A HOOVER INSTITUTION ESSAY

# Cutting the Fat Tail of Climate Risk

## CARBON BACKSTOP TECHNOLOGIES AS A CLIMATE INSURANCE POLICY

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### Introduction

Has the development of new and promising but currently expensive and thus largely unused clean technology options already created a credible insurance policy that reduces the likelihood of severe climate change?

Answering this question first requires acknowledging a growing conceptual gap in climate change science and economics: how much climate change will cost and what we are willing to pay to avoid it.

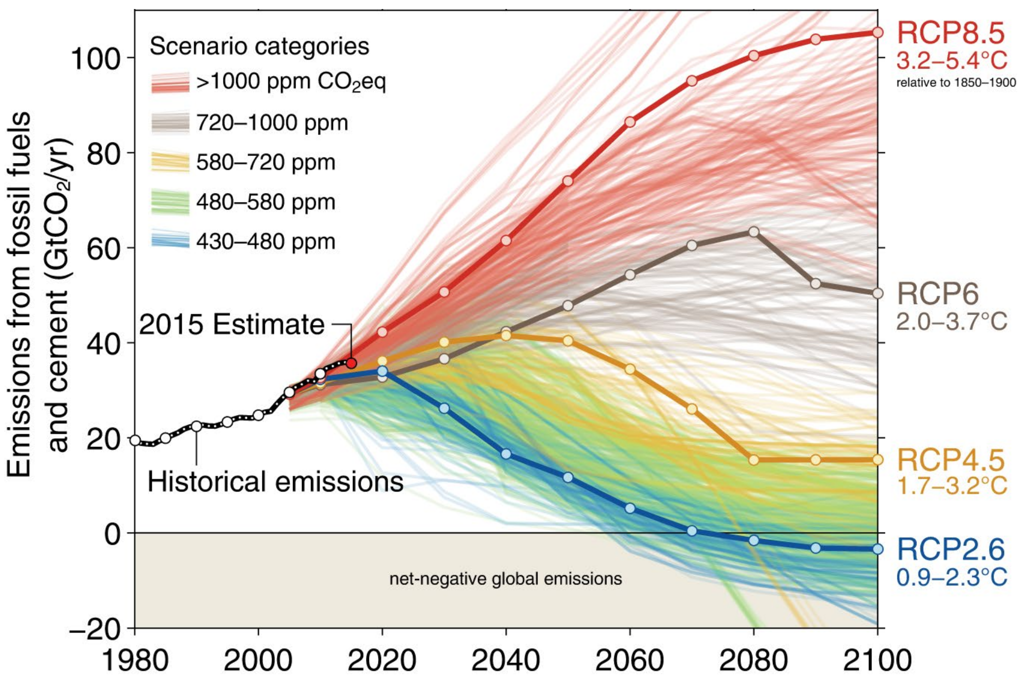


**Figure 1: IPCC energy and industrial greenhouse gas "representative concentration pathways" and potential warming scenarios.**

Credit: Global Carbon Project. 2015. "Global Carbon Budget 2015." Summary presentation created December 7, 2015.
https://www.globalcarbonproject.org/carbonbudget/archive/2015/GCPbudget2015_v1.02.pdf
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To stylize, in one camp are those who expect moderate climate costs and also endorse economically efficient policy solutions. These moderates see climate change as an important but basically gradual process with expected benefits and damages, though mostly damages. Human carbon dioxide emissions are therefore seen as having nonmarket external damages that will be reflected in climate-linked human economic systems, like agricultural productivity or coastal infrastructure inundation or building heating and cooling, or even contingently valued environmental goods and services like biodiversity.

The cost of climate damages to these and other economic systems are considered in so-called economic-environmental integrated assessment models—economist William Nordhaus's DICE models, for example, or Richard Tol's FUND—and from that an expected marginal social cost of carbon can be assigned to each marginal ton of carbon dioxide emissions. Various approaches to estimating this social cost of carbon dioxide have yielded estimates of approximately \$30–\$70 per ton (e.g., US federal government Interagency Working Group estimates, as described in EPA 2013). Economic theory would then argue that this external cost of emissions be passed on to emitters so that they weigh both the costs and benefits of the activity that results in emissions. As a corollary, society should undertake costs to reduce emissions up to, but not exceeding, that marginal damage estimate because the benefit of avoided climate change would net society more than the price tag to reduce emissions. Notably, this approach implicitly suggests an efficient amount of climate change; where the costs of emissions reduction given available technology options exceed the expected damages from warming, then it is better to allow some warming to occur rather than overspend on emissions reductions and leave oneself with fewer resources for other social investment priorities. Broad-based carbon pricing that reflects this conceptual model—for example, through a revenue-neutral carbon tax—is a first-best policy approach to avoiding climate change for this economically minded cohort. And many carbon taxes or cap-and-trade markets globally remain at price levels that might deliver this level of moderate or gradual decarbonization in their host economies (see Carl and Fedor 2016 for a global survey).

Another group, meanwhile, increasingly discusses climate change as a phenomenon with extreme or otherwise unacceptable human and environmental costs, and therefore something that should be stopped through any feasible means. For example, some earth scientists who study the ecosystem effects of a warming planet have argued for much of the last decade through the Intergovernmental Panel on Climate Change (IPCC) process that an average increase in global temperatures beyond two degrees Celsius from preindustrial levels represents an inflection point above which planetary and biological impacts substantially increase, many of them deleterious. They have thus proposed that societies do what it takes to reduce carbon dioxide emissions to avoid that outcome, which they believe to be unacceptable.

Notably, this target, which has since been adopted by many climate activists and in rhetoric by political leaders in the developed world, is not generally based on a cost-benefit analysis. Rather, it is an ethical or value-based stance (also one based in marketing that uses round numbers) that positions the benefits of avoiding climatic change as being large enough to pursue by any means necessary. As this target has gained social currency, various modeling exercises have been undertaken to estimate the costs of achieving it. Because this goal would require essentially complete decarbonization of the global energy economy by the year 2050, it is expensive, with marginal costs per metric ton of avoided carbon dioxide emissions reaching $500 to $1,000 (as estimated in Williams et al. 2014, Energy Modeling Forum 24 2014 Clark, Leon, Allen Fawcett, John Weyant, James McFarland, Vaibhav Chaturvedi, and Yuyu Zhou. "Technology and U.S. Emissions Reductions Goals: Results of the EMF 24 Modeling Exercise," or Borenstein, Bushnell, and Wolak 2017, for example). Those who aspire to a two-degree target and see the moderate current global progress on decarbonization to date despair that society is not tracking what would be needed to deliver that result. They therefore propose that society engage in wholesale economic and behavioral transformations to move faster toward their goals.[1]

We acknowledge our own bias toward the first group. While climate damages may be significant, we believe that states and countries must nonetheless continue to balance a wide variety of economic, security, and environmental goals, with climate change being an important and perhaps novel one among them.[2]

In this paper we propose one bridge across the conceptual gap between these two camps by arguing that recent technological innovations have begun to fill the solution space between the climate pragmatists and climate idealists with a variety of emissions circuit breakers we call carbon backstops.

What might a global carbon backstop technology reserve that offered a presumed insurance policy against severe climate change look like? Backstop technologies could be defined as those with the following characteristics:

a. They would offer very low or even negative carbon dioxide–equivalent emissions profiles.

b. They would be technically scalable on demand, and ideally with significant speed. That is, their potential drop-in deployment within an existing energy supply environment or demand use case would not be substantially limited by resource availability or grid operational capacity.

c. They would be compatible with existing political and social constraints or observed consumer behavioral tendencies.

d. They could be unilaterally adopted by any single political jurisdiction willing to pay their price of deployment.

e. And finally, they must have per-ton carbon reduction costs that are higher than some other low-carbon technology or management options in use today, but less than the social costs of extreme climate damages.

In short, carbon backstop technologies would be impactful, they would scalable, and they would be available for rapid deployment—but they would also be too expensive to justify broad deployment today. If, however, social consensus were to move in the direction of more rapid reductions in emissions, perhaps because of a change in either political priorities or observed environmental conditions, then these currently out-of-the-money options could be economically deployed, credibly avoiding runaway emissions pathways.

Even if such backstop technologies are never deployed at scale, pursuing research and their continued technological development today could be worthwhile. This is because they would already have significant social *option* value as an insurance policy—and therefore are worth paying modest sums to maintain today, as one might retain an option to buy a stock at a certain strike price—even if they do not exhibit substantial *market* value in today's economic and policy environments.

This perspective contrasts with a view currently held by some commentators that the emergence of low levelized cost of energy options—that is, winners—obviates the need for continued development of other promising but not yet mature low-carbon technologies—that is, losers (e.g., Romm 2009, Shah 2013, Lovins 2013). It furthermore supports a policy implication that the *research and development* of fat-tail backstop technologies should be supported through public funding, given their non-privately-appropriable social option value even today, but that public funding for *deployment* (i.e., exercising the option) should be considered only on a case-by-case basis unless market conditions or public norms regarding climate impacts appreciably shift.

Various promising technologies that might be considered carbon backstops are emerging today. In this paper we consider: (1) the clean-energy holy grail of dispatchable zero-carbon energy, here through small modular nuclear reactors, (2) negative emissions, on demand, as a means to cancel out an industrial society's "sticky emissions" through the direct air capture and sequestration or use of carbon dioxide, and (3) a collection of other emerging concepts that potentially increase civilization's overall ability to tweak the composition and behavior of the atmosphere, including carbon-negative fossil fuels through advanced enhanced oil recovery, soil carbon management, and solar geoengineering.

A number of techno-economic analyses have considered the feasibility of low carbon technology portfolios from a least-cost deployment or engineering integrated assessment modeling perspectives. In this paper, given our intent to relax the price constraint as described above, we instead focus on the underexamined soft constraints of political viability, regulatory landscape, and market structure attributes. That is, what sort of a deployment and scaling environment might such technologies face for a society that decides at a future point that it is willing to pay considerably more to make rapid progress on decarbonization? To conclude, we suggest strategies for improving the carbon option value of these technologies to improve credibility as an insurance policy to help cut off the fat-tail risk of severe climate change.

**Fat-Tail Climate Change Risks**

The Fourth US National Climate Change Assessment in 2017 described the risks associated with global greenhouse gas emissions thus:

> Continued growth in carbon dioxide emissions over this century and beyond would lead to an atmospheric concentration not experienced in tens to hundreds of millions of years. There is broad consensus that the further and the faster the Earth system is pushed towards warming, the greater the risk of unanticipated changes and impacts, some of which are potentially large and irreversible. (GCRP 2017, 11)

The precise correlations between carbon dioxide emissions and specific climatic changes or weather events may never be known to universal satisfaction. This is true even as we already begin to experience some of these changes in the global environment today. But a few things are known with confidence.

- First is a general sense among our scientific community that there exists some lower bound of expected climatic responses to elevated carbon dioxide concentrations—that is, minimum climate sensitivity (see, for example, Knutti and Hegerl 2008).
- Second is that this climate sensitivity could actually be much higher—that is, more climatic response than expected at a given level of emissions. While the chances of that are thought to be relatively low (Allen et al. 2008), the environmental impacts if it were true would be severe. One recent analysis put the chance of the climate being two standard deviations more responsive to carbon emissions than currently expected at 2 to 10 percent (Wagner and Weitzman 2015).
- Third is that, while it is hard to know the net balance of human and economic impacts that would result from any given small change in climate (see, for example, Tol 2018), the chance of those impacts being very costly on the whole goes up significantly when the amount of climate change is very high.

Combining these points—the potential for higher than expected climate sensitivity plus the potential for higher than expected economic damages from a given amount of climate change—results in what is termed a "fat-tail" risk distribution. This is when an unlikely scenario, but one that is extremely costly if true, becomes as important a planning metric as an intermediate risk might be. Examples of low-risk/high-impact fat-tail planning environments in modern society include reducing threats from nuclear war or global pandemics. At the individual level, a more prosaic fat-tail risk might be a household fire: a threat one could mitigate by installing smoke detectors and fireproof insulation, as well as by buying a compensatory insurance policy. For each of these circumstances, we do not really expect the worst outcome to occur but nonetheless undertake substantial efforts to mitigate that risk because the results of it happening would be terrible.

Given this, on climate change, too, some American thought leaders have now advocated adopting a similar insurance-policy approach to carbon dioxide emissions: assume moderate ongoing costs today to improve our chances of avoiding those fat-tail climate impacts that are less likely to occur but so costly were they to actually happen that they would be deemed politically unacceptable (e.g., Shultz 2015). Examples of such extreme abrupt or dangerous climate outcomes might include the widespread melting of subsurface or undersea methane hydrate formations, reversal of oceanic thermohaline circulation patterns, mass heat-stress mortality, or the rising of average sea levels beyond ten feet by the end of the century (see NRC 2002, Schellnhuber 2006, and NRC 2013 for a discussion of possible abrupt climate changes and the state of knowledge for each). An insurance policy that effectively took these extreme fat-tail outcomes off the table would helpfully bound the complex social and economic trade-offs inherent in any decarbonization effort and at the same time facilitate a more reasoned political dialogue on consensus near- to mid-term decarbonization pathways.

