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Climate Policy Enters Four Dimensions

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ABSTRACT

This chapter addresses what needs to be done to craft a politically stable and economically sound climate policy that includes balanced reliance on the four mechanisms to manage climate risks, which we call the climate control mechanisms: emissions reduction, adaptation, carbon dioxide removal, and solar radiation modification. Assessing the balance requires attention to (1) technology development, performance, and cost over a range of control options, (2) integration of the technology architecture with the prevailing economic, regulatory, and policy context, (3) public attitudes to climate policies and programs, and (4) implementation of a planning programing system to implement the new balanced climate policy. If the United States achieved a stable balance it could serve as the basis for extended international agreements.

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Introduction

The climate crisis is a global problem that requires country level policies. These policies require significant short-term costs to obtain benefits that are not easily understood by the public. The varying responses to the crisis by different political leaders indicate the importance of strong and steady leadership, guided by science and transparency. The current COVID-19 pandemic illustrates many of the politically difficult decisions that we must also confront with the climate crisis. Given the highly infectious nature of the virus, it is a global problem with huge negative spillovers between countries. In this sense it is similar to the global climate challenge.

A politically stable and economically sound climate policy should include a balanced reliance on four complementary mechanisms to manage climate risks: emissions reduction, adaptation, carbon dioxide removal, and solar radiation modification. In this chapter we discuss what these measures are and how they could be used to address the global climate challenge.

Before we review the climate science of the four mechanisms we highlight, it is useful to outline the relevant policy context. At the 2015 Paris Conference of the Parties (COP21) to the 1992 United Nations Framework Convention on Climate Change (UNFCCC) world leaders announced the ambitious goal of keeping the rise in global temperature below 1.5°C–2°C. More than 190 nations agreed to participate in a "Nationally Determined Contribution" process to achieve these goals (UNFCCC, n.d.). Yet COP21's ambitious temperature goal obscures the hard truth that the Paris Agreement's voluntary, pledge-and-review emissions reduction process is a step back from the 1997 Kyoto COP's aspirations of binding emissions reduction targets. The United Nations Emissions Gap Report (2019) suggests that several countries (including the United States) will not reach their first tranche of intended NDC's and will not meet their submitted 2020 reduction targets. Indeed, global emissions continued to rise until the COVID-19 crisis.

COP21 also set a goal to increase funding for adaptation, signaling a concern that the world might not reach its ambitious global warming targets based on emission reduction alone (UNFCCC, n.d.-b). Small island nations and some developing countries are particularly concerned because of their vulnerability to sea-level rise, especially as global temperatures increase beyond 1.5°C. UNFCCC parties have agreed that substantial financial flows are needed from parties with resources to more vulnerable parties with fewer resources, but a facilitating mechanism is not yet in place (UNFCCC, n.d.-c). The upshot is a growing consensus among climate policy experts that emission reductions are insufficient to prevent substantial climate damages, and that the climate response must consider tools beyond emission reductions.

While the Trump administration has begun the process of withdrawing the United States from the Paris Agreement, the climate issue has captured greater attention from a much broader segment of the global public. Youth movements like "Fridays for the future" have mobilized a new political generation (Ramzy 2019). Public leaders from across the political spectrum are calling for action. Young progressives, especially on university campuses, are forming activist groups both to advance a low-carbon agenda and to call to proscribe energy companies. Opinions are even shifting among young voters who identify as Republican. New York state, the European Union, and other political entities have passed aspirational laws requiring 100 percent carbon-free economies in their jurisdictions by mid-century. Responding to pressure, many businesses have also begun to take serious steps toward a carbon-free world: auto companies are aggressively moving toward electric vehicles, California utilities are planning on storage and renewable generation to meet anticipated load, and oil and gas companies such as Shell have small, but active programs to develop fossil-free, liquid fuels.

These positive trends face headwinds. The rising tide of nationalism and populism makes crafting international agreements implausible. The COVID-19 pandemic has shifted public attention away from climate and is driving up public debt, which will likely reduce appetite for new investment on climate.

Over the last decade, the climate policy community has widened its field of view, from an exclusive focus on *emissions reduction* to include *adaptation*. In the years since COP21, *carbon dioxide removal* (CDR) from the atmosphere, also referred to *negative emission technologies,* have become a central part of discussions about climate technology and policy. Most recently, the possibility of direct intervention with reflecting particles in the upper atmosphere to reduce incoming solar radiation, referred to as *solar radiation modification* (SRM) have entered the mainstream, climate policy debate. Adaption, CDR, and SRM now need to be considered along with emissions reduction as the four tools for managing climate risk.

The remainder of this chapter discusses these four promising and necessary climate control mechanisms.

CLIMATE SCIENCE PRIMMER

The single most important finding of climate science for policymakers is that climate change is proportional to the *cumulative* emissions of carbon dioxide (CO_2). This means that if emissions are brought to zero, the problem does not get better; it simply stops getting worse, because it takes hundreds of years for carbon dioxide in the atmosphere to equilibrate into the deep ocean. The atmospheric lifetimes of other greenhouse gases are not as long. For example, methane (CH_4), which has a 10-year half-life, produces warming roughly equivalent to its current emissions rate, rather than its cumulative emissions.

Scientists are confident that carbon dioxide emissions and temperature are linearly proportional, but the proportionality constant—the climate sensitivity between the radiation that causes the change in temperature for a given amount of carbon dioxide emissions—is still uncertain by at least a factor of two, despite half a century of research.

The uncertainty about climate sensitivity to carbon dioxide emissions is caused by several feedback mechanisms in atmospheric dynamics, such as clouds, water vapor, and sea ice. The uncertainty is captured by a probability density function for temperature increase that has a "fat tail" due to the non-linearity of the feedback mechanisms that influence the climate sensitivity (Roe and Baker 2007).

1. The Climate Control Toolbox

We discuss four climate-risk control mechanisms:

Emission Reduction: Lowering carbon emissions without reducing economic growth, which is accomplished by reducing the carbon intensity of energy (CO2/E) or lowering the energy intensity of the economy.

Carbon Dioxide Removal (CDR): Technologies that have the potential to transfer carbon dioxide from the atmosphere at gigatonne scales into physical or chemical storage, or into biological sinks, such as biomass or soils.

Adaptation: human-designed programs that aim to protect communities, commerce, and the environment from anticipated damage and adverse impacts from climate change.

Solar Radiation Modification (SRM): The deliberate use of technical methods to alter the Earth's radiative balance.

Each control mechanism has a very different "technology readiness level," a formal classification system that uses specific qualitative parameters to characterize the technology's maturity and readiness for deployment. A vast amount of field data is needed to support cost and performance estimates necessary to plan projects and attract public or private financial support. There also is a vast difference in the maturity of the regulatory frameworks that support each mechanism, and in the public's acceptance of each mechanism (see Table 1).

