.

The optimal emissions path in our analysis also has an associated optimal path for adaptation investments. Minimizing the total cost to society would also require that the adaptation investments occur — an important point and a subject for future research. In addition, the mitigation cost curve and the cost curve for adaptation and damage are aggregate global curves. Mitigation and adaptation costs will differ greatly across geography, and thus efficient actions will also differ from place to place. One-size-fits-all mitigation goals are not an efficient solution, as the new Paris Agreement recognizes.

More aggressive policies will be appropriate in certain places, particularly among countries with greater capacity to pay and those with a large, cost-effective endowment of renewable energy resources. Considering how countries with differing starting points, socioeconomic circumstances and resource endowments can efficiently contribute to the global goal is a logical next step in this process, and could be a valuable contribution to help inform the Paris process as countries revisit their NDCs over time.

Although this analysis looks at very long-term emissions paths, policymakers will typically consider actions over the shorter term, rather than over decades or centuries. This approach is appropriate and will allow policy to incrementally adjust to additional knowledge about climate and to changing mitigation and adaptation costs.

The economic costs associated with climate change will also not be evenly distributed. The calculation of a globally efficient outcome will not necessarily be acceptable to those with the most to lose in a changing climate. This raises fundamental issues of equity which can only be solved through effective global cooperation. Achieving a global climate change policy outcome that effectively balances the legitimate desire for economic development with the need for environmental sustainability is likely to remain one of the greatest challenges facing energy policymakers throughout the 21st century.

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# Notes

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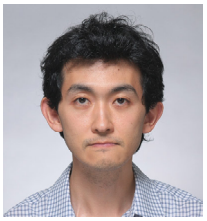

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## About the Project

This study examines potentially efficient global decarbonisation pathways that incorporate mitigation and adaptation to achieve more cost-effective outcomes. It forms part of a joint research program into practical approaches to climate change policy being undertaken by KAPSARC and the Institute of Energy Economics, Japan (IEEJ). This research program aims to help inform the debate around the development of more practical and cost-effective ways to help close the gap between national contributions and agreed global goals in the context of future climate negotiations.

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