## 1. Small Modular Reactors

*Summary: Dispatchable small, modular, light-water nuclear reactors (SMRs) have the technical potential to significantly decarbonize a variety of global electricity and heat markets, facing neither fuel nor grid penetration constraints with known technologies. Electricity and heat production currently accounts for 42 percent of carbon dioxide emissions from fuel combustion, a share that could easily increase with the emerging electrification of the light vehicle fleet and potential future applications in aviation and shipping. The SMR emissions impact would be most cost effective in emerging countries where the existing grid is reliant on fossil fuels, particularly coal, and electricity demand is growing quickly. Social acceptance for nuclear power is mixed but likely to be higher for SMRs than existing nuclear, especially new SMR designs that could be considered "walk away safe"—without any action required by the operator to safely shut the reactor down. Costs for early SMR deployments are expected to be higher than for other new higher emission generation technologies, but these plants are financeable by a broader pool of investors than conventional nuclear power plants due to their smaller absolute size, and costs have the potential to come down with scaled manufacturing.*

### *Emissions*

Small modular reactors (SMRs) are an extension of conventional nuclear power generators and share those plants' near-zero carbon emission profiles. One metastudy from the US National Renewable Energy Laboratory, for example, puts lifecycle carbon emissions from nuclear power (including fuel cycle, construction, and other operations) at just 2 percent that of an equivalent coal-fired power plant (NREL 2013). SMRs furthermore emit no local criterion air pollutants, and their heat-shedding needs, which can disrupt certain aquatic ecosystems, would likely not surpass those of a conventional thermal plant. Spent fuel and other radioactive waste output would also be commensurate to existing light-water fission reactors per unit of power output.

### *Technical Scalability*

Though the category in fact includes a variety of proposed designs and underlying nuclear technologies, the term *SMR* generally refers to a class of integral light-water fission reactors with electricity-equivalent outputs of approximately 10 to 300 megawatts. The reactors are therefore extensions of existing and largely mature pressurized or boiling water reactors but ten to twenty times smaller in output as well as physical size.

To avoid additional fuel-cycle complexity, many designs, including the leading proposal from NuScale, specify the use of conventional low-enriched uranium fuel in standard configurations. SMRs' design characteristics are specifically intended to make them suitable in more diverse global electricity markets:

- For example, smaller output means that such plants could potentially be more technically suitable for deployment than their larger conventional forebears on electric grids that are remote—for example, in developing countries or rural areas—or in microgrid environments such as military bases or other critical facilities where islanding to mitigate physical or cyber attack may be desirable.

- A smaller output also makes SMRs suitable on grids that are experiencing slow growth in electricity demand—such as in the United States, which is expected to see annual demand growth of just 0.7 percent over the next two decades (EIA 2016). In such cases, a single plant site could potentially add additional reactors to a shared balance of system as demand grew.

- In electric grids that experience daily or seasonal variability in generation—for example, from wind, water, or solar generators—an SMR-based generation plant could also selectively curtail generation across clustered rectors to meet grid-balancing needs. Plant-level dispatchability is increasingly becoming a prerequisite of new power-generation infrastructure investment in developed markets, and SMRs offer one of the few ways to achieve dispatchable zero-carbon and zero-criteria air pollution electricity.

- From a financial perspective, a smaller physical size furthermore reduces the size of the construction project, which reduces absolute up-front capital requirements and, potentially, time to completion. This opens up SMR projects to a broader set of equity or debt financial backers.

- Finally, a smaller size means that more of the project inputs can be supplied modularly—that is, as standardized interconnecting components. To the degree that modular components can be manufactured in a controlled, centralized facility and transported to the project site in near-complete form, construction workforce training requirements and project completion risk are potentially reduced. Lack of recent experience among contractors and the associated nuclear-rated human capital requirements for large nuclear projects have been identified as a limiting factor in the ability to deploy conventional large-scale nuclear plants even in advanced countries such as the United States (Myers 2017a).

As to remaining technical and engineering risks, while SMRs' use of integral reactor pressure vessels that combine some balance-of-system components within the radiation containment unit itself is not technically novel (it has been used in more than one hundred US Navy fission reactors), such a design has not been deployed in modern US commercial power generators. This represents a risk to rapid technical scalability in the current absence of demonstration units.

Approximately thirty SMR designs of various chemistries have been proposed globally across twelve countries (Ingersoll 2016), and more exotic SMR designs or use cases would have less technical precedent and more risk than integral light-water SMRs. Designs from Korea (SMART) and India (AHWR-300), for example, envision a standard light-water nuclear chemistry, but instead of directing all thermal energy into steam generation to feed an electricity-producing turbine, they instead use a portion of the reactor's heat output directly as district or industrial process heat for chemicals, metallurgy, or desalination (McMillan et al. 2016).[3] Other proposed designs rely on advanced nuclear chemistries that have been employed in test reactors but lack an extensive track record in civilian power applications—for example, small liquid salt-cooled reactors such as developed by Canadian firm Terrestrial Energy's 192MW integrated molten salt reactor.

Long-term nuclear fuel availability is unlikely to be a significant limit to SMR scalability. Fifty-one countries are thought to have significant identified, recoverable domestic uranium resources at a cost of extraction in the range of historical prices (NEA and IAEA 2016), while the passive harvesting of uranium dissolved in seawater—now believed to be a near-economic alternative to mining uranium ore (Liu et al. 2017)—would potentially be available to any country in international waters, if not near shore, and represents a near-unlimited uranium resource base.

A functional nuclear fuel cycle does, however, require more than access to uranium ore—including, typically, capacity for the conversion of refined yellowcake into gaseous uranium hexafluoride, enrichment capabilities to increase the concentration of uranium to usable levels, fuel fabrication, and spent fuel and waste handling facilities.[4] All such capabilities require specialized technologies and expertise that may be subject to export controls, a topic described below. As an alternative, new or expanding nuclear states may simply choose to import uranium yellowcake, enriched uranium, or finished nuclear fuel from established suppliers. Ninety-five percent of global uranium supply today comes from just fifteen countries, and the majority of global nuclear fuel supplies today are already traded internationally.[5] Only two nuclear countries today choose to meet all domestic nuclear power plant needs through domestically supplied uranium (NEA and IAEA 2016).

### *Political and Social Acceptability*

New nuclear power reactor designs typically require certification by regulatory authorities of the host country, and individual plants using approved reactor designs must themselves be licensed before beginning construction (and later commissioning). Design certification by the US Nuclear Regulatory Commission (US NRC) is considered a global gold standard and is sometimes pursued by international nuclear vendors in addition to their host country regulator's approval for purposes of customer and social assurance. But this process can take years and hundreds of millions of dollars in applicant costs, making it a potential roadblock to deployment of a desired new nuclear technology (Madia, Vine, and Matzie 2015).

To this end, at least six SMR designs are currently undergoing or have completed preliminary design certification globally, including in Korea, China, Russia, and Argentina (IAEA 2014). In the United States, the US NRC in 2015 declared its institutional readiness to review integral light-water reactor SMR designs (Ostendorff and Cubbage 2015).[6] The commission has engaged in preapplication discussions with three SMR vendors and accepted its first formal SMR design certification application from NuScale Power Inc. in March 2017. That process is expected to take forty months. Following successful design certification, one municipal utility in the western United States now expects that the first-of-a-kind NuScale SMR plant could obtain a combined construction and operation license for construction beginning in 2022.

Some degree of public support, or at least a lack of organized resistance, would be necessary for a broad SMR build out. Today, public support for conventional nuclear power plants is mixed, particularly in developed countries. In the United States just 36 percent of polled respondents favor tax breaks for new conventional nuclear power plants, for example (Resources for the Future, New York Times, and Stanford University 2015). In Germany, a rise in antinuclear public sentiment following the 2011 meltdown at Japan's Fukushima Daiichi nuclear plant reinvigorated latent public fears of the technology spanning back to the country's front-row seat on the Soviet Chernobyl incident. This supported the majority political coalition's efforts to prematurely shut down many of that country's existing nuclear power fleet. And in Japan itself, reactors are gradually restarting with the support of the current government, but at a conservative pace—just nine of forty-two were operating as of February 2019.

Meanwhile, French leaders have recently had to step back from their own nascent plan to rapidly replace their nuclear fleet with renewables, given the costs and potential carbon dioxide emission implications of doing so. South Korea has bid aggressively to develop nuclear plants in new global markets over the past decade, and in the United Kingdom generous subsidies have been offered to finance the development of new conventional light-water reactors in part to replace shuttering coal plants in that country.

In parts of the developing world, new nuclear power development is proceeding rapidly alongside growing electricity demand and concerns over both energy import security and pollution from fossil fuels. As of early 2018, China had twenty conventional reactors under construction, Russia had seven, India had six, and Pakistan two. The United Arab Emirates, Bangladesh, and Belarus are constructing nuclear reactors for the first time. At the same time, some other interested countries, such as Indonesia and Vietnam, have not yet begun construction of initial plants despite years of ongoing interest in the technology—a situation attributed by some to inadequate public support or political will (Cogswell et al. 2017).

For the purposes of identifying carbon backstop technologies, it is important to ask (a) if attitudes toward new nuclear designs with better safeguards, such as SMRs, would be significantly more positive than those toward conventional plants described above, and (b) if public and government support for nuclear power would increase alongside significantly increased attention to negative impacts of climate change.

Perceptions of safety have been observed to influence public support for nuclear power (MIT 2003). To that end, improved walk-away passive safety has been a central design goal in SMR development, for example relying on in-cell convection rather than auxiliary-powered pumps to ensure fail-safe reactor cooling, reducing the number of interfaces across the containment vessel and the source-term of the reactor by having smaller fuel assemblies or even undergrounding (Madia, Vine, and Matzie 2015). The US NRC recognized one element of this recently when it declined to require that NuScale Power's SMR design maintain high-reliability off-site auxiliary power in case of a station blackout (US NRC 2018). There will always be an activist constituency that opposes nuclear power on safety grounds, but these substantial design-based safety improvements offer a step change in how those who may wish to build out a large number of such facilities could credibly describe radiological risks to a general public whose minds may otherwise rightly go to the Fukushima or Chernobyl incidents. Notably, it is the general public or in-region but nonlocal residents who would be the key constituency on such matters—locals who live in the immediate vicinity or host towns of today's US nuclear plants already tend to have higher levels of education on nuclear risks and support for nuclear power.[7]

Regarding emissions, US attitudes toward nuclear power today, for example, would not appear to be determined by its zero-emission attributes. Only 25 percent of Americans polled in 2014 correctly stated that nuclear power plants do not emit greenhouse gases, versus 67 percent who thought nuclear to emit either "a little" (44 percent) or "a lot" (23 percent) (Bisconti Research 2014). Similarly, poor educational levels have been observed in Europe (EC 2010). A supermajority of Americans also failed to correctly identify nuclear as the country's largest low-carbon power source from a list of choices (Bisconti

Research 2015). This suggests that additional public education on power generation technologies might change attitudes, particularly since attitudes toward nuclear power are not particularly partisan: just 17 percentage points currently separate liberal Democrats from conservative Republicans in their support for nuclear power, compared to a spread of 52 percentage points for natural gas fracking, for example (Funk and Kennedy 2016). Polls in developed countries have shown that concern over global warming is a good predictor of one's openness to nuclear power (Truelove and Greenberg 2013). And in a 2016 nuclear industry survey, 59 percent of public respondents who initially said they opposed nuclear power switched to saying that using the technology should be "very" or "somewhat" important in the future when informed that nuclear does not emit air pollution (Bisconti 2016).

### *Unilateral Adoption*

Could SMRs be deployed rapidly and at scale by a single jurisdiction that wished to do so, notwithstanding the approval of neighbors or other countries? The question is relevant given the history of international efforts to manage the diffusion of nuclear technologies and fuels so as to mitigate weapons development.

Nuclear power today represents only 10.5 percent of global power generation (and just 4.5 percent of total energy demand). On one hand, it could stand to grow substantially without considering the spread of nuclear technologies to new host countries. Thirty-one countries, which together account for nearly three-quarters of global electricity demand, already have operating nuclear power plants—including key developing countries with rapid growth in electricity demand, including China and India. And within these existing nuclear states, nuclear provides only 13.6 percent of total domestic electricity generation. This suggests that there is significant headroom for nuclear uptake to be expanded simply among existing nuclear states.