Table 1: The Climate Control Toolbox

1.a. Emissions Reduction

MECHANISM		TECHNOLOGY READINESS	COST RANK	REGULATORY FRAMEWORK	PUBLIC ACCEPTABILITY
Emission Reduction	First half of emissions	Functioning clean energy market	2	Fed & State established.	Established
	Last third of emissions	No market proven technology for non-electric industrial or heavy freight	4	Strong global markets.	
CDR	Storage in Biological sinks	Some technology and markets exist for forestry and soils but monitoring inadequate and lifetime uncertain	1–3	Weak – verification challenging	Moderate to high
	Physical or chemical storage	No market proven technology, some funding for DAC and BECCS very little for other scalable technologies	4	Limited	Moderate
SRM	Implementation	Technology for some methods exists and costs are low	1	Nonexistent Contentious	Low and uncertain
	Consequences	Efficacy and impacts deeply uncertain	2–4		
Adaptation		Mixed: e.g., markets for managing current agricultural risks but little long-term R&D	2–3	Diverse	High

Emissions reduction has historically been the focus of national and international climate policy. There is a direct relationship between fossil fuel use for energy and emissions. If the proportion of the energy sources remain fixed for the economy, then the growth rate of carbon dioxide emissions and economic growth will be proportional to one another. The purpose of emissions reduction is to lower emissions without reducing economic growth. The famous Kaya identity summarizes the linkage. Over any fixed time period the following relationship must hold:[1]

$$dCO_2/CO_2 = d\,(CO_2/E)/(CO_2/E) + d\,(E/Y)/(E/Y) + d\,Y$$

1 The identity follows from taking the first differential of C = (C/E)(E/Y)Y.

where E is energy use of the economy and Y is the economic activity. If the economy is to experience emission reduction, $d\ CO_2 < 0$, with no loss of economic activity, $dY \geq 0$ there must be a compensating reduction in the carbon intensity of energy (CO_2/E) or in energy intensity of the economy (E/Y).

For both energy and carbon intensity, improvement is realized through change in energy infrastructure that is driven by a combination of market incentives and regulatory mandates. Higher energy or carbon prices encourage firms to adopt more energy-efficient or low-carbon means of production. For example, many U.S. states have adopted renewable portfolio standards (RPS) for electricity generators, while the federal government has adopted fuel economy standards for automobile manufactures. The world has benefited from a remarkable fall in the cost of photovoltaic solar and wind power and from a shift from coal to natural gas electricity generation due to a fall in in the relative price of natural gas.

Deep emissions cuts will be achieved primarily by replacing the high-emission capital stock with low-emission capital stock in the energy system, as when solar or nuclear power are built to replace fossil fuel-based power generation. Because emissions cuts mostly come from the replacement of long-lived capital stock rather than from changes in the use of existing capital or from changes in consumption patterns, there is substantial lag between flows of money and long-term reductions in emissions.

Among the most important measures to reduce emissions is investment in clean energy—the flow of funds that builds up the low-emission capital stock. The massive investment required greatly outstrips the current global effort. Bloomberg-Energy (2020) reports that financial inflow rose rapidly in the first decade of the century to roughly $300 billion per year, but spending levels have been roughly flat since 2010. This represents 0.3 percent of global GDP, which while not insignificant, is perhaps a factor of 10 smaller than it would need to be to have any chance of achieving the goal of “net-zero carbon emissions” by mid-century.

As the energy system becomes more decarbonized, it becomes more costly to further reduce the carbon content. Marginal control costs rise as emissions are squeezed out. Because of the relatively low capacity factor and variability of renewable solar and wind generation, increasing costs at the margin come from systems to compensate for the low capacity factors and to meet load: storage, transmission, and excess solar and wind capacity that is often curtailed. This high cost will be transmitted to a transportation system that will increasingly use electricity to replace fossil fuel. The transition to this new, low-carbon economy will require massive amounts of capital and a very long time period of market adjustment until the benefits of decarbonization are realized.

Government policies in the United States and Europe have strongly supported clean energy innovation. But neither funding for innovation nor emissions cuts lived up to the rhetoric. For example, the Mission Innovation Initiative, announced at COP21 by 24 countries and the European Union, pledged to double public clean energy research, development, and demonstration (RD&D) expenditures over five years (Mission Innovation, n.d.). After three years, 55 percent of the investment commitment has been reached, but not necessarily deployed. While there is some coordination between member countries, in practice each country follows its own program at its own pace, without any overarching strategy (Mission Innovation 2019).

On a global basis, the U.S. Energy Information Agency's (EIA) 2019 International Energy Outlook projects that carbon dioxide emissions will continue to increase through 2050 at an average annual rate of 0.6 percent, due to economic growth in Asia and Africa.

The EIA also predicts that carbon intensity over the period 2018 to 2050 will decline at an average annual rate for the globe by 0.6 percent, with the carbon intensity of the United States, China, and India projected to increase annually by 0.3 percent, 1.2 percent and 1 percent, respectively, while that of OECD countries is projected to decline by 0.6 percent per year.

1.b. Carbon Dioxide Removal (CDR)

As the prospects for emission reductions that are consistent with the temperature goals of the Paris Agreement look increasingly doubtful, attention has shifted to CDR technologies that have the potential to transfer carbon dioxide from the atmosphere at gigatonne scales. There are many who advocate turning to CDR, sometimes referred to as net zero technologies, but some urge caution (Davis et al. 2018; Field and Mach 2017; Krupp, Keohane, and Pooley 2019).

As described in Table 1, CDR technologies may be divided into two broad categories depending on the longevity of the carbon storage.

Technologies that rely on *physical or chemical storage* work by injecting carbon dioxide deep underground or into the deep ocean, forming stable minerals or dissolved salts. Whatever the cost and environmental impacts of operating these technologies, there is confidence that the carbon is stored for geologic timescales (thousands of years). These technologies include bioenergy with carbon capture and sequestration (BECCS); direct air capture (DAC); and carbon mineralization of carbon dioxide (the addition of alkalinity to the ocean).

Technologies that rely on *biological sinks* depend on managing ecosystems to increase the flow of carbon into biomass or soils. Carbon in these systems can readily be returned to the atmosphere in years to centuries, as when a forest burns or a farmer shifts management practices to allow carbon in soils to deplete. They include storage of carbon in coastal ecosystems; enrichment of soil carbon (such as biochar, crop modification, and other agricultural practice); and terrestrial carbon removal and sequestration (including afforestation, reforestation, and forest management).

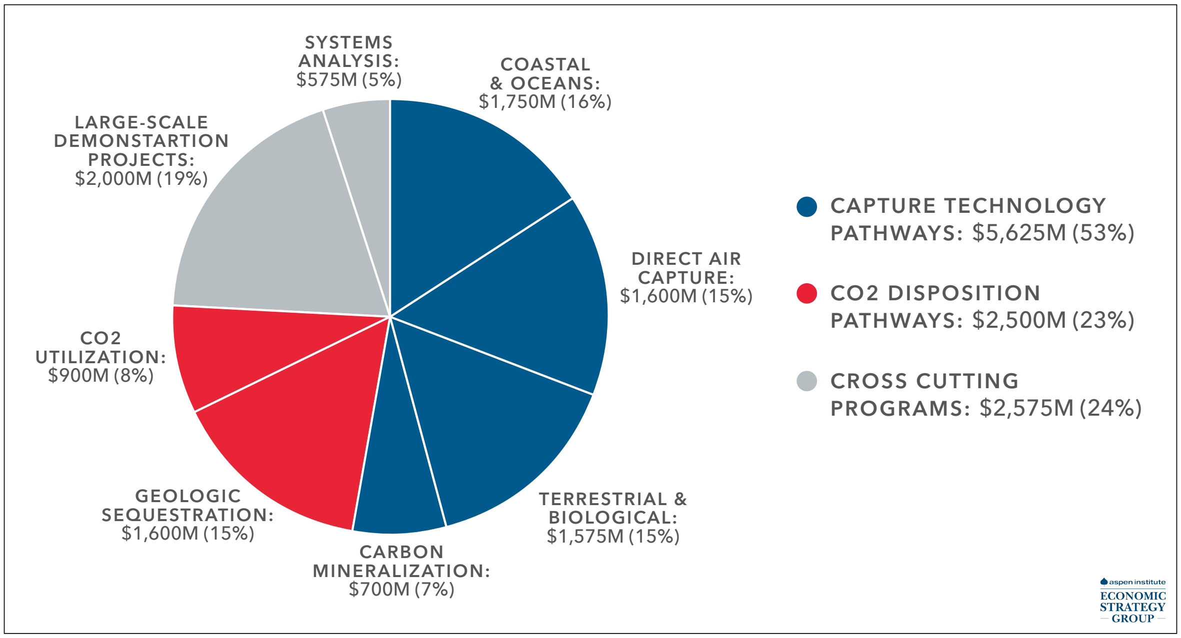
Some of the biological sink technologies are inexpensive, as they involve little more than adjusting existing management practices in forestry or agriculture. Their challenge is measuring the amount of carbon that is stored, and accounting for the fact that carbon can return to the atmosphere on timescales that are relevant for climate policy.