On the other hand, it's also important to consider the sorts of global acceptance issues that new nuclear power states might face were they to introduce the technology in, for example, high-growth countries in Latin America or Southeast Asia. Here Africa stands out. According to the most recent UN estimates, Africa's fifty-four-country population is now expected to more than double from about 1.2 billion today to 2.5 billion by 2050, and then again to 4.5 billion in 2100 (representing just 16 percent of the global population today but 26 percent by 2050 and 40 percent by 2100). Nigeria's population alone will exceed that of the United States by 2050, and Europe by 2100. Meanwhile, more than 600 million people in tropical Africa lack electricity, a number that has increased in absolute terms in recent decades as the rate of population growth outstrips the rate of new electrical connections. The average tropical African household consumes less electricity each year than a typical US refrigerator, and more than a million people on the continent die from indoor air pollution resulting from noncommercial household energy sources. Meanwhile, many parts of the continent struggle deeply with governance and the rule of law. Could the international community's nuclear controls abide significant use of nuclear power in tropical Africa, should countries elect to pursue it?

The history and landscape of such supply controls start with the 1970 Nuclear Nonproliferation Treaty (NPT), to which 190 countries are currently signatories and which regulates a country's access to both nuclear weapons and civilian nuclear energy technologies.[8] Of the latter, the treaty guarantees the right of nonnuclear-weapons states to "research, develop, and use nuclear energy for non-weapons purposes" and furthermore encourages international cooperation to this end so long as that pursuit does not result in the development of nuclear weapons technologies. The NPT therefore implicitly permits the unilateral development of uranium fuel (low-) enrichment capabilities that would be necessary for power plants—thirteen states currently have enrichment capability—or the possession of fuel and relevant technologies through international trade. Such trade, though, continues to be the focus of layers of export controls—multilateral, bilateral, and unilateral—on the part of more advanced nuclear energy countries.

Forty-two countries with commercial nuclear power export or foreign construction capabilities meanwhile participate in the Nuclear Suppliers Group (NSG), which imposes further trade limits meant to limit pathways from commercial nuclear power technologies to weapons proliferation. The International Atomic Energy Agency, associated with the United Nations, furthermore carries out international monitoring of nuclear fuel-cycle activities.

Bilateral supplier treaties have historically been more limiting. The United States, for example, requires the negotiation of bilateral "123 agreements" with potential foreign buyers—or resellers—of US nuclear power technologies to specify technologies and fuel cycle formats to be employed by the host country. When the United Arab Emirates wished to pursue civilian nuclear power in the middle of last decade, it agreed to a relatively restrictive US 123 agreement in which the country pledged not to engage in its own domestic uranium enrichment or spent fuel reprocessing, before ultimately purchasing four nuclear reactors of a Korean design (with US components). It is thought that the United Arab Emirates agreed to such terms to assuage US or other international observers' concerns about nuclear technologies being deployed in the Middle East. In other words, without the 123 agreement in place, the United Arab Emirates might have faced substantial international repercussions for pursuing nuclear power.

That norm, however, is changing. As nuclear power technologies spread around the world, with non-Western countries gaining more experience and expertise in power plant design and operation, nations will increasingly be able to pursue nuclear power technologies on time scales or in ways that traditional suppliers such as the United States or France may not support. For example, the United States for decades dissuaded potential nuclear suppliers in Europe from aiding Pakistan's nuclear power plant development, but that pressure has become functionally trivial given expanding Chinese-Pakistani nuclear cooperation.

China has financed and provided designs, engineering, and fuel for four Pakistani reactors and is involved in the construction of at least three additional reactors.[9] Similarly, Russian nuclear suppliers have enthusiastically pursued turnkey power plant development and operation in a number of countries without substantial nuclear experience, including Egypt, Turkey, and Hungary, and the country now holds a 60 percent share of the global export market: Russian suppliers have contracted to build thirty-four reactors in thirteen countries, and state-run Rosatom engages in nuclear fuel supply or other technical business in seven more (*Japan Times* 2017). Tellingly, when Saudi Arabia conducted 123-agreement negotiations with the Obama administration, it was unwilling to agree to UAE-style terms that limited the country's uranium enrichment interests in the face of credible nuclear supply alternatives from Russia and China.[10]

For historically nonnuclear states, a bigger challenge to rapid unilateral (yet responsible) action than acquisition of nuclear technologies or fuel may now be the development of robust domestic nuclear regulatory and safety frameworks. Early nuclear states have been able to ensure a certain threshold of safety by piggybacking on the complex and comprehensive reactor design certifications carried out by advanced civilian nuclear powers such as the United States. Development of satisfactory indigenous regulatory bodies and processes for plant construction and operations would, however, be a prerequisite to broad nuclear development. The speed at which this capability could be developed would be limited by the availability of trained graduates (potentially from foreign universities with established nuclear engineering programs) or the ability to hire and retain experienced foreign practitioners such as former regulators or nuclear utility executives.

### *Costs*

Deployment costs for new clean-energy technologies are notoriously hard to predict and can be variable across markets, even when relatively mature. Conventional large-format nuclear plants have been in use for decades, but overnight construction costs for new plants built in the 1990s and 2000s ranged from just under $2,000 per kilowatt of new capacity in France, Korea, and India to more than $4,000 in Japan (Lovering, Yip, and Nordhaus 2016).[11]

An SMR cannot be ordered today, so observed costs are unknown. Generally speaking, however, experts expect that SMRs would cost at least as much as new conventional nuclear power plants on a per-kilowatt levelized cost of energy basis for both first-of-a-kind and other early plants (see, for example, Anadón et al. 2012 or Abdulla, Azevedo, and Morgan 2013). Such expectations are attributed to both novelty and lack of "in the field" economies of scale versus larger plants, where fixed costs can be spread across higher power ratings.[12]

Three key dynamics are expected to further influence SMR economics. One is the potential for cost reduction due to learning if the scale of SMR manufacturing output were to rise. Outside of Korea, learning effects have been mixed in conventional nuclear power plant construction due to nonstandard designs and irregular order cadence (Zimmerman 1982; Lovering, Yip, and Nordhaus 2016). But given that major components of an SMR plant, including the reactor pressure vessel, could be manufactured in a centralized facility rather than built on site by ad hoc teams of contractors, the potential for internal learning by doing (i.e., appropriable within a single firm) improves. Internal learning has been observed to dominate external (i.e., non-appropriable, industry-wide) learning in other clean-energy technologies (Bollinger and Gillingham 2014). Furthermore, a higher number of production replications of smaller-size reactor units (i.e., a series of 50-megawatt reactors ganged together versus 1,000 megawatts for a conventional reactor) would in general be expected to improve overall learning effects, which are based primarily on cumulative firm production volume (Spence 1981). Such learning trends may set SMRs on a steeper cost-reduction curve, which could put overnight costs below those for historical conventional nuclear reactors—though the timing of that crossover point is uncertain (Abdulla, Azevedo, and Morgan 2013).

A second important cost dynamic is the extent to which the absolute (smaller) scale of an SMR project reduces project risk. Construction delays are common in conventional nuclear projects—as of 2014, an estimated two-thirds of new nuclear plants under construction globally had experienced some construction delay (including plants under construction in China), with projects taking an average of seven years to completion (Froggatt and Schneider 2015). Financing of conventional nuclear power projects is already difficult considering the very large amounts of capital needed and long lead times to first revenue.[13] This means that financing alone can be responsible for up to one-third of total plant construction costs. If SMRs are able to inherently reduce total project construction time (by virtue of the project simply being smaller) or reduce the risk of construction delays (through more standardization of plant components or less complexity), then this would be another factor affecting affordability of SMRs as a carbon backstop technology. It has been further observed, at least in the United States, where electric utilities tend to be smaller regional entities, that SMRs could offer a new option for access to nuclear power that simply has not been historically available to most potential buyers given their relatively small balance sheets (Myers 2017b).

A third consideration on SMR costs is the degree to which regulator-imposed safety requirements affect both capital and operating costs. Up-front costs, for example, could be affected by the size of emergency planning zones around a plant's periphery—US SMR applicants have recently requested two-mile rather than the standard ten-mile radius zones, which could ease the potential of locating SMRs in existing industrial sites such as refineries or decommissioned coal plants (Nuclear Energy Insider 2018). Ongoing operational costs, meanwhile, could be significantly affected by regulator determinations around multireactor plant control room staffing requirements or physical security needs.[14]

Further to this discussion of cost, it should be recognized that the value of any carbon backstop technology as an emergency response to severe climate change would specifically be in the marginal reduction of carbon dioxide emissions attributable to each unit of deployment. In that sense, we can consider the costs of SMRs in terms of comparable carbon savings and not just levelized energy production costs. This figure would vary even more than the overnight construction costs described above, as it adds in the external variable of grid displacement—that is, what alternative form of power generation on each regional grid and wholesale power market would be replaced or avoided through SMR investment.

Those regions in which power-generation carbon intensities are highest would see the most climate benefit from SMRs. China's coal-heavy Shandong province, for example, averages over one thousand kilograms of carbon dioxide emissions per megawatt hour of electricity production (Ma and Ge 2014). Hydro-rich Ontario meanwhile emits just forty kilograms of carbon dioxide to do the same (NEB 2017). In California, with a mix of nuclear, natural gas, and renewables, one megawatt-hour emits about 240 kilograms (CARB 2017a). Against this backdrop, investment in an SMR that falls near the upper end of historical nuclear construction and operating costs—$100 per megawatt-hour—might cost $100 per metric ton of carbon dioxide emissions avoided in Shandong, $417 per ton of emissions saved in California, and $2,500 per ton in Ontario. This illustrates how both the efficacy and value of SMRs as a carbon backstop technology would be centered on their deployment in those countries and regions with the highest emissions intensities, current and future.[15]

To contextualize these figures, it should be noted that in current US electricity markets, particularly deregulated states where generators must compete for buyers based upon competitive production bids, even existing nuclear power plants with largely depreciated capital costs have faced substantial economic and regulatory pressures resulting in their early closure (Carl and Fedor 2017). And similar pressures now exist in other developed nuclear power nations with low electricity demand growth, such as France. Two conventional nuclear plants have been slated for early closure in California, for example, where as described above, a conservative cost estimate of emissions abatement through nuclear power might be $417 per ton. A nuclear plant in coal-rich Wisconsin closed in 2013 despite a low, China-like avoided-emissions cost of nuclear there of about $125 per ton (emissions intensity as reported in Kaldunski 2014). Similarly, low costs of avoided emissions through nuclear would apply in other proposed closure areas in the US Midwest. This reveals that Americans' preferences for buying currently available carbon dioxide emissions reduction (at least through nuclear power) today remain surprisingly modest. And it suggests that despite political and media attention, American concerns over climate change damages may still have to rise substantially to significantly mobilize any carbon backstop technology in the electricity sector.

**Carbon Backstop R&D**

Continued public support and private incentives for long-term clean-energy research and development that could identify and advance the viability of a portfolio of carbon backstops underlies our "insurance-policy" approach.

A historical analogy would be the development of horizontal drilling in and hydraulic fracturing of shale source rocks, which was long thought to be a technically promising but unnecessarily expensive technology (Shultz and Armstrong 2014). The results of a series of small-scale government-sponsored research programs through the 1970s and 1980s, though, were picked up by interested entrepreneurs in the private sector and refined through another decade of iterative experimentation in the field, using side funding as available (Trembath et al. 2012). Eventually, these small bets paid off handsomely for both the private parties who improved them and for the public at large, when oil and gas market prices rose beyond expectations, making the once marginal fracking technologies commercially viable (Wang and Krupnick 2013). And as those techniques have been rapidly deployed at massive scale across the country, costs have come down, too, to levels that would have seemed unimaginable for the technologies' forebears decades earlier (Crooks 2018).

That successful model of backstop technology option generation can be contrasted, however, with a massive government-led deployment failure. The Synthetic Fuels Corporation, established through its eponymous 1980 congressional act, did not just seek to cultivate US technological capacity to produce liquid transportation fuels from coal and natural gas. Rather, it actually aimed to deploy the nascent technology at scale—two million barrels per day of production—using $88 billion in public funding in the form of loans, offtake price support, and joint equity ventures (Hershey 1983). That hasty expenditure was motivated by the 1970s oil crises, which left Americans feeling anxious at the prospect of energy import dependence and looking for quick solutions.

What lessons can the Synthetic Fuels Corporation experience give to a modern reconceptualization of carbon backstops as climate change insurance? After all, this was arguably an example of the United States trying, and largely failing, to exercise the technology option in another time and value space. One takeaway might be the importance of a credible strike price—that is, not to commit lots of spending in response to a short-term panic that may pass and leave one's strategy out of the money and with a lack of ongoing social support. When President Carter called for the corporation in 1979, converting the country's massive solid fuel resources to transport fuel was seen as the best bet for energy security in a future of global oil scarcity and the keystone of US energy strategy. But just a few years later, oil prices had collapsed as a result of a variety of other innovations and market efficiency improvements in both the supply and demand sides of transport fuels. Synfuels were in fact not the keystone they were made out to be. Technologically, the synfuel project might have eventually become a success story. But changing conditions on the ground meant that the public was no longer willing to foot the bill, and the corporation was shuttered in 1986 after earlier rounds of budget cuts (*New York Times* 1986).

Another lesson from the synfuel experience might be the importance of a portfolio approach—even for expected backstops. As it happened, synfuel deployment did not turn out to be an immediately successful way to reduce US oil prices despite decades of previous research. But simultaneous research efforts on shale source rock pore flow—likely unknown to those involved in the centerpiece Synfuel Corporation—eventually turned out to be the real energy game changer: fracking. The more credible backstop options that can be identified and cultivated at low cost today, the lower the risk (and cost) of striking out when we decide we need them. This is precisely the sort of small-bets portfolio approach currently pursued by the $300 million annual ARPA-E (Advanced Research Projects Agency–Energy) risky energy research effort, which has now given grants to more than five hundred third-party research projects. Yet even this promising program has in recent years been singled out for defunding in White House proposed budgets despite its bipartisan origins and continued support. More broadly, US cross-government federal funding of energy R&D stands at just $7 billion annually, which is less than current annual federal tax expenditures on wind and solar power deployment subsidies. Given the potential scale of future impacts, additional funding for R&D to help identify and improve potential carbon backstop capabilities and certainty is arguably the most cost-effective climate policy that could be pursued today.

## 2. Direct Air Capture of Carbon Dioxide

*Summary: The direct capture of carbon dioxide from ambient air is one of the few known technically and geographically scalable negative-emission technology options, though it is not widely practiced. While the capture technology is well known, its efficiency of operation should be improved by four or five times and powered by primary zero-emission electricity and heat sources to justify a broad deployment. Use of the captured carbon dioxide should also be better characterized to improve its credibility. In its best formation, the direct air capture and sequestration or use of carbon dioxide could be seen as a way to credibly dispatch negative emissions to offset other sticky emissions sources for which direct reductions would be cost prohibitive.*

*A variety of attributes of this technology make it attractive for unilateral adoption by different parties interested in offsetting new carbon dioxide emissions in this way or in further reducing existing atmospheric concentrations. Direct air capture does not produce energy or some other cobenefit in its operation, a unique characteristic that is both potentially limiting and compelling for some models of adoption. With current costs in the hundreds of dollars per ton, air capture of carbon dioxide can be viewed as a ceiling price against which other emission reduction policies and technologies should be benchmarked, but for broad uptake, society's demonstrated willingness to pay for emissions reduction would have to rise substantially above today's levels.*

### *Emissions*

The direct capture of carbon dioxide from ambient concentrations in the air (direct air capture, or DAC) is one of a class of carbon-negative or carbon-management technologies or practices. Such approaches include terrestrial rangeland and cropland soil-management practices, afforestation, biochar production, the development of bioenergy with carbon capture and storage (BECCS), and at sea, potential marine photosynthesis stimulation. In contrast to these biological approaches are engineered carbon-management practices such as carbon capture from carbon dioxide–rich flue gas or the enhanced weathering of silicate rocks.

Direct air capture and storage of carbon dioxide is an extension of these latter engineered systems: in one formulation, ambient air from the atmosphere is blown at low pressure by a fan across an amine sorbent matrix of nano-fibrillated cellulose (in which a fiber suspension is freeze-dried to create a solid). Every two to three hours the sorbent becomes saturated, and industrial-grade heat is used to separate the captured carbon dioxide at a temperature around the boiling point of water, drawing it off in a vacuum. In terms of scale, one early DAC manufacture and operations firm, Switzerland-based Climeworks, estimates that each of its stackable two-by-three-meter modular units can capture fifty metric tons of carbon dioxide annually. A six-unit shipping container's worth of Climeworks units would capture about three hundred tons annually. A competing Canadian firm, Carbon Engineering, claims plant-level capture of approximately one hundred thousand tons annually.[16]

The stream of high-purity carbon dioxide (in Climeworks's case, 99.9 percent, plus water at a 2:1 weight ratio) can then be used for food or industrial purposes, in synthetic fuel production, or for enhanced oil recovery, or permanently injected into subsurface formations for storage in gaseous, liquid, or solid mineralized forms. While all uses of carbon dioxide derived from DAC could be considered emissions-negative versus current practice,[17] DAC's emission-reduction potential is probably greatest when the captured carbon dioxide is geologically sequestered. This is equivalent to the amount stored, minus any incremental emissions generated through the manufacture and operation of DAC infrastructure (including electricity use for fans and carbon dioxide compressors, along with low-grade heat needs).

Energy input operational overhead for capture and subsurface injection differs based upon choice of sorbent chemistry and other design parameters. One current operational estimate is that approximately 1.5 megawatt-hours of heat and electricity are required per ton of captured carbon dioxide (at a ratio of about 4:1 heat to electricity), with a research and engineering goal to reduce that energy intensity by at least five times toward its theoretical minimum.[18] In practice, today's early DAC commercial and demonstration plants in Switzerland and Iceland have sought out zero- or very low-carbon electricity and heat sources, such as from renewable or nuclear power and incinerator waste heat, to maximize the efficacy of their removal operations.

### *Technical Scalability*

Two attributes make DAC technology stand out as a unique and potentially appealing carbon backstop candidate. First, DAC is one of the few demonstrated engineered carbon-negative technologies. The more DAC systems that can be manufactured and operated, the more carbon dioxide can be captured. This is in contrast to biological carbon-management systems like afforestation, agricultural practices, or BECCS, which can be directly limited by geography or resource availability.

Second, DAC with geologic sequestration is notable in that it does not directly rely on some other specific energy system or market to function. This means that it is not limited by the distribution patterns of any complementary technology. For example, conventional carbon capture and sequestration (CCS) from fossil-power-plant or industrial-flue-gas streams is an attractive and potentially significant carbon-management option, but it is also limited by the suitability of plant designs and site configurations of existing retrofittable or new host infrastructure. While DAC does require power and heat to operate, those inputs are low-specification commodities and widely available (see below).

And while DAC is not tied to any specific existing fuel, distribution infrastructure, or technology stack for its operational inputs, it does retain some other potential scale-limiting requirements, which we discuss below: energy inputs, offtake of captured carbon dioxide, and footprint.

As one limiting factor, DAC requires some form of low-carbon electricity and heat feedstock. At current relatively poor efficiencies, as described above, capturing and sequestering one billion tons of carbon dioxide (about one-fifth the United States' current annual emissions) would require the equivalent of nearly two hundred gigawatts of baseload zero-carbon power (and heat) generation—roughly equivalent to the entire US currently installed capacity of zero-carbon power. Improving that energy efficiency would clearly be necessary to consider DAC's suitability for broad use, and current system architectures suggest a theoretical thermodynamic efficiency limit of approximately one-tenth of today's level—about 130 kilowatt-hours per ton. Were that the case, just half of the current US zero-carbon generation fleet could power enough DAC units to offset the entire country's emissions.[19]

An obvious second technical limitation is what to do with the captured carbon dioxide. DAC proponents have suggested two main options: attempt to employ it usefully as an industrial feedstock (and generate revenue in doing so, as discussed later) or geologically sequester it at scale as cheaply as possible. Any CCS project faces similar limitations.[20]

The International Energy Agency (IEA 2010) has estimated a theoretical global geologic sequestration potential of 16,800 billion tons of carbon dioxide, broadly distributed around the world in sedimentary or saline aquifer formations—and a conservative likely potential viable storage capacity of 20 percent of that figure. That viable capacity equals about one hundred times the 2017 global carbon dioxide emissions from fossil fuels, suggesting that raw geologic storage capacity itself is unlikely to be a limiting factor for widespread DAC deployment. Other appraisals of the literature have reached similar conclusions (e.g., Dooley 2013). As just one example, the West Texas Permian Basin, now a focus of well-intensive frac-based oil and gas production, would likely have thousands of billions of tons of accessible storage capacity alone (NETL 2015).

Because some forms of sequestration involve the carbon dioxide remaining as a gas in subsurface pore space, even the presence of a sealing reservoir cap rock still prompts an important question of potential leakage—greater than 0.1 percent of which could more than offset the benefits of any initial storage operations. Large-scale leakage would be a further safety and liability concern. This is an important area for future research in proving the credibility of DAC as a potential carbon backstop (Zoback and Gorelick 2012).[21]

To this end, one new area of research is the potential for carbon dioxide mineralization and storage in leak-resistant igneous basalt-based geologies, as opposed to more conventionally studied saline aquifers or depleted oil fields.[22] Such geologies are also broadly accessible globally, especially around continental margins. One study estimated the mineralized carbon dioxide storage potential in the area of the Juan de Fuca plate off the coast of the US Pacific Northwest at over 700 billion tons (equal to more than one hundred years of current US emissions; Goldberg, Takahashi, and Slagle 2008). And Iceland's known on-shore basalt formations are thought to be able to accommodate twenty million tons of carbon dioxide injection each year, for example, approximately twenty times that country's current annual emission levels. Reactive magnesium-, calcium-, or iron-rich basalts are ideal for forming solid carbonates with injected carbon dioxide (Seifritz 1990) and are found in about one-tenth of terrestrial areas and over much of the ocean floor.

Potential limitations to the solid mineralization approach include the need for substantial volumes of surface water for initial injection alongside the dissolved carbon dioxide, at about a 20:1 ratio in testing in Iceland. This source could be seawater, but such efforts would need to manage the same potential aquifer contamination or induced seismicity risks that current oil and gas industry produced water-reinjection operations do, for example by avoiding existing active faults (Gan and Frohlich 2013; Walsh and Zoback 2016). Larger-scale mineralization projects may also suffer from well failure over time as the injection site itself mineralizes, decreasing throughput and necessitating expensive redrilling.[23]

A third potential concern around the scalability of DAC with sequestration could be expansive land-use requirements, which have been a criticism against other low-intensity, low-carbon technologies, such as wind and solar power (though refuted: see, for example, Arent et al. 2014). Would DAC face such limitations?

One estimate from the literature (from variables in Socolow et al. 2011, as reported in Smith et al. 2015) suggests that medium-scale DAC facilities could provide roughly 650,000 tons of carbon dioxide removal per square kilometer annually. Using today's DAC energy and heat input requirements—and assuming that all such collectors were powered using only natural gas combined-cycle power plants—would in the worst case reduce that net land-use efficacy to closer to 250,000 tons of carbon dioxide removal per square kilometer (including dedicated power plant footprints). Offsetting all current US fossil fuel emissions would therefore require about 21,000 square kilometers of land—or roughly the size of the San Francisco Bay Area.[24]

By contrast, using bioenergy cultivation paired with CCS carbon-removal technology (BECCS), as currently favored by most IPCC technology scenarios, is more land intensive. Removing the annual equivalent of all US carbon dioxide emissions would require from approximately 200 to 350 million hectares (or about 500 to 850 million acres) of productive cropland—equal to two to three times all currently planted US grain acreage—or 600 million hectares (about 1.5 billion acres) of forestland, equal to twice all US grazing lands (Field and Mach 2017). This illustrates how engineered negative-carbon systems may actually be promising from a land-use perspective.

### *Political and Social Acceptability*

Infighting among industry groups can slow clean-energy deployments when it is perceived that subsidy or preference for one technology may come at the expense of another technology or an existing market position. Political economy challenges such as these are particularly difficult in low-growth markets, such as those for oil products or for electricity in developed countries, and they can limit the rate at which any new clean-energy technology can likely scale in the real world.[25] For instance, the US Energy Information Administration (EIA) now expects that most US states will see less than 0.5 percent annual growth in power demand through 2030. This means that subsidizing the deployment or production of one clean technology—for example, wind or solar—can unintentionally affect the profitability of other desirable participants in that same market, such as nuclear power plants (Carl and Fedor 2017) or result in stranded assets.

DAC plus sequestration is notable, however, in that it not only lacks ties to any one existing energy industry, technology, or market for its technical functionality, but it also is not likely to negatively affect incumbents or even new industry entrants. An existing electricity provider, for example, is not threatened by the deployment of a DAC system (and would rather welcome the additional source of electricity or waste heat demand). The same could be said of oil-product or coal suppliers. DAC is not a substitute for any existing energy provider or technology, in part because it is not an energy supply system. Furthermore, unlike other forms of carbon management, DAC is not necessarily tied to the agricultural sector (though it could conceivably be a supplier to the greenhouse industry).[26]

One flip side of this scarcity of natural political opponents might be a commensurate lack of obvious politically powerful allied industries to lobby for an early-stage deployment subsidy or policy and regulatory support. That calculus could shift, however, were incumbent sticky carbon dioxide emitters to see DAC as a way to credibly within-the-fence offset emissions from existing or new uses and industrial processes that are valuable but difficult to decarbonize. Perhaps with these considerations in the background, DAC did actually enjoy recent legislative support in the United States when the sector won access in early 2018 to section 45Q federal tax credits alongside traditional CCS projects (a technology itself buoyed by politically relevant coal producer associations): approximately $30 per ton for captured carbon dioxide reused in enhanced oil recovery and $50 per ton of captured carbon dioxide geologically sequestered. While such amounts only represent about one-tenth of current DAC costs, as described below, they could be significant for conventional point-source CCS industry development. Legislatively, the credits were attached to a bipartisan budget deal and were passed without major dispute, and they were made available for facilities built over the next seven years, without any volume cap. That legislation could signal a shift in political and social attitudes toward a field that has at times been viewed with suspicion in developed countries, and the lack of volume cap furthermore suggests an appreciation of scale considerations as explored in this essay.