CDR technologies, particularly those that involve physical or chemical storage methods, are at an early stage of technology readiness. If pursued they will need to follow the conventional system development path: first, the candidate CDR technology is assessed for its technical readiness; second, a cost-benefit analysis of the CDR technology is conducted upon deployment; third, an RD&D program is constructed with technical milestones and costs which, if successful, will confirm feasibility; and finally, environmental, health, and safety characteristics are established for the technology.

Having a well-defined development path does not mean the project will be implemented, especially for technologies of gigatonne scales. Crossing the "innovation bridge" requires addressing multiple, interconnected factors relevant to climate policy beyond technical considerations, such as matters of economics, regulation, and market design. Importantly, for a new CDR solution to gain policy approval and access to the necessary resources, advocates must come forward with a practical plan for its management.

The National Academies of Sciences, Engineering, and Medicine (2018) identified four technologies that are ready for development: aforestation/reforestation, forest management, uptake and storage in agricultural soils, and biofuels with carbon dioxide capture and storage (CCS). The study recommended an annual federal RD&D budget in the \$300–\$400 million range. The Energy Futures Initiative (EFI) (2019) recommended a 10-year, \$10.7 billion federal budget as allocated in Figure 1.

Figure 1: CDR RD&D Initiative Proposed Total Funding by Portfolio Categories



Source: Energy Futures Initiative (2019). Report. "Cleaning the Air: A Federal RD&D Initiative and Management Plan for Carbon Dioxide Removal Technologies.

The EFI recommendation is more than twice the amount recommended by the NAS, but the two studies did not address the same programmatic landscape. As a benchmark, the 2019 budget for the Department of Energy's Energy and Science programs was about $12 billion.

Direct air capture (DAC)[2] is the chemical scrubbing processes for capturing carbon dioxide directly from the atmosphere via absorption or adsorption separation. DAC has attracted wide interest, but the process—which requires two steps, separation and compression—is technically challenging because carbon dioxide is so diluted in the atmosphere (about 400 parts per million by volume). There is a wide range of estimates about its cost, from $60 to $500 per metric ton of carbon dioxide captured. Rajan and Herzog (2011) conclude: "Estimates of $27/tCO_2$) to $136/tCO_2$ found in the literature for DAC are just not believable." In an engineering cost study biased on commercial engineering development of DAC, Keith et al. (2018) found levelized costs over a range of plant configurations of $92–$232 per ton of carbon dioxide.

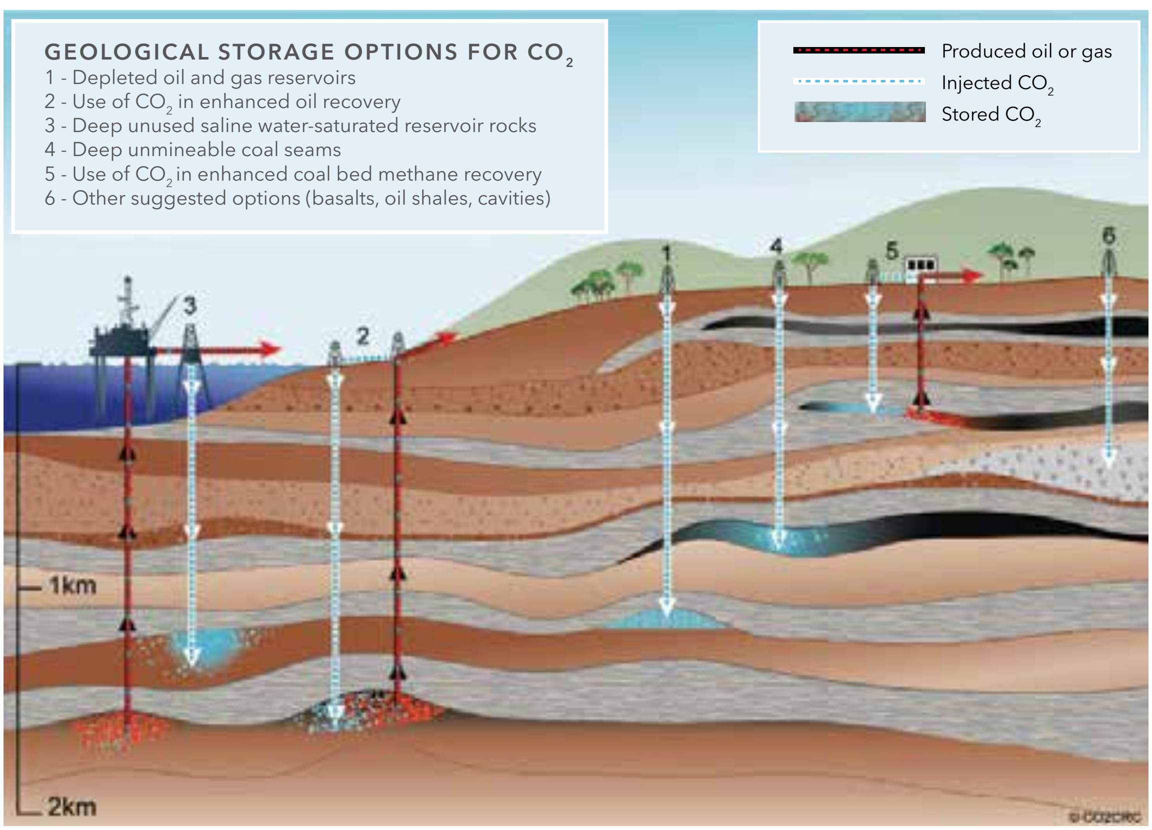
One should view such cost estimates skeptically. If it were possible to accurately assess the cost of future industrial technologies using academic studies or expert panels, financial investors would no-doubt use such studies to make investment decisions.

2 We comment on DAC here because one of us, David Keith, is a long-time researcher of this technology, and the founder of Carbon Engineering, one of the leading DAC firms.

Costs can only be known with confidence once technologies are widely deployed in commercial markets, but that deployment requires huge up-front investments. Government decisions about investment allocation should be informed by cost estimates derived from experts with relevant industrial expertise and commissioned from independent consultancies during the development phase as an intermediate step between academic papers and the commercial market.

Both DAC and the conventional emissions reduction option of the capture of carbon dioxide from fossil fuel-based electricity generation require deposition of the captured carbon dioxide, referred to as carbon capture and storage (CCS). There are a number of deposition pathways including utilization by enhanced oil recovery, chemical transformation, and geological storage in deep underground aquifers. Developing commercial scale (greater than one million metric tons per year of carbon dioxide for each facility) CCS has been a goal among scientists for years. The United Nations Intergovernmental Panel on Climate Change produced a report on CCS in 2005 with an informative graphic, Figure 2, which describes different methods for underground storage of carbon dioxide.