Notably, this development contrasts with a continued perspective held by some environmentalists and climate scientists that any type of negative-emissions technology represents “a moral hazard par excellence” for emission mitigation goals, that “negative-emission technologies are not an insurance policy, but rather an unjust and high-stakes gamble” (Anderson and Peters 2016).[27] The extent to which such anti-CCS social sentiments ultimately affect the current option value of DAC as a carbon backstop turns on one’s beliefs as to how effective those voices would later be in preventing the technology’s rapid deployment given a changed environment where climate damages are recognized to be significantly worse than today’s expectations. In other words, when the chips are down, are CCS detractors bluffing? We suspect they are.

To that end, DAC has another unique attribute in its favor—completely verifiable emission reductions. To appreciate this, consider alternative emission reduction interventions. A new low-carbon power generator, for example, must justify its emissions mitigation contributions by some indirect counterfactual expectation of what dirtier generation technology might have been deployed in its place (or which existing generator was displaced). The carbon emission efficacy of an energy efficiency measure similarly depends on one’s beliefs about how that intervention has changed the sum of a user’s behaviors from business as usual. Even other carbon-negative strategies, such as afforestation, have to be considered from a systems perspective. These so-called baseline problems affect almost all existing low-carbon technologies.[28]

But this is not the case with DAC plus sequestration. Its fundamental economic weakness—in that it does not produce some other valuable energy service or commodity alongside its carbon mitigation attributes (such as electricity or fuel)—is its strength in terms of verifiability. Any ton of carbon captured and sequestered by an operating DAC-plus-sequestration system is one that would be in the atmosphere were that system not operating.[29]

### *Unilateral Adoption*

The characteristics of DAC plus sequestration described so far generally support the potential for its unilateral adoption by a motivated country or other entity, with some caveats. In contrast to the nuclear power considerations described above, there is little in the way of mature international law expressly limiting the use of carbon capture technologies. The technology and chemistries employed in today's DAC systems are not exotic and do not have military dual-use potential that might otherwise limit export.

Regarding the handling of captured carbon dioxide itself, there is currently no relevant comprehensive global treaty or agreement—due more to novelty than to state-based resistance. This has mixed implications for a state that might be motivated to quickly develop DAC with sequestration. On one hand, the absence of a multilateral bureaucratic process permits swift deployment and experimentation. One the other hand, an unresolved legal framework can create investment uncertainty or unintended consequences. For example, until the mid-2000s, the 1996 London Protocol would have prevented the offshore injection of carbon dioxide as a form of marine waste dumping. Article 6 of that same convention today potentially restricts cross-border trade in captured carbon dioxide as a form of pollution export, and international joint project leakage-liability issues remain unresolved (Global CCS Institute 2009).

This suggests that domestic sequestration might be preferred. To that end, countries may have different knowledge levels and capabilities regarding subsurface geologies suitable for carbon dioxide sequestration, which could be a limiting factor. As described above, however, a variety of potential sequestration geologies are available and broadly distributed globally. And because of domain crossovers with the conventional oil and gas industry, even small states tend to have practical knowledge of and expertise in local subsurface conditions; country-level comprehensive evaluations of potential CCS reservoirs are, however, lacking, with Australia having undertaken perhaps the first detailed assessment in partnership with the private sector (McCoy 2014).

Domestic regulatory frameworks for CCS have begun to be developed but in general remain modest. The International Energy Agency's CCS Law and Regulation Database (2018) lists thirty-four known instruments at federal or local levels across twenty-six potential regulatory issues, with most activity concentrated in Australia, North America, and Europe but very little elsewhere in the world. Overlapping regional and federal jurisdiction over liability issues remains problematic, for example (de Coninck and Benson 2014). Stronger domestic legal frameworks would be a prerequisite for rapid scaling up of DAC or any other carbon-sequestration technology.

One key characteristic supporting unilateral deployment of DAC is that atmospheric carbon dioxide is fungible across international borders. The atmospheric commons problem is often seen as a weakness in the political economy of low-carbon energy technologies: the host country bears the full private costs of emissions reduction, but the climate benefits are spread globally. But for DAC, this same dynamic can be viewed as beneficial: any country can capture and domestically store carbon dioxide for the benefit of any other willing buyer globally—perhaps the world's most liquid market. When a buyer exists, the captured carbon dioxide is a free atmospheric resource (with zero transport costs), which can be monetized by storing it underground or otherwise utilizing it. Moreover, for small states or remote areas, carbon could be captured and stored in excess of local emissions. This makes DAC potentially attractive to regional arbitrage opportunities.

One obvious historical analogue to this dynamic is the Kyoto Protocol's novel Clean Development Mechanism (CDM). That framework created an international market for carbon dioxide emissions offsets with the idea that low-carbon infrastructure investments in poor countries would be cheaper than in rich nations. But the CDM suffered from poor market transparency and significant investment baseline concerns. A better analogy for DAC, with its inherent robust emission-reduction verifiability, might therefore be large computing data centers. The rise of cloud computing has created a market for data storage and computation; combined with the internet's low network latency, this has allowed such data centers to be developed in modular fashion at distances of hundreds of miles from the customer in locations best optimized for cost of operation: good land availability, low construction and labor costs, and cheap energy.[30] To this end, one early DAC firm recently announced two contracts for DAC-based voluntary carbon-offset purchases: one from an individual living in continental Europe and one from an American nonprofit organization—both to take place at the CarbFix CCS project located outside of Reykjavik (Climeworks 2018).

This suggests not only that a motivated individual state might choose to unilaterally deploy DAC in excess of its own emissions to lessen concerns from its citizens on global climate change, but also that there is a potential revenue opportunity to incentivize entrepreneurial nonstate actors to do so as well.

One particular group of key nonstate players who may be motivated to pursue unilateral DAC at scale is fossil fuel producers. Today's oil and gas producers increasingly face activist organizations or shareholders who argue that future or even current booked reserves may not be exploitable given government targets for decarbonization (Carbon Tracker Initiative 2017). While firms have generally refuted this perspective given the continued global need for fossil fuels (see, for example, ExxonMobil 2018, Chevron 2018, Shell 2018), over the long term it is conceivable that a demand-constrained fossil fuel market could affect the regional profitability of some large individual producers.[31]

A potential response to this challenge would be for oil and gas producers to attempt to diversify into other energy businesses; Royal Dutch Shell has suggested "new energies" as one of its strategic options going forward (Bousso 2018). But oil and gas firms have also argued that it is difficult for them to achieve the same return on capital in alternative energy ventures when compared to their core competencies of subsurface geology, fluids handling, field operations, distribution, and logistics (Downing and Gismatullin 2013, Ferris and Gronewold 2014, Browne 2016). DAC therefore presents a compelling investment space in that it provides a way for oil and gas firms to extend the market for their core products by relying on their existing technological and operational strengths, potentially offering a net zero- or lower-carbon fossil fuel product when paired with atmospheric carbon capture. Proposed amendments to California's Low Carbon Fuel Standard, which regulates the carbon intensity of gasoline and diesel blends sold throughout the state, have suggested that CCS could play such a role (CARB 2018). This could create an incentive for obligated firms to unilaterally pursue various forms of carbon capture and sequestration, including DAC.

### *Costs*

Estimated capture and sequestration costs for the few operational DAC sites today are too high to be competitive versus many other available clean-energy technologies, but technology and manufacturing roadmaps suggest that DAC costs could be substantially reduced with scaled production. This contrasts with other negative-emissions technologies, such as bioenergy CCS, which tend to become more expensive at very large-scale deployments given scarcity of suitable land and water resources. At modest deployment levels, today's DAC technologies may be commercially viable for relatively niche applications in which the captured carbon dioxide can be sold as a product to offtakers in the greenhouse or beverage industries.

Climeworks, for example, estimates that its initial eighteen-unit DAC demonstration installation in Zurich had a levelized cost of $600 per metric ton captured carbon dioxide in 2016. That facility was installed on the roof of an existing municipal waste incinerator, which provided it a cheap source of input heat and free real estate. Furthermore, the project faced no additional sequestration costs as the captured carbon dioxide was then sold to a nearby greenhouse, helping to offset the operating costs. The firm claims that the following year their next operational unit, outside of Reykjavik, was able to capture and sequester carbon dioxide to mineralized rock for about $500 per ton (Shultz-Stephenson Task Force on Energy Policy 2018). That project in turn benefits from the island's cheap low-carbon electricity sources, with wholesale power rates on the order of two or three cents per kilowatt-hour (though comparable to some of the lowest power prices seen in recent years in Texas and the US Midwest).[32] A competing DAC firm, Canada-based Carbon Engineering, recently published its own somewhat more optimistic detailed engineering cost accounting, based on its own pilot plant data, to estimate attainable scaled combined construction and operational costs of $94 to $232 per ton of captured carbon dioxide (Keith et al. 2018), though those estimates have been criticized as unrealistic in the field.

What goes into DAC's high costs? Elsewhere, the carbon-sequestration component of CCS projects has been estimated to cost around $20 per ton, meaning that the air-capture component of DAC processes still overwhelmingly dominates its cost structure.

The near- to mid-term path to DAC cost reduction lies first in manufacturing cost and delivery reductions through volume: today's DAC firms expect that from innovations already in hand, costs can be reduced by two-fifths within two years given strong customer demand. Beyond that—achieving a cost threshold of $200 per ton, for example, comparable to typical costs regularly incurred globally today to avoid carbon dioxide emission through the deployment of solar and wind power—would require additional manufacturing innovations such as the use of automated assembly.[33] Reductions in cost beyond that level would require innovation in operational efficiency such as novel amine sorbents, as described earlier, as well as broader continued low-cost availability of low-carbon power and heat supply sources to improve the net carbon dioxide capture efficiency of DAC operations.[34]

Given the high costs outlined above, today's pure-play DAC entrepreneurs are likely to pursue offtake agreements for the captured carbon dioxide, which pay more than the limited regulatory incentives or subsidies to geologically sequester carbon. One established global source of demand for high-purity carbon dioxide is the beverage industry, which may typically pay a range from $150 to $1,000 per ton of supplied carbon dioxide depending on location. This high-end estimate exceeds current costs for deployed DAC systems, suggesting that their operating costs could be more than covered in remote locations where a conventional carbon dioxide supplier may not otherwise have access to it as a by-product of bioethanol production or a concentrated flue gas stream from a thermal power plant. Of course, beverage industry demand is many orders of magnitude smaller than the levels of capture that would be necessary to materially affect global climate change.

Beyond beverages, some have envisioned the development of a broader industrial supply chain that uses carbon dioxide as a long-lived input. Richard Riman of Rutgers University, for example, proposes using carbon dioxide to densify mono-calcium silicate to produce concrete (analogous to the in situ basalt mineralization process described above). Such a process would benefit from similar geographic economies to distributed atmospheric carbon dioxide capture and transport—a roughly two-hundred-mile economic delivery radius, for example—but would have to be capturable at costs below $100 per ton to be competitive with today's portland cement production (Richard Riman, personal communication, October 20, 2017). Jennifer Wilcox of the Colorado School of Mines, meanwhile, has proposed the economic use of less energy-intensive low-purity (30 to 50 percent) carbon dioxide from DAC systems as a feedstock for microalgal biofuel production (Wilcox, Psarras, and Liguori 2017). Harvard's David Keith, meanwhile, through Carbon Engineering, is pursuing the production of a synthetic liquid hydrocarbon fuel (suitable for drop-in use in transport) from the carbon dioxide captured through their larger-scale, continuous-capture process (Kolbert 2017).

In sum, cost is the limiting factor of scaled DAC deployment given the combination of today's high unit prices and relatively low social willingness to pay for pure-play carbon reduction efforts. The extent to which both those factors do or do not intersect over time—for example, through the existence of a sufficiently high-revenue neutral carbon tax that would make DAC economic at the margin—will dictate this technology's future.[35] Alternatively, DAC may emerge from a desire (or mandate) to verifiably and transparently net out emissions from hard-to-mitigate but otherwise high-value and growing emission sources such as aviation or industrial processes, where few technological alternatives currently exist. But given its likely scalability in the noncost realms described above, DAC is nonetheless an encouraging example of a carbon backstop option offering a credible price ceiling against which other relatively costly emissions reduction efforts should be considered. In the words of one former DOE official, "It never costs more than this to stop climate change."

**Market Considerations of Deploying Carbon Backstops**

The discussion in this essay presupposes that the emergence of social and political will to rapidly slow climate change through massive investment could arise at a point in time when carbon backstop technologies remain expensive. To put it another way, the experience of negative climate impacts could make social demand for emissions reductions more inelastic. And we have furthermore explored the nonprice characteristics that might allow backstop technologies to rapidly diffuse into existing social and economic systems. But what policy mechanisms might even a very motivated government use to enact such a deployment into a market economy without complete distortion of existing investments, obligations, and the rule of law? Many of the tools used today to mandate or otherwise incentivize the gradual deployment of certain energy technologies may not be suitable for use at large scale or on shorter time frames.

- For a sector such as electricity, where a new scalable zero-carbon technology like SMRs would face competition from incumbents, government procurement could provide some initial movement. The US federal government, for example, buys \$15 to \$30 billion in energy each year, largely for the Department of Defense (EIA 2017), and electricity consumption for federal facilities is about 1 percent of the US total (EERE 2018). Replacing all of that electricity with new SMR-produced long-term power purchase contracts as new plants come online would finance the output of around ninety NuScale-size reactor units. Purchasing from first-of-a-kind SMR units would come at above-market rates for electricity, and compelled agencies would likely require additional budgetary support from Congress, but this process would help reduce technology risk and costs for subsequent commercial SMR units (see, for example, Hamre 2015.)
- A more scalable financing option might be the use of reverse auctions, whereby the federal government would offer tranches for given amounts of SMR (or other zero-emission) power purchase or, in the case of DAC carbon dioxide sequestration, to the lowest credible bidder.

For power, publicly contracted deliveries could then be resold onto the competitive market. Doing so would likely depress market power prices, however (as do existing federal subsidies to zero-carbon power generators such as wind), and would drive existing high-marginal-cost producers out of the market; care would then need to taken to protect existing low-emission power generators from these effects. While resale of power through such a clearinghouse would mitigate the economic impacts of massive purchases and would largely protect existing consumer markets from added costs, it would still undesirably create a new government bureaucracy and would require significant new tax revenues (and associated macroeconomic dead weight loss) or deficit spending.

For DAC, acquisition of carbon dioxide sequestration credits through reverse auction would be more straightforward because of the lack of existing markets to distort but would also be more expensive because of the lack of an associated resellable product. One might imagine a more generic corollary, in which not just sequestration but other marginally less verifiable, but still credible, carbon dioxide emissions reductions could be bid into a pool for purchase. This might include efforts such as efficiency retrofits or changes in land use but would still suffer from baseline and transparency issues observed in similar international efforts such as the Clean Development Mechanism.

- A more exotic alternative—in-sector, targeted “feebates”—is another potential regulatory option that would be revenue-neutral to the government, reducing the need for new revenues, but would instead pass compliance costs on to incumbents and their end consumers. Under a feebate, carbon dioxide emitters in a particular sector (such as power generation) would be assigned an emissions performance standard near the existing median level across that sector. Those who emit in excess of that standard per unit of production would be assigned a fee proportional to that performance, while those emitting below the standard would receive an equal rebate funded by the earlier fee levied. The sector standard is then gradually reduced over time. Feebates have been proposed since the 1970s by energy economists as attractive for their relative efficiency, their contained economic impacts, and the smoothly ramped incentive landscape they would conceivably provide to both incumbents and those entering a market. But they have been little used in practice, perhaps due to perceived information complexities in implementation and the commensurate need for a supporting bureaucracy.

Ultimately, though, it is clear that all such policy mechanisms would have major downsides. They could significantly affect tax revenue needs, consumer prices, and ultimately consumer choice. Some of this is inherent to the realities of the sorts of massive technology and infrastructure transitions imagined in this essay. They point to the bitterness of the medicine of having to employ a carbon backstop, even were it technically and socially possible to do so.

They also point to the general desirability of pursuing technology-agnostic solutions in climate or energy policy. A broad-based revenue-neutral carbon tax, for example, as described elsewhere in this essay, is a first-best policy solution that would incentivize a host of emission-reducing actions from across the economy through price discovery as the tax is gradually increased. While consumer prices would change—perhaps significantly, depending on the level of the tax—it would mitigate through direct rebates overall consumer budget impacts and avoid government outlays. A high carbon price would cause wealth transfers across consumers based on their comparative ability to reduce their direct and embedded emissions, but that effect would be moderated over time as more low-emission options became available.

Importantly, the revenue-neutral carbon tax puts trust in the market to determine which emissions reductions to buy first. To that end, it may not actually end up financing the deployment of the sorts of specific carbon backstop technologies, such as SMRs or DAC plus sequestration, we describe in this essay. Were it to find more affordable emission-reduction solutions, though, that should be regarded as a success. One criticism often levied at carbon taxes by those who favor more direct government control of the economy is that they do not provide “emissions certainty.” That is, one does not know in advance how much they will drive down emissions or how (in truth the same criticism could be directed at command-and-control policies as well, given the unintended side effects they can produce). But given social and political willingness to sustain a sufficiently high carbon tax rate, recognizing the existence of potential ceiling carbon backstop technologies across different price points and different emissions sectors should provide the confidence that revenue-neutral carbon taxes can deliver even deep decarbonization for societies willing to pay for them.

## 3. Other Emerging Potential Carbon Backstop Technologies

This discussion has highlighted the potential of recently developed technologies such as fission SMRs and carbon dioxide DAC plus sequestration—and also their challenges. As with any risk-management strategy, a broad portfolio of such technologies would lessen the risk that a failure in one or two might compromise the overall investment. To that end, it is important to recognize that there are now in fact a number of emerging or proposed low-carbon or carbon-negative technologies and practices that are uncommercial in today’s market and regulatory framework but hold the promise of scalability were those conditions to change. Taken together, these technologies offer the potential for increased human control over the composition of the atmosphere or aspects of its effects.

### *Carbon-Negative “Advanced” Carbon Dioxide-Enhanced Oil Recovery*

The petroleum industry in the United States has used the subsurface injection of concentrated streams of carbon dioxide into depleting oil reservoirs since the 1970s to increase oil-extraction rates. Gaseous carbon dioxide helps to maintain reservoir pressure and mixes with oil to improve its flow through rock pore space and toward the producing well head. This form of enhanced oil recovery (EOR) is currently used to produce about 3 percent—about 300,000 barrels annually—of US oil production through at least 136 injection sites, most of them in Texas (Kuuskraa and Wallace 2014).[36]

As outlined in a recent article by Benson and Deutch (2018), though projects are variable, on average about 0.4 metric tons of carbon dioxide are injected in this process today to generate each additional barrel of oil. This level of injection already results in marginal oil production (which a field generates through the use of EOR over and above conventional recovery methods) that is nearly net-zero from a carbon dioxide emissions perspective once that oil is combusted as fuel. The concept behind carbon-negative advanced EOR would therefore be that oil producers could use existing or new injection and distribution infrastructure to intentionally increase the amount of carbon dioxide injected for each barrel of oil they produce—for example, doubling to 0.8 tons carbon dioxide per barrel. Doing so in existing oil fields would likely result in marginal oil production with net-negative carbon dioxide emissions, effectively leaving carbon in the ground.

Advanced EOR shares many of the same feasibility attributes and political economy dynamics of DAC plus sequestration as described above, and it could be considered a complement to that approach. Notably, advanced EOR would first require an affordable supply of relatively pure carbon dioxide at scales suitable for oil field production. In fact, with most of today's carbon dioxide used in EOR being largely sourced from other natural geologic—as opposed to anthropogenic—sources, availability already constrains the economic use of this technology (and also negates some of its emissions mitigation value). Thus any set of technologies that could economically capture anthropogenic (flue stack) or existing atmospheric carbon dioxide would be a prerequisite for use of advanced EOR at scale.

Compared to DAC with conventional geologic sequestration, advanced EOR would have a few added benefits. Namely, it would provide revenue to offset the cost of DAC (or conventional carbon capture) through the production of additional crude oil from known sources that might otherwise go unproduced by traditional recovery methods alone. While this would require substantial new infrastructure development to support the injection of the carbon dioxide in potentially remote locations, it would also help extend the economic life of oil production infrastructure—and know-how—already in the field. The Department of Energy estimates that advanced carbon dioxide EOR such as described here could result in additional domestic oil production of more than 200 billion barrels—worth at least $10 trillion at today's prices.

Even with that potential value, costs, as with other backstop technologies described in this essay, would preclude broad deployment of advanced EOR today. Benson and Deutch (2018) and NETL (2010) estimate that current carbon dioxide EOR operations result in infrastructure overhead expenses of $35 per incremental barrel of oil production (assuming a typical hypothetical field of 180 million barrels of oil), plus roughly another $10 for the carbon dioxide itself (about $25 per ton). Increasing that to support higher injection rates—almost one ton of carbon dioxide per barrel of oil produced—would both increase the overhead costs (to about $56 per barrel) and double the carbon dioxide needs. As described earlier, today's power plant carbon capture systems produce high-purity carbon dioxide at costs three to four times what oil producers pay for naturally sourced (but limited in supply) carbon dioxide, and DAC-sourced carbon dioxide would be ten to twenty times the cost without major cost reductions. In short, in a $50 per barrel conventional oil market, carbon-negative oil from advanced EOR would entail marginal production costs closer to $150 (for conventional flue stack CCS) or $400 (DAC) per barrel, depending on the source of the carbon dioxide.[37]

While those costs are daunting, the political economy of such an approach is somewhat more promising. The previous discussion of DAC plus sequestration argued that the technology could provide a business plan "out" for oil and gas producers who might otherwise see carbon emission–reduction policies as existential threats. Using that captured carbon dioxide for new oil production, at net-negative carbon emission rates, more credibly furthers a scenario whereby such firms could continue to do business by doing what they already do well, with better profit margins to be had by getting even better at that over time. Thought leaders have proposed that existing oil and gas infrastructure (plus regulatory, operational, and subsurface knowledge)—which is one of the few global industries already built to manipulate product at the large scales needed to significantly reduce carbon dioxide emissions—could even be repurposed to focus on carbon dioxide injection in this manner (Mark Zoback, personal communication, December 19, 2018). And in more liberal jurisdictions, where a social license to operate may be increasingly necessary, the nexus between carbon dioxide reduction and oil production would be even clearer than with DAC, with retailers, for example, being able to assure buyers that more carbon dioxide was necessarily sequestered to produce the oil than would be emitted in its combustion.

Finally, on cost, there does appear to be a path toward continuing to scale the carbon dioxide EOR industry, even its advanced net-negative emissions form, given current economic and regulatory conditions in the United States. The same 45Q tax credits described earlier would apply to this activity—in this case at least $35 per ton, or about $30 per barrel of oil in advanced EOR uses. Then there is the possibility of exploiting currently existing anthropogenic carbon dioxide emissions from less-considered point sources such as bioethanol fermentation facilities or fertilizer producers. Both processes already produce carbon dioxide streams of high purity (over 99 percent for ethanol and 40 percent for ammonia) at costs that fall between today's naturally sourced EOR supplies and that from flue-stack carbon capture at power plants. Potential carbon dioxide production from US ethanol plants could exceed 35 million metric tons (Kansas $CO_2$ EOR Deployment Work Group 2017). Complete use of those resources would require new carbon dioxide pipeline transport capacity from agrarian to oil-producing regions but would also motivate political interest by improving the value of those agricultural processes for the energy and climate sectors.

### *Soil Carbon Management*

The impacts on radiative forcing of the earth's climate from the anthropogenic increase in atmospheric carbon dioxide emissions illustrates the precarious balance of the global carbon system. Of the 850 billion tons of carbon currently in the atmosphere (equivalent to about 3,120 tons of carbon dioxide), the balanced process of plant photosynthesis and respiration cycles about 120 billion tons in and out of that atmospheric pool each year; human emissions, by contrast, only add about 6 billion tons (net) of carbon to the atmosphere each year (though, importantly, that flow is largely one way and is net positive). In a field where scale matters, however, this carbon cycle math is nonetheless receiving increasing attention: could the natural plant carbon cycle be engineered to store more carbon dioxide each year than it releases back into the atmosphere?

While afforestation and land management have long been considered part of emissions management, another potentially scalable approach would be to change the biology of commercially grown crops worldwide so that each plant stores more carbon in its roots and keeps more of that carbon stored in the soil carbon bank after harvest instead of decaying and making its way back into the atmosphere. The La Jolla–based Salk Institute for Biological Studies has advocated for this mechanism while pursuing research on test species through a program they dub the "ideal plant." That program has used selective breeding to boost the production of suberin—also known as cork—in plant roots to slow decay in the soil (Salk Institute 2018). Salk scientists estimate that incorporating such attributes into half the existing acreage of the world's six major commercial crops could store one-fifth of current anthropogenic emissions, or about 7 billion tons of carbon dioxide annually (Hook 2019).