Figure 2: Methods for Storing Carbon Dioxide in Deep Underground Geological Formations



Source: CO2CRC Ltd and IPCC (2020)

It will generally cost more to capture carbon dioxide from the atmosphere than to capture it from point sources such as power plants or cement kilns that have higher carbon dioxide concentrations. But the cost of CCS from power plants has been significantly greater than other emissions reduction options in the electricity sector. CCS will likely become more relevant as attention turns from early penetration of low-cost renewables to harder-to-decarbonize, industrial sectors. The development of CCS and of CDR technologies will be intertwined—sound policy requires integrated treatment of the two technologies. Both large-scale CCS and CDR facilities will raise significant legal, regulatory, and public concerns.

1.c. Adaptation

Adaptation refers to human-launched programs taking action to protect communities, commerce, and the environment from anticipated damage and adverse impacts from climate change. In contrast to CDR, adaptation does not rely exclusively on the development and deployment of technology, but rather on undertaking projects or procedures to reduce environmental damage and associated costs if a destructive event occurs. Chapter 17 of the Working Group II's contributions to the UNFCCC Fifth Assessment report, which addresses *the economics of adaptation*, offers these examples of adaptation:

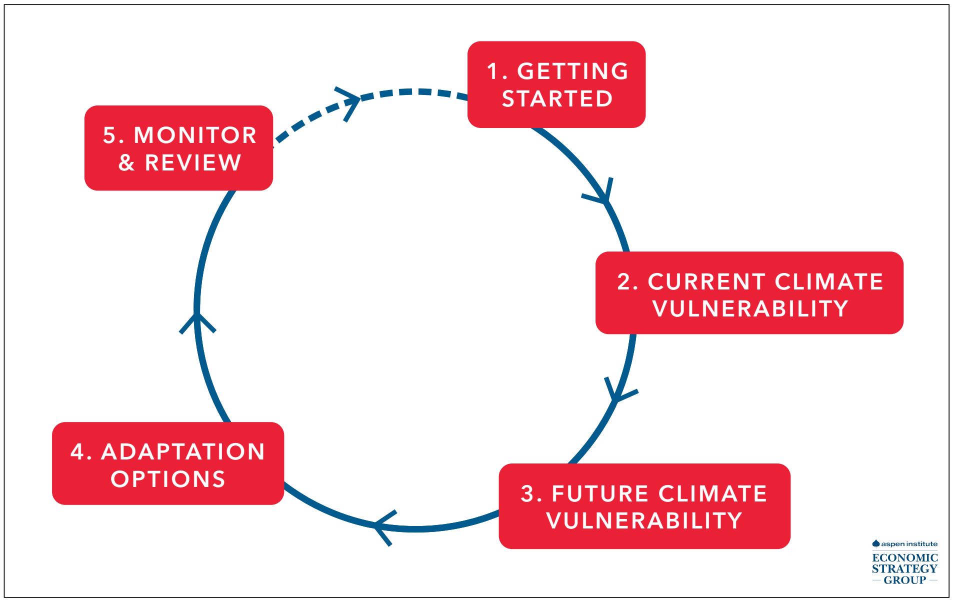
- Altered patterns of enterprise management, facility investment, enterprise choice, or resource use (mainly private)
- Direct capital investments in public infrastructure (e.g., dams and water management—mainly public)
- Technology development through research (e.g., development of crop varieties—private and public)
- Creation and dissemination of adaptation information (through extension or other communication vehicles—mainly public)
- Human capital enhancement (e.g., investment in education—private and public)
- Redesign or development of adaptation institutions (e.g., altered forms of insurance—private and public)
- Changes in norms and regulations to facilitate autonomous actions (e.g., altered building codes, technical standards, regulation of grids/networks/utilities, environmental regulations—mainly public)
- Changes in individual behavior (private, with possible public incentives)
- Emergency response procedures and crisis management (mainly public)

Adaptation does not slow climate change; rather, it acts as an insurance policy that reduces the costs of damage from the impacts of a global temperature increase should it occur. The diversity of adaptation actions presents a challenge to its analysis as a control mechanism and to setting a common scale for comparing the costs and benefits of different proposed adaptation efforts.

Adaptation has co-benefits that give it an advantage over other climate control measures. For example, revising building construction codes to make buildings more resilient to extreme weather events also improves infrastructure by conveying a longer useful life. But adaptation also has a disadvantage compared to emissions reduction. For emissions reduction, the incremental damage attributed by one additional kilogram of carbon dioxide is usually easily attributed to the emitter. This makes it possible to adopt policies that link emissions costs to emitters. Meanwhile, adaptation projects are usually regional (e.g., ambitious New York and Miami resiliency projects to protect their waterfront from anticipated flooding as sea level rise). Such projects are quite costly and it is not evident how these costs should be allocated across all city taxpayers.

The literature on adaptation as a climate control mechanism is vast. Because of the complexity mentioned above, the literature stresses general features: the significance of adaptation, tools required for planning, and the importance of gaining community approval for projects. Chapter 28 of the 2018 Fourth U.S. National Climate Assessment is devoted to describing federal efforts to reduce risks through adaptation actions. The European Commission's approach to adaptation, carried out by the European Environment Agency, is to "share adaptation information across Europe." The agency issues guidelines, methods, and tools for this purpose. However, the narrative is general; there are no quantitative measures that are proposed to evaluate benefits and costs of alternative adaption projects. The UKCIP "adaptation wizard" tool follows five steps summarized on the wheel in Figure 3.

Figure 3: UKCIP Adaptation Wizard Wheel that Describes Five Steps of Adaptation.



Source: European Environment Agency (2020)

A climate policy optimized among four climate control mechanisms requires the ability to investigate the trade-off between adaptation and emissions reduction. Because of the general character of adaptation and precise nature of emissions reduction project analysis, measuring the trade-off(s) between these two important climate control mechanisms is rarely attempted.

A notable exception is the work of de Bruin, Dellink, and Tol (2009), who attempt to modify the emission-centric Dynamical Integrated Model of Climate and the Environment (DICE) model to allow adaptation and emissions to be substitutes, competing for available resources but without explicit consideration of the different time lags for deployment. The AD-DICE study shows that Nordhaus' implicit assumption of optimal adaptation can be replaced with an explicit assumption of optimal adaptation, and that the latter model can be calibrated so that the results do not change. Adaptation is difficult to include systematically in global models of optimal trade-offs because adaptation is intensely local and it is hard to separate money spent on adaptation from general spending on infrastructure that is subject to some environmental risks.

The availability of reliable data is extremely important to climate policy and science. However, empirical data that is sufficiently reliable to support behavioral and system relationships is frequently lacking. Variability in data quality is commonly ignored, although there is almost always a large gap between average and best (or worst) of class performance. The differences between global and regional projections are massive because many countries do not have adequate resources devoted to climate data collection and analysis.

The discussion of the AD-DICE model illustrates data challenges: results are based on a single year (1999); there is no indication of how the global result can be disaggregated to regions; and there is no discussion of how technology will influence economic performance parameters out to 2200. The study does include, as it should, sensitivity analysis to test its conclusion, but only for a few high-level variables: the discount rate; climate sensitivity, which sets the relationship between warming and atmospheric concentration; and adaptation protection costs. Econometric models do provide insights that should guide climate policy deliberations, but the quantitative results do not have sufficient fidelity to support program choices.

A final point concerns adaptation for the rich and poor. The United Nations Department of Economic and Social Affairs policy brief (2016) correctly states:

> Climate change has a differential impact on people and communities. The people at greatest risk are the poor, the vulnerable and the marginalized that, in most cases, have been excluded from socioeconomic progress.
>
> Far reaching, transformative policies are needed which simultaneously address immediate vulnerabilities as well as existing structural inequalities.