Additional costs for such an approach are unknown but importantly would take advantage of existing mature development, distribution, and market systems. Plants have long been bred for desirable characteristics such as dwarfism or herbicide resistance to boost yields, and are bought and sold throughout the world by farmers and agricultural suppliers. Improving confidence in this approach to large-scale emission offsets would first require better demonstration through technical trials for the introduction of carbon-storing traits alongside existing desirable yield-oriented characteristics in major crops such as corn, soybean, rice, wheat, sugarcane, alfalfa, or cotton. A second requirement would be policy changes to create mechanisms that incentivize the efficient uptake of carbon-oriented plant technologies, particularly if these traits came at the cost of other economically desirable characteristics. The legal and regulatory framework to encourage carbon storage in soils is immature and has largely focused on conservation tillage and crop-cycling practices. It is reasonable to expect though that were new technologies proven to enable carbon farming, then well-organized agricultural and rural political interests would be motivated to pursue policy for this new market, just as policy has driven other farming practices through the modern era in the developed world (see for example, Cuéllar et al. 2014).

And while it may seem far-fetched that such carbon-storing characteristics could be widely distributed throughout the global agricultural system, this would actually be quite similar to the rapid and dramatic genetic improvements seen through the Green Revolution's program of selective breeding in the second half of the twentieth century, the gains from which now underpin global nutrition. More recently, we can observe the rate of spread of genetically engineered plant traits. Monsanto Corporation (now owned by Bayer), for example, introduced its first Roundup Ready glyphosate-tolerant genetically modified soybean in 1996; by 2011, this trait was present in 93 percent of US soy production and 75 percent globally (Bøhn et al. 2013). A successor product, Xtend soybeans, was expected to account for 44 percent of US soybean plantings—40 million acres—within its third year of sales (Bousso 2018). The introduction of low-cost precision gene editing through CRISPR/CaS9 technology has led some experts to speculate that dramatic improvements could be made in the time and expense required to demonstrate favorable crop genetics (see, for example, Shapiro and McAdams 2018). It is notable, then, that some scientists in this field have to date consciously limited their plant carbon-storage research to conventional breeding techniques, acknowledging that while research progress may be slow, the final product may encounter less public resistance to its broad uptake in food crops once available (Salk Institute 2018).

### *Solar Geoengineering*

The greenhouse effect, which helps regulate the earth's climate, is driven by a variety of elements: noncondensable greenhouse gases, such as carbon dioxide or methane, which trap escaping energy as it radiates from the warm surface of the earth back out to space; atmospheric water vapor, which acts similarly; and reflectivity from the ground or low-lying clouds, which controls how much incoming sunlight is absorbed by the earth's surface or the atmosphere in the first place. The first of these elements—greenhouse gas concentration—is being intensified as a result of human carbon dioxide emissions, with predominantly negative effects. But reducing those emissions to desirable levels has proven costly. Researchers have therefore asked if those efforts should be accompanied by efforts to engineer other parts of the greenhouse equation as well, such as the earth's balance of reflected light. Proposals to this end have included the stratospheric injection of common aerosol particles—sulfur or, perhaps less damaging to the ozone, limestone—from dedicated fleets of aircraft around the world, which would limit the total amount of incoming solar energy (e.g., Keith et al. 2016). Another form of so-called solar radiation management would instead aim to extend the natural reflective effect of low-lying stratocumulus clouds through marine cloud brightening—continuously atomizing salty seawater from ships or other offshore infrastructure to seed condensation nuclei for extensive cloud formation (e.g., Latham et al. 2012, Wood et al. 2017). Both approaches would result in cooling.

Solar geoengineering is an interesting counterpoint to the technologies described above because its barrier to adoption is perhaps the opposite of those: historical observation and modeling suggest that it is effective at reducing the radiative forcing that leads to higher average surface temperatures; it is technically scalable globally without the need for new invention or scientific breakthroughs; and it is very rapidly implementable through unilateral action. But it is also cheap. Recent studies have estimated that using these techniques to slow warming impacts equivalent to offsetting half a century of anthropogenic emissions (~1.5–2 degrees Celsius) would cost less than $10 billion annually, perhaps one-tenth that amount (e.g., Salter, Sortino, and Latham 2008, McClellan, Keith, and Apt 2012, Smith and Wagner 2018). On a marginal cost of carbon dioxide emissions equivalent, this would be hundreds of times cheaper than even the modest emission reduction steps being taken today in the energy sector or through carbon capture.[38]

The solar geoengineering option, then, is not waiting for a higher economic climate damage strike price to be exercised. Instead, it is constrained by political and social acceptability. The topic engenders political taboo—either because of the risk that its use at scale could result in unintended environmental side effects or because of the moral hazard it poses for more conventional emission reduction efforts—and even scientific research in this area has been very limited, currently receiving essentially zero public funding in the United States and less than $10 million annually globally (Wanser 2017). Initial efforts to bound the risks and develop norms and institutional frameworks have been largely limited to small, nongovernmental associations of enthusiasts (e.g., the Solar Radiation Management Governance Initiative or the 2010 Asilomar Conference on Climate Intervention). And even as public concern about global warming has grown in the United States, there have been only nascent efforts to understand how public attitudes toward solar geoengineering (or even awareness of it) measure up to the stance so far adopted by political leaders and climate interest groups (Mahajan, Tingley, and Wagner 2018). Given these uncertainties, it remains perhaps the backstop of backstop technologies. But, as with each of the other options described in this essay, it is important to recognize that any additional effort taken to research and de-risk it today would actually have value even if the continued development of other options meant it was never deployed.

**The Montreal Protocol as an Insurance Policy**

The Montreal Protocol on Substances That Deplete the Ozone Layer, signed in 1987, has been described as the most effective example of an international environmental agreement. At the time, President Ronald Reagan described it as a “monumental achievement.” Former secretary of state George Shultz has since described Reagan’s initial choice to pursue protocol negotiations, which ultimately phased out the use of ozone-depleting chlorofluorocarbon (CFC) gases through the introduction of a variety of substitute technologies, as a sort of “insurance policy” (Shultz 2015).

Parties have debated the applicability of the Montreal Protocol experience—which focused on an industrially important but still relatively narrow sector of the global economy—to today’s more fundamental climate change challenges. Notably, former deputy assistant secretary of state Richard Elliot Benedick, who was the protocol’s chief US negotiator, has himself argued that there are in fact useful lessons to be drawn (Benedick 1991). In what ways might that experience inform the credibility of carbon backstops as climate insurance today?

- Early steps were taken to replace nonessential CFC uses with cost-effective solutions, such as CFC use as a propellant in canned aerosol products. This particular use was banned in the United States in 1976, relatively rapidly after early credible academic observations that CFCs could damage ozone and following an initial task force set up by President Ford to scope the issue. Trickier, essential uses of CFCs, such as for refrigeration and in foam production, were a growing global market, though, without good identified substitutes, so that larger problem was left for a political and social consensus to develop. This phase could be compared to the low-hanging fruit, marginal decarbonization steps that we have seen in the United States and elsewhere globally over the past decade.

- Meanwhile, technology development toward more comprehensive substitutes accelerated. The DuPont corporation, for example, which held an approximate one-quarter global production share of CFCs, through the late 1970s and early 1980s researched and patented more than twenty potential substitutes for the various essential uses of CFCs, including HFC-134a, which would later gain major global market share (Pielke 2010). An important characteristic of these options was their ability to drop into existing supply chains and consumer-use cases. While these potential substitute technologies had been identified as promising, however, they simply remained too expensive to justify their use—somewhat analogous to the carbon backstop options we have described here.
- Finally, the Reagan administration was able to build bipartisan support for regulatory action on the ozone issue by adopting a "no-regret" or "little regret" framework. The president and contemporaries, including British prime minister Margaret Thatcher, acknowledged continued uncertainty in the complex science of ozone depletion but also considered the magnitude of potential damages should some of the worst-case conditions actually arise—later estimated to potentially have resulted in more than one million additional skin cancer deaths worldwide had CFC use continued unabated (Garber 2017). His administration effectively argued that relatively low-cost steps could be taken by the country to prepare itself to phase out CFC use should that become publicly desirable and technologically possible (Shultz 2007). By the 1985 scientific discovery of the Antarctic ozone hole, political willingness to pay had grown and the availability barrier for desirable substitutes had shrunk (*New York Times* 1988b). Montreal Protocol commitments—criticized by some advocates at the time as being too modest (*New York Times* 1988a)—were unanimously ratified by the Senate. And as both scientific understanding of the CFC threat and replacement technologies to mitigate that threat matured, the flexibility of the treaty allowed President George H. W. Bush to speed up the replacement process in the early 1990s ahead of the original schedule (*Washington Post* 1992).

## Discussion

### *Strategies to Improve the Credibility of Carbon Backstops*

An effective insurance policy must be credible, with a promise that is both practically possible to deliver on and that the buyer trusts. If one does not believe the insurance policy is credible—for instance, if one does not believe that the fire department will arrive when needed or that a policy will pay out upon damages—then one would both underinvest in that insurance option and likely overinvest in personal mitigation actions, using the precautionary principle.

In the climate realm, what might be done to improve the public credibility of technologies such as SMRs or DAC as "plan B" carbon backstops? Since we argue that the generation of the future option actually creates present value, it would also make sense for such moderate preparatory steps to be undertaken now rather than waiting for a later time when the option is ready to be exercised.

Climate mitigation political rhetoric often invokes the imagery of massive wartime industrial mobilization as the needed course of action for emissions mitigation. But the analogy is flawed in both scale and acceptance: the immediate expected damages of climate change are not of the same order of magnitude as those of an imminent large armed conflict, and broad social priorities are not aligned such that impacted parties would be willing to make large sacrifices for the public good. A better military analogue might therefore be not battle but defense planning. Everyone agrees that major conflicts are undesirable, and we therefore take steps to mitigate the chances of that through diplomacy, negotiation, and alliance building. But a military must nonetheless be ready to enter into and win large-scale conflicts should they become unavoidable. Part of that planning is understanding and cultivating surge production capacity for military hardware. What normally unavailable resources can the nation draw upon in times of dire need, and what conventional rules and protocols might it override, to overcome a significant challenge? The Department of Defense and federal government agencies regularly carry out such assessments of defense industrial base capabilities. The same cross-government approach taken toward a climate plan B would help improve the credibility of future options as described in this essay. Such contingency planning could include:

1. *Funding and analysis of low- or negative-emission technology scalability potential from first principles.* Many energy-economic climate modeling exercises focus on expected deployment levels of available technologies to achieve emissions reduction targets. Their choice-based results tend to emphasize near-term cost competitiveness expectations, which underemphasize the potential of uninvented options or radically different social environments. The option value of potential carbon backstops could be improved today through improved quantitative analysis of the technically addressable scale of each technology's emission reduction reach under extreme circumstances.

In this essay we have discussed a few backstop candidates, but a portfolio of high-impact options should be evaluated—again, less for their deployment suitability today than for the option value they do or do not offer in terms of future potential scalability. For example, non-light-water reactor Generation IV advanced nuclear technologies are a promising avenue for low-carbon power generation at scale but likely face at least as many challenges as SMRs, given their current system-level technical risk. Another area for study might be the potential to combine high levels of intermittent renewable power generation with storage or grid-balancing technologies effective enough to enable resilient, year-round electricity supply (see Clack et al. 2017 for a discussion of current technical challenges). Such enabling technologies might include new grid-scale batteries, molten salts, large-scale hydrogen- or ammonia-based energy storage, interseasonal geologic storage of heat, or substantial new deployment of continental-scale high-voltage transmission lines.

2. *Appraisal of manufacturing surge capacity for carbon backstop technologies.* What industrial supply chain resources could be brought to bear in this country if called upon, what high-impact steps could be taken today to alleviate identified bottlenecks, and what are the estimated costs of executing such a conversion of productive capacities? For example, operating 50 to 100 million of Climeworks's collectors could offset about 10 percent of annual global carbon dioxide emissions. And each two-by-three-meter DAC unit is about the size and material composition of a passenger car. Similarly, reaching that deployment level over ten years would require a manufacturing unit output volume similar to the annual production levels achieved by today's leading global auto manufacturers. Would there be public value in developing a credible plan for the retooling of existing or retired vehicle assembly plants to produce DAC units at scale? What about for the far more complex nuclear-rated supply chain to develop SMRs? Which manufacturing duties in that supply chain might be offloaded to nonnuclear civilian producers, or to today's nuclear-rated military suppliers, at an acceptable safety risk margin in a time of crisis?

A corollary of this deployment barrier analysis could be identification and resolution of regulatory and legal impediments, such as unresolved gray areas concerning captured carbon dioxide transport and liability. An early public education component could also help reduce the risk of social backlash to technologies such as SMRs to help mitigate the low energy literacy issues from which today's nuclear technologies suffer.[39]

3. *Establishing the climate change "strike price" of the carbon backstop option.* At what climate change threshold might we expect a general social consensus—sufficient to assume some of the disruption and costs outlined above—to declare a climate catastrophe and activate the carbon backstop insurance policy? Importantly, such determinations are likely to be different in different countries given both the scientifically expected variability in regional climate costs and benefits and the global variability in social tolerances.