Adaptation is the climate mechanism that runs most directly into the vulnerability and adaptive capacity of rich and poor counties. In rich countries, much human adaptation can be expected to be put in place by private sector investment that is guided by a realistic view of future costs and benefits. Firms have access to capital for investment in projects with reasonable expectation of positive financial returns.

In poor countries, where there is inadequate access to capital and many competing demands for public investment such as health, education, and economic growth, adaptation projects are generally unaffordable and do not command high priority. The 2018 UNFCCC *Special Report on Global Warming to 1.5°C* is a comprehensive and eloquent statement of these issues. While the financing problem is acknowledged, there has been little progress toward agreement on the mechanism and pace of the transfer of funds.

1.d. Solar Radiation Modification (SRM)

SRM is the deliberate use of technical methods to alter the Earth's radiative balance. This could be achieved by adding aerosols to the atmosphere to increase the Earth's reflectivity so that the climate absorbs slightly less solar energy, which would partly offset the heat-trapping effect of greenhouse gases. SRM is a deliberate intervention into *Radiative Forcing (RF)*, defined as the net effect of human actions altering the Earth's energy balance. SRM can reduce global temperatures and other adverse climate changes, such as storm frequency and sea level rise, that are produced by accumulated greenhouse gases. The climate effect of SRM can be complimentary to actions that reduce the amount of greenhouse gases.

The technology is not new. SRM has been proposed to combat the risk of climate change at least since a report to President Lyndon Johnson in 1965, and was included in reports on climate change issued by the NAS in 1977, 1982, and 1992. Yet the political attention to climate change that grew after the 1992 United Nations Conference on Environment and Development in Rio de Janeiro, also known as the Earth Summit, placed exclusive attention on emissions reductions, and SRM largely disappeared from discussions of the science and politics of climate change. There were also concerns that SRM presented a "moral hazard," tempting policy makers to choose an apparently easy and cheap SRM solution over emissions reduction efforts. Interest in SRM has risen again over the last few years, in part because it may be needed to meet the goal of keeping global temperature increases below 2°C (or even 1.5°C), and in part because research suggests is might be less risky and more effective than had been commonly assumed.

Plausible methods of solar geoengineering include:

- Stratospheric Aerosols: adding aerosols to the stratosphere, where they reflect some (~1 percent) of incoming sunlight back to space (Irvine et al. 2016; NRC 2015; NAS 1992).
- Marine Cloud Brightening: adding cloud condensation nuclei (a specific class of aerosols) such as sea salt to specific kinds of low-lying clouds over the ocean, with the goal of increasing the reflectivity or lifetime of these clouds (Latham 1990).
- Cirrus Thinning: adding ice nuclei (another class of aerosols) to high-altitude cirrus clouds, with the goal of reducing the density of such clouds (Mitchell and Finnegan 2009).[3]
- Other methods include space-based reflectors, tropospheric aerosols, and increasing the reflectivity of crops or other land cover.

There are natural analogs that provide valuable data for assessing SRM effects. Volcanic eruptions (e.g., Pinatubo, Tambora, Krakatoa) released substantial amounts of stratospheric aerosols into the stratosphere, scattering light and producing a negative radiative forcing change (cooling), similar to that expected from adding aerosols to the atmosphere (Robock 2013).

3 Low clouds tend to cool the Earth's surface, so increasing them has a cooling effect, while high clouds tend to warm the surface, hence reducing them will also tend to cool the surface.

1.d.1. Climate response to solar geoengineering

The radiative forcing from solar radiation modification is not the same as the radiative forcing from greenhouse gases (GHGs), so while it's possible to restore the global average surface temperature, the resulting climate would be different from the climate without GHGs (Kravitz et al. 2013). The question is how different? Or, to what extent can some solar radiation modification reduce important climate changes at the regional level?

Climate model simulations show that if SRM is adjusted to offset roughly half the radiative forcing from GHGs, then the change in important climate variables would be spatially uniform, reduced in most locations, and increased in only a small percentage of the land surface.[4] Other SRM methods, such as marine cloud brightening, are expected generally to produce a more uneven climate response.

Around half of the long-run climate responses to a change in radiative forcing are realized within a decade, which means that rapidly scaling up or ending SRM deployment would produce sudden changes in climate.[5] The consequences of such sudden and large changes are not known, but could be highly damaging.

The uncertainty in climate predictions grows with total radiative forcing. Thus, it is plausible that the climate response to a scenario where SRM offsets some radiative forcing can be predicted with greater confidence than a scenario with an equivalent amount of GHGs alone. Reducing uncertainties in the climate response to radiative forcing from GHGs will also improve our understanding of the climate response to radiative forcing from SRM.

1.d.2. SRM uncertainties could be addressed by research

SRM uncertainties that can be narrowed by research and development can be roughly divided into two major domains: *making* radiative forcing and *predicting the climate* response to that radiative forcing. Some useful R&D can be conducted "indoors," but eventually experimental data confirming theory and simulation needs to be conducted "out of doors."

Making radiative forcing: Developing practical SRM methods that could achieve a substantial reduction in net radiative forcing would require collaboration between science and engineering: Scientists need to evaluate if a proposed intervention would result in a substantial reduction in radiative forcing (e.g., testing under what

4 Our quantitative analysis demonstrating this result is currently under review, but Keith and Irvine (2016) reviews the literature to present an argument why this is likely.

5 See Parker and Irvine (2018) for a discussion of the risks of a so-called "termination shock" arising from a sudden cessation of large-scale SG deployment.

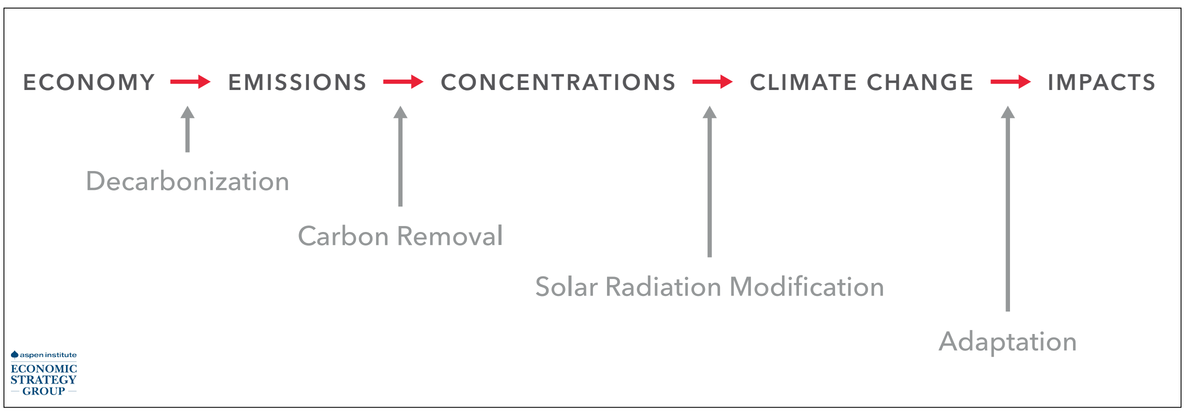
conditions sea-salt aerosols reaching the base of strato-cumulus clouds would result in an increase in cloud albedo), while engineers would need to develop and test the practical means of producing the intervention (e.g., developing and testing a device designed to produce sea-salt aerosols).

Predicting the climate's response to a specific deployment of SRM is a problem closely related to the problem of predicting response to other human influences on climate, most obviously GHG emissions, but also the climate impacts of aerosol pollution. Useful predictions require empirical confirmation from well-specified interventions. This is a challenge for climate science.[6]

2. Idealized Economics of Climate Choices

How might the four instruments be deployed to reduce climate risks? Figure 4 illustrates the causal chain from economic activity to monetized impacts along with the opportunities to disrupt this chain using the four climate control mechanisms.

Figure 4. The Causal Chain



Economic models of global climate choices are often called Integrated Assessment Models (IAMs). While their structure varies substantially, they generally include at least three elements: (1) an energy-economic model of the cost of reducing emissions; (2) a climate model predicting climate change from emissions trajectory; and (3) a model of climate damages. IAMs vary greatly in complexity. The most complex include sectoral and spatially detailed, energy-market models, along with regional models of climate and agriculture. The simplest use just a few equations treating

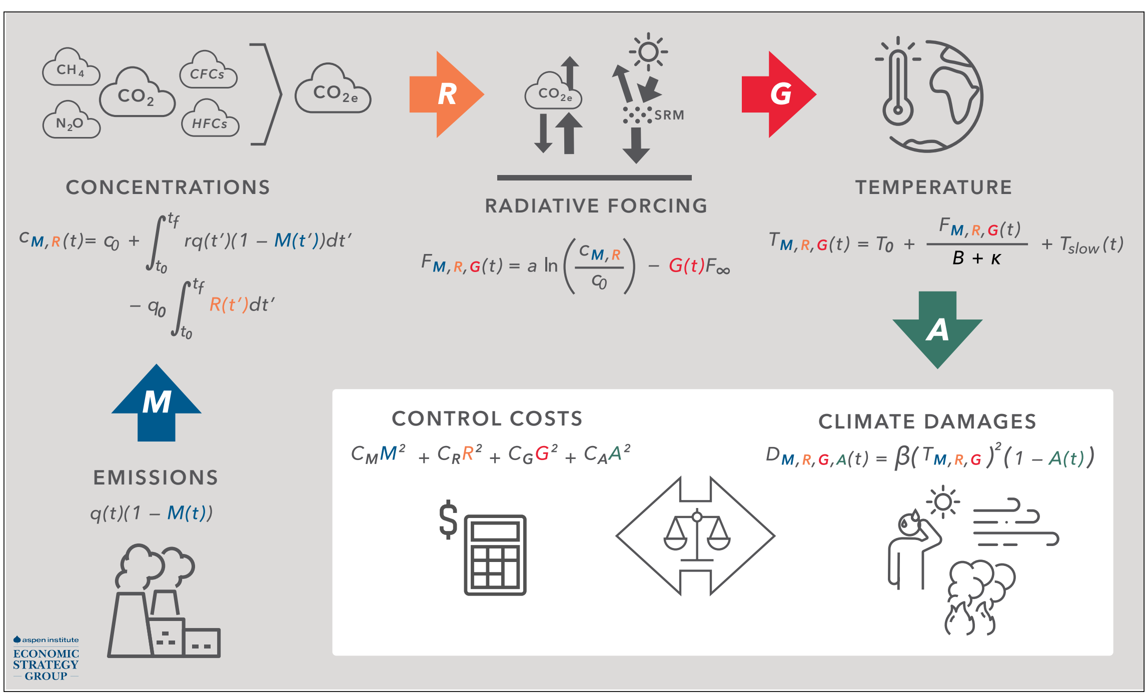
6 Note that David Keith has helped to develop the Stratospheric Controlled Perturbation Experiment (SCoPEx), which aims to reduce uncertainty around microphysics and atmospheric chemistry in stratospheric SRM using a balloon-born experiment that will generate a small aerosol plume .

the world as a single region and specifying a supply curve for emissions mitigation and a single, climate-damage function. The first IAM was the DICE model, developed by Nobel Laureate Bill Nordhaus at Yale University.

IAMs can be used to find an optimal way to allocate scarce resources to maximize welfare by trading off the cost of emissions cuts against monetized climate impacts. Because of the extremely long climate horizon, the enormous number of behavioral relationships, uncertain parameter values, regional variations, and the absence of verifying field data, it is not sensible to take numerical IAM results as a prescription for policy. Yet economic policy models are valuable for policymakers because they reveal linkages, identify structural trade-offs, and expose gaps that inform new research directions. IAMs are also used for regulatory purposes, such as in the United States for calculating the social cost of carbon (SCC)—the environmental damage to the economy from the incremental release of one kilogram of carbon dioxide into the environment.

Most early IAMs considered emissions reduction as the only control mechanism and considered adaptation only implicitly by folding it into estimates of climate damages. Many models now consider some form of CDR, and some have begun to examine SRM. We are both involved in separate efforts to develop simple IAMs that take this more comprehensive view and we report preliminary results here. Figure 5 provides the most important equations in the MARGO model, which illustrate key modeling assumptions in the causal chain of Figure 4.

Figure 5: Modeling Assumptions Underlying the Causal Chain

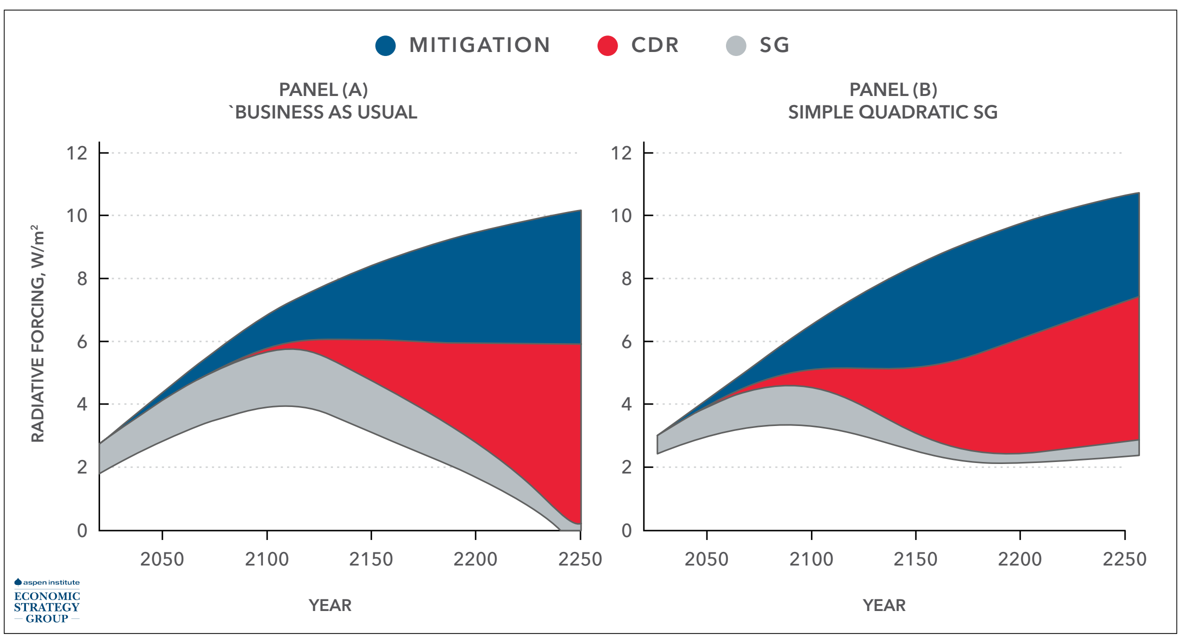


Source: Drake et al. (2020)

Given the deep uncertainties and the structural differences between our models it is surprising and interesting that they agree on the rough time sequence for deployment of emissions reduction, CDR and SRM (Figure 6). Both models find that an optimal policy deploys emission reduction early and uses carbon removal at large scale only after emissions have been substantially reduced while SRM is used for an intermediate period while carbon concentrations are high and is then phased out as concentrations are reduced by CDR.