One body of climate literature, for example, has suggested the concept of expected times of emergence for different environmental factors—defined as the point at which new weather patterns or other natural phenomena statistically attributable to climate change outnumber the distribution of such events due to expected natural variability (Lopez et al. 2018). Though the timing of such emergence would vary even within a single large country such as the United States, a dispassionate selection of such indicators could nonetheless be established well in advance of their potential occurrence. Observation of that point-of-emergence threshold would then trigger a defined backstop response. Other commentators have similarly suggested making climate science more relevant through the development of broader frameworks in which to establish regional risk indicators suited to both local climate impacts and social values (Kennel, Briggs, and Victor 2016).

Overall, these approaches would open up the possibility of political precommitment; it could also permit prefunding of automatic financial appropriations for the planned response, avoiding the need for further legislation. Both steps would reduce the political uncertainty of being able to exercise the carbon backstop option when needed, improving credibility today. Precommitment also potentially improves the short-term politics of climate change by turning the normally unfavorable temporal dynamic on its head: today's participating politicians would actually be able to claim climate progress for their constituents now by committing their successors to future spending requirements. This could be viewed as a sort of social climate entitlement program.[40]

Of course, a number of detrimental global or regional climate change phenomena have already arguably been observed today.[41] Given this, one might ask the value of discussing a potential future large expenditure in response to climate change versus immediate deployments today, before the worst of those damages are experienced. In a broad sense, this can be attributed to a current and persistent gap between social willingness to pay and potentially observable climate damages, an issue for which there is historical precedent in the United States. For example, for decades a majority of economists and health professionals have agreed that local and regional criterion pollutant emissions from fossil fuel combustion in the United States alone—such as $SO_2$, $NO_x$, and particulates—result in thousands of premature deaths annually (CATF 2014, Caiazzo et al. 2013). And while efforts to reduce local pollution have resulted in continuous gradual improvements since the 1970s, a certain level of ongoing damages is nonetheless tolerated given the concurrent benefits provided by those polluting services.[42]

Even so, widespread public and political support for more costly pollution interventions has increased throughout modern history when salient and striking environmental damages became plainly visible—common examples include smog in the Los Angeles basin in the 1960s and 1970s or popular attention to Ohio's 1969 Cuyahoga River fire. It would appear that today's natural disasters that may be partially attributed to climate change have yet to produce the sort of durable step change in attitudes and willingness to pay across broad portions of the public that would be needed to support the significant ongoing costs and livelihood disruptions associated with deep decarbonization—but that could change.

4. *Weighing the value of international cooperation.* The discussion above has largely focused on the potential for unilateral action to reduce the political risk of carbon backstop deployment when desired—the reasoning being that a willing host nation would not need to take the time or make compromises to bring other countries, with potential divergent interests, on board to make significant emissions reductions. But some forms of bilateral or multilateral cooperation may nonetheless improve the credibility of the carbon backstop insurance policy. For example, "climate clubs," as proposed by William Nordhaus (2017), or other forms of "shallow cooperation" (Keohane and Victor 2016) have been suggested as ways

for nations to take advantage of collective action given already aligned climate or energy preferences, without relying on new political breakthroughs at the negotiation table. In national security terminology, this would be the equivalent of building a like-minded *coalition* focused on execution toward a shared goal, rather than developing strategic long-term *alliances* where the relationship itself is an objective.

For carbon backstops, this could mean pursuing preagreements for future coordinated deployment responses given the jointly acknowledged triggering of some negative climate phenomenon. More concretely, nations might engage in planning for shared, cross-border surge capacity in low-carbon technology manufacturing: the United States negotiating priority access to Japanese nuclear-rated steel forgers to rapidly produce future SMRs, for example. Drawing again on the military analogy, the United States today, for example, already explicitly identifies aspects of the Canadian industrial manufacturing base—both public and private components—for its own military equipment surge production capability (Hunter et al. 2017).[43]

Overall, were there to be a general public and political acceptance of the carbon backstop concept—that such technologies could significantly reduce emissions, are technically feasible at scale, would be socially acceptable, and are unilaterally pursuable at will (noncooperative)—one consequential implication today might be a reconsideration of the risk of worst-case emissions and climate change scenarios. For example, of the four standard representative concentration pathway (RCP) emissions-linked scenarios modeled in current IPCC reports (see figure 1, title page), the most pessimistic, known as RCP8.5, projects global average warming as high as 4.9 degrees Celsius and 0.82 meters sea level rise by 2100. In that scenario, global carbon dioxide concentrations continue to rise through the entire century and in fact persist through 2300, when a warming of 12.6 degrees Celsius is possible. In a scenario such as this, there would be ample time—decades—during which major damages from climate change would be broadly evident, yet emissions would continue to rise. That suggests a future in which society decides that even very high environmental damages do not justify the cost of a significant decarbonization response (unlikely) or one in which it is simply not feasible to rapidly reduce emissions—that is, a world without a carbon backstop. For those who particularly wish to reduce the risk of such a dire situation, investment in carbon backstop options today would be one prudent form of insurance.

### *Bridging the Climate Conceptual Gap*

Finally, it is worth repeating that this insurance-policy framework should not be interpreted as an argument against continued emission reductions and clean energy technology deployment today, much of which is justifiable in its own right through climate or other publicly valued rationales. Rather, our interest is in policy frameworks to help cut off the tail of the climate risk distribution and thereby preempt the notion that broadly disruptive economic and behavioral changes are needed to address climate change.

At the same time, an acceptance that this option does exist—or could exist with modest preparatory efforts as described above and continued public and private support for long-term research and development—has the added potential to help clarify the public discussion over clean-energy deployment goals today. It offers an antidote to some of the more apocalyptic climate rhetoric increasingly seen in the political discussion. For example, some advocates have pushed for regional policies that mandate specific deployment targets, such as 100-percent-renewables portfolio standards, hard caps or reductions on total oil-product consumption, or even the complete technological, economic, and social transformation of the country—despite the obvious technical and economic difficulties in doing so (Siders 2015, Brick and Thernstrom 2016, Trabish 2017, Ocasio-Cortez 2019). Where these efforts have received political support, it has sometimes been accompanied by scare-tactic warnings of extreme climate damages if these specific policies are not pursued, as if no other viable carbon emission reduction options existed (Christensen 2015).

Here we have described a portfolio of potential carbon backstop technologies across different parts of today's energy and climate landscape—zero-carbon dispatchable electricity, direct air capture of carbon dioxide to net out sticky emissions, and the development of an atmospheric radiative forcing toolkit. They are emerging, but they remain immature. Early demonstration of the viability of these or other options, even if they are expected to exist only in the future, might therefore create the space for a more deliberative public and political dialogue on the relative merits, objectives, and costs of the piecewise clean-energy and decarbonization choices that we as a society can pursue today. Of course, there is always the potential that research and development surprises us on the upside, such that it becomes attractive to employ some of these improved technologies without first waiting for a crisis. Together, this argues for the cultivation of carbon backstops today as part of a balanced approach to climate change.

## NOTES

1 Evidence to date suggests that many countries today do not value the damages of climate change highly enough (or, to formulate it differently, do not value the benefits of avoiding current climate change highly enough) to justify the large costs of pursuing a two-degree target. While some government or policy regulatory programs today incur marginal emission reduction costs of hundreds of dollars per ton, they do so in ways that are not immediately transparent to the general public, are done at generally low deployment levels, and are arrived at through the expenditure of significant political capital. See Hahn and Ritz 2015 for more discussion of the role of the social cost of carbon in policy making.

This has been acknowledged even in environmentally oriented California, where recent political efforts to increase the publicly visible component of that state's carbon market to reach even moderate social-cost-of-carbon levels, through a carbon tax or other means (Wara and Cullenward 2016), was blocked partly on the expectation that it would result in public and political turmoil. Similarly, witness the social pushback incurred in the late 2018 French *gilets jaunes* public protests, which were triggered by an anticipated rise in a (non-revenue-neutral, nonrefunded) national carbon tax from approximately \$62 to \$100 per ton.

2 While these two camps do not form a clean split—there are economically efficient policy supporters who may also expect severe global warming damages, for example, and simply advocate for a very large carbon tax—they illustrate how even among those who support undertaking real costs to avoid climate change there are competing sets of mental expectations at play.

3 Nuclear desalination of water from heat output has been used historically in just one land-based nuclear plant, the BN-350 prototype fast reactor in Kazakhstan, which operated from the 1970s to the 1990s.

4 Though, as the United States' own experience has shown, long-term spent fuel storage is not necessarily a prerequisite for development of a functional interim fuel cycle.

5 While much trade is through direct contracts, the Chicago Mercantile Exchange offers uranium futures, for example, and about 20 percent of global uranium is traded on spot markets. Firms in the United States, Europe, Russia, and Japan offer commercial uranium conversion and enrichment services—there are thirteen such facilities globally—and contracts for fuel fabrication are available from suppliers in eighteen countries operating a total of thirty-four facilities (Nikitin, Andrews, and Holt 2008).

6 As of early 2018, thirteen generic SMR certification process technical and policy issues were considered "resolved" (including questions regarding variable annual fees for smaller reactors, plant control room staffing requirement determinations, and aircraft impact performance) while five were still under review (including questions regarding source term calculations, liability insurance, and site security requirements).

7 US federal and state policy makers have anecdotally noted that constituent attitudes toward new nuclear technologies such as SMRs cut across existing preference groups for conventional nuclear plants (Shultz-Stephenson Task Force on Energy Policy Roundtable 2016). When nuclear power is presented as an innovative new low-carbon technology—alongside solar and wind technologies that people are more familiar with—people place it in a new mental bucket based on its attributes as opposed to preconceived images.

8 India, Israel, North Korean, Pakistan, and South Sudan are not signatories.

9 This is despite Pakistan's refusal to sign the NPT and an ongoing embargo placed against it by the NSG (of which China has been a member since 2004).

10 Upon resuming 123-agreement negotiations in early 2018, a period in which Saudi Arabia was reported to be pursuing technology supply agreements with ten different countries, one former US State Department official remarked that this time, the United States should "show some flexibility" toward Saudi interests (Mufson 2018).

11 The costs of crystalline solar photovoltaic installations—which can be considered a relatively mature technology—are similarly variable and currently range by over 2x among different US states (NREL 2017) and 3x across deployment formats (e.g., utility scale versus rooftop, Fu et al. 2017).

12 In contrast, others have argued that recent cost overruns, due in part to construction delays on new Generation III+ large-scale nuclear facilities in the United States and Europe, may actually make smaller pressurized water SMRs relatively less costly due to lower financing costs (e.g., EIRP 2017).

13 This has led to a variety of efforts and other workarounds to socialize financing costs through direct state financing, government loan guarantees, utility and EPC firm consolidation, or billing of regulated utility customers for approved construction costs as they are incurred rather than waiting for project completion.

14 Payroll costs are substantial in the nuclear power sector: a conventional US nuclear power plant today has on-site staffing needs approximately twenty times that of a combined-cycle natural gas power plant.

15 Even this regional formation is simplified, however, as it does not account for the greater disparity between marginal and average environmental benefits from low-carbon power-generation deployment across different regional electric grids (see Siler-Evans, Azevedo, and Morgan 2012 for an analysis of variation across US states, for example). NB: This most conservative cost formulation assumes zero-sum displacement of an existing typical generator by an SMR for the sole purpose of new carbon emission reductions; the marginal cost of emission

abatement of deploying an SMR versus some other proposed new carbon-intensive power generator in a demand-growth environment would be smaller—only the cost premium for the SMR.

16 For reference, a typical 650-megawatt-capacity modern natural gas combined-cycle power plant, operating in continuous baseload configuration, might emit two million tons of carbon dioxide per year, and NRG's Petra Nova CCS facility in Texas captures more than 1.8 million tons from just one of that plant's four coal-power units.

17 Today, for example, carbon dioxide gas is at times actually generated for express use as a chemical feedstock or for use in greenhouses.

18 For comparison, a typical natural gas combined-cycle power plant in the United States can generate around 2.46 megawatt-hours of electricity per ton of carbon dioxide emitted (see EIA 2014; this is an electricity-emission productivity rate that is similar to the overall US grid average). One of today's DAC systems, run from a natural gas power plant, would then result in a relatively unattractive 61 percent haircut on carbon-removal efficacy. Achieving future DAC operational efficiency goals, however, would reduce that natural gas–equivalent efficacy loss to just 8 to 12 percent.

19 As a rule of thumb, it is generally more realistic, however, to expect any engineered system to reach an optimum cost point closer to four to five times the thermodynamic limit: for a country like the United States, such energy input requirements would suggest that DAC could substantially offset carbon-dioxide emissions of large economic sectors with sticky emissions, such as air travel or various industrial processes. However, achieving even this optimal efficiency level would require continued improvements to today's primary amine chemistries through the development of new sorbents with better thermodynamics and kinetics. Notably, however, thermodynamic analysis suggests that the energy requirements of ambient DAC of carbon dioxide are theoretically equivalent to carbon capture from conventional concentrated flue gas streams (Wilcox, Psarras, and Liguori 2017).

20 Though, for both input and storage pathways, the upper limit of