When the models are tuned to the same simple specification of the damages from SRM they produce quantitatively similar results. Figure 6 shows simulation results from both models for radiative forcing, which is proportional to warming, over a two-hundred-year time horizon. Panel (a) shows results from Belaia, Moreno-Cruz, and Keith (n.d.) using model parameters with a simple quadratic high-end estimate of the damages from SRM chosen for simplicity in matching with MARGO. While in Panel (b) Drake et al. (2020) tuned the MARGO model— a flexible model that allows users to explore various assumptions and compare different cases and parameter values—to the assumptions and parameter values of Keith et al.'s DICE climate model. Perhaps the central lesson is that both models supplement emissions cuts with SRM and CDR to achieve an absolute reduction in temperatures and climate risks within a century—a result that cannot be achieved by emissions cuts alone.

Figure 6. Two Models of the Contributions to Reducing Radiative Forcing from Emissions Reduction "Mitigation," SRM, and CDR



Source: Panel (a) is from Belaia et al. (n.d.); panel (b) Drake et al. (2020)

It is interesting to compare the results for the value of SRM—that is, for the difference between the base model (with SRM) and a version of the same model where SRM is not allowed and only emissions reductions (M) and carbon dioxide removal (R) are included. These results are given in Table 2, which shows the present value (US$ trillions) of baseline damages, control costs, damages after control mechanisms are employed, and the net present benefits for the time period 2020 to 2220 with a 3 percent discount rate. The net present value benefit from including SRM is $39 trillion for MARGO and $58 trillion for modified DICE. The implication here is not the numerical comparison between the two models, but rather confirmation that SRM has significant economic benefit. The benefit is driven by the assumptions of increasing cost of mitigation with penetration and the decreasing cost of CDR with time. Delay in the development or deployment of CDR or SRM may lead to reduction in the social benefit of climate control.

Table 2: Comparison of Optimal Welfare Results for MARGO and Modified DICE.

3% DISCOUNTED PV FOR PERIOD 2020 TO 2220 IN US$ TRILLIONS				
	MARGO		MODIFIED DICE	
	MRG	MR	MRG	MR
Baseline damages	384	384	301	
Control costs	166	176	28	55
Controlled damages	22	51	125	156
Net PV benefits	196	157	148	90

Note: "M" indicates emissions mitigation, "R" indicates carbon dioxide removal, and "G" indicates geoengineering (or solar radiation mitigation). Thus, "MRG" indicates the model includes all three climate control mechanisms, while "MR" excludes SRM.

3. U.S. Policy

Progress controlling climate change requires a massive and rapid increase in the capacity for climate innovation. Innovation refers to the complex process of translating new technology and new business practices into practical application. To be successful, the innovation process must integrate technical, economic, environmental, and regulatory considerations. Increasing R&D spending in federal agencies may be necessary, but it is not sufficient to assure deployment of new climate innovation at scale.

- Successful climate innovation necessitates the mobilization and coordination of a wide range of federal, state, local, and private sector efforts. The traditional federal approach to managing innovation is neither flexible or fast enough especially at the later technology demonstration and first-of-a kind deployment. Changes in climate innovation management we recommend include: Adoption of a multi-year RD&D program plan with input from climate experts, private sector firms, government officials, and the public;
- A single agency with the responsibility and authority to implement the approved program;
- Multi-year climate budgets to finance this program overseen by a single joint congressional climate action committee;
- Adoption of a stable GHG emission charge that will stimulate private sector investment;
- And greater global climate data collection, modeling, and simulation.

We are pessimistic about the likelihood of such fundamental change in the policy landscape. The required changes in the energy economy cover all stages of the innovation process, from idea creation to deployment. This amounts to "industrial policy." We believe government-sponsored innovation initiatives are necessary for advancing climate policy and would benefit the broader U.S. economy. However, there is considerable, thoughtful skepticism toward such "industrial policy." Critics correctly note that the government record in advancing innovation is mixed; the government does not have the expertise that is necessary to make uncertain investment decisions, and the political system has little tolerance for the failures that inevitably occur with RD&D projects. Success is very unlikely unless the changes we recommend in federal innovation management are adopted.

The recent bipartisan *Endless Frontier Act* expands the National Science Foundation's responsibility to maintain U.S. global leadership in innovation, renames the agency the National Science and Technology Agency, and authorizes an additional $100 billion over the next five years. The legislation acknowledges U.S. innovation shortcomings that go well beyond climate change. But the legislation is largely focused on early stage R&D and not the later stages of new technology demonstration and deployment. It will rekindle the ancient debates about creation of an executive department for science and technology, so its passage is far from certain. Other countries are pressing ahead with innovation initiatives. China's strategy is the most comprehensive and impressive. Unsurprisingly, there is great bipartisan concern about the United States maintaining its technical and economic competitiveness.

We next turn to the specific policy issues that arise with management of CDR and SRM. Emissions reduction through clean energy technology and improved energy efficiency will deservedly continue to receive priority attention through established avenues. Expanding adaptation programs deserves high priority, but their structure and implementation depend on local circumstances. Our discussion of CDR- and SRM-innovation policy issues will further underscore the need for fundamental change to how the United States manages innovation.

3.a. Policy Challenges Facing Carbon Dioxide Removal

As discussed above, advancing CDR as a climate control option requires a well-defined development path. However, having a well-defined development path does not mean the project will successfully find funding to cross the “innovation valley of death” to demonstrate commercial viability, especially for technologies that require gigatonne scale to have a substantial impact.

CDR’s primary challenges are deployment cost and trusted accounting. Deployment cost is the central barrier for industrial technologies, such as DAC and bioenergy, both of which require carbon capture and sequestration. Trusted accounting is crucial for low-cost, impermanent carbon storage in agriculture or forestry. The private sector cannot be expected to invest in a CDR technology until it has a proven technical performance, an acceptable environmental impact, and a demonstrated market-competitive cost.

The fundamental challenge for policymakers is to design incentives for CDR demonstration that will establish the conditions for future commercial viability of the technology at a time when it is cheaper to avoid emitting a metric ton of carbon dioxide into the environment (or pay an emission charge, if one is in place). Climate models make a clear case that some combination of negative emission technologies or SRM will be needed to limit warming to policy targets such as 20C or 1.50C. Thus, there is a clear public interest in supporting CDR RD&D that will enable this climate control option. We do not believe this readiness can be achieved by exclusive reliance on carbon markets, if they exist, or on mandatory regulation. Some federal support will be required to demonstrate the technical performance of initial, commercial-scale plants.

A number of different federal government-assistance methods are available:

Direct government support for the construction of a first-of-a-kind, commercial-scale demonstration plant on a cost-plus basis: This approach has the disadvantage of requiring the use of Federal Acquisition Regulations that drive costs higher than costs which prevail in the private sector. The government often insists on cost sharing, so contractors have "some skin in the game," and grant intellectual property rights as an incentive to the contractor; a practice which will slow the spread of a successful innovation. This method is widely used by the Department of Defense (DOD) and NASA, but these agencies are single buyers.

Direct government involvement in the planning, structure, and management of a large-scale demonstration project: A pertinent example is CCS, discussed earlier, that supports two key CDR technologies: DAC and BECCS. Absent a carbon emission charge, the private sector cannot be expected to invest in CCS, especially since natural gas-generated electricity is even more economical than coal. On two different occasions, the Department of Energy (DOE) and Congress have chosen to support significant CCS demonstration projects, both of which were not successful (Kelly 2018; Tollefson 2015).

There are several, indirect incentive measures available to the government to provide assistance to CDR demonstration projects that have the advantage of permitting the project to be undertaken on a private-sector basis.

For example, the Renewable Fuel Standard program requirement that motor gasoline must contain 10 percent ethanol, or the Renewable Portfolio Standard program requirement for electric utility generators to dispatch a certain percent of renewables. The latter has been effective in the United States in the great expansion of solar and wind generation and the accompanying dramatic reduction in cost. California's Low Carbon Fuel Standard is a strong incentive for DAC.

Tax credits are an important federal support measure. The 45Q tax credit, as amended in 2019, provides a tax credit of between $35 and $50 per metric ton for the storage or utilization of carbon dioxide. It has a similar intent as federal production tax credits for wind development (KPMG 2020).

Loan guarantees. The government extends guarantees for the debt portion required for project financing. Congress likes this mechanism because it gives the illusion of not requiring a budget outlay. In fact, loan guarantees are scored as a budget outlay. In all administrations, the Department of the Treasury does what it can to block this mechanism and places onerous conditions on DOE loan guarantees for commercial manufacturing and renewable energy (U.S. DOE 2010). Rural cooperatives that are important in energy and farming in many parts of the country are not private firms, and thus receive no benefits from federal loan guarantee programs. More fundamentally, loan guarantee programs protect failure rather than rewarding success.

Production payments. The conceptual basis for this incentive is that the production payment is compensating for a market imperfection—the gap between the private and public costs of carbon emissions. Public payments are intended to be temporary, until such time that the CDR technology learning drives down costs to the point that the technology becomes market competitive, or until a charge is levied on private producers to internalize the external social costs of emissions, thus repairing the market imperfection.

There are a number of production payments that have been tried in different countries for different purposes. Feed-in tariffs were popular to encourage the installation of solar photovoltaics. The United States has extended a 3¢-per-kilowatt-hour production payment for wind generation. Fancier mechanisms, such as reverse auctions for fixed quantities, have also been proposed.

We believe properly designed production payments are the most efficient assistance method, especially for technologies that operate at large scale that the government wants to develop and demonstrate.

3.b. Policy Challenges Facing Solar Radiation Modification

The political issues bearing on SRM are entirely different and more complicated than the issues bearing on CDR. The key issue with CDR technologies is cost. Meanwhile, the direct costs of the SRM methods that are most likely to be implemented appear to be quite small, with the global annualized costs perhaps under $20 billion per year well into the latter half of the century. By comparison, the damage-reduction benefits could be 100 times this amount. It seems reasonable that the favorable cost-benefit potential of SRM justifies a vigorous public R&D effort and careful consideration of the potential role of SRM in future climate policy. However, this proposition is by no means universally agreed. Many believe the uncertainties and dangers of SRM are so great that the option should be ruled out entirely. We outline key political issues facing SRM that need to be resolved in order to move forward.

First, SRM has global reach, and there is no credible mechanism to preclude one nation from premature deployment because of a perceived or real regional impact that might affect their interests. There is a vigorous debate about the nature of the international governance structure that might be desirable to monitor and deter a potential rogue actor.[7] However, there is no way that a SRM deployment would meet the varying interest of all parties equally, because they live in different regions of the world (Ricke et al. 2013).

Second, the unknown global and regional impacts of an extended SRM deployment and the consequences of stopping a long-term deployment are also central issues.

7 Todd Stern, who served as U.S. chief climate negotiator from 2009 to 2016, has written an eloquent article laying out "How to Shift Public Attitudes and Win the Global Climate Battle," in YaleEnvironment360.

Third, many opponents fear the low cost of SRM will reduce efforts on emissions reduction, and possibly prompt a premature deployment by a rogue nation (Parker 2014). There is opposition to any SRM R&D, either indoor or outdoor, because it might confirm low SRM cost.[8]

Finally, there will be some winners and some losers from even the best-managed SRM system. Implicitly, many countries will assume that SRM is being used by rich countries such as the United States to avoid the expense of relying on emissions reduction and increasing climate risk for poorer countries.

We believe immediate implementation of SRM would be premature and will perhaps never be advisable. However, because of its enormous potential benefit, it is in the United States' interest to undertake an aggressive R&D program to acquire a knowledge base for SRM. Such research is obviously relevant in the event SRM is deployed. Because of the global character of SRM, the U.S. effort should cooperate with the SRM efforts of other countries, but not await or expect agreement on a global governance framework. While global governance of deployment is vital, we see no case for global governance of research and development, with the sole exception being experiments that pose significant trans-boundary risks.

We further believe SRM should not be implemented by firms competing in a commercial market. Rather, governments should directly procure and manage SRM deployment activities, much as the DOD and DOE do for national security programs today.

Availability of SRM does not change the reality that net global emissions (including CDR) must eventually be brought to zero. The results of the global climate model summarized earlier suggest that SRM has an important intermediate role in an optimal, low-cost mix with the other three climate control mechanisms—emissions reduction, adaptation, and CDR—in keeping the global temperature increase below 2°C. If SRM is a cost-effective climate control measure that the world may need, it is important to have as much information as possible about its benefits and risks before climate circumstance might make it the only available measure to meet an unforeseen climate emergency.

3.c. Technology Management

Technology management needs to be tailored to the needs of CDR and SRM if there is to be progress on innovation of these two necessary climate control measures. A management and governance structure must be in place at every stage of the

8 Techno-economic assessments suggest that stratospheric aerosols could be delivered with aircraft at a cost of less than $10 billion per year for 2 Wm-2 (McLellan, Keith, and Apt 2012).

innovation process, from R&D today to possible deployment in the future. At each stage, there needs to be specification of technical objectives, schedules, anticipated cost, and regulatory constraints as well as periodic, independent evaluation of progress.

At the early stage of innovation (low technology readiness) the current process for managing R&D support by the existing federal agencies—notably the DOE, DOD, NSF, and NOAA—is adequate, but certainly could be improved by introducing greater cooperation among private firms and university, government, and independent laboratories. At the later innovation stages, which involve greater investment, we recommend a new, quasi-public agency of the type described above.

We are far from agreement on a governance and management structure with the decision authority needed to implement any specific objective with regard to technical management, hardware development and testing, and operations and performance evaluation. While the pace of development (if it occurs) will be quite different for the two climate control measures, modeling and simulations based on climate data is needed feedback for the system.

Technology development of SRM has particularly important requirements.

- • Research on SRM needs to be tightly integrated with atmospheric science and earth observation. This suggests that NOAA or NASA should be the host agency for SRM.
- • SRM R&D should be mission-oriented. It must go beyond acquiring background knowledge about means and consequences of human intervention, to design and testing of components and systems, with the prospect of eventual integration into an operational system.
- • The SRM program must be managed in a transparent manner because of its international character. Debate about the governance structure will and should continue. We believe a U.S.-led SRM program should respect future governance arrangements, but not await their creation.

3.d. Costs: Who Pays?

We are neither sufficiently brave nor foolish to open a discussion about anticipated total public and private costs of a transition to an essentially carbon-free economy. We offer three brief comments. First, it will be a lot. The U.S. costs could plausibly exceed the annual investment in the energy sector (net of depreciation). One policy objective is to minimize the sum of damages plus the cost of the four climate control mechanisms. Another goal could be to minimize the these same costs subject to maintaining the global average temperature increase under 2°C or 1.5°C over a given time horizon. There is no agreement on a credible plan to transfer and manage the enormous amount of capital required by many of the less wealthy nations of the world.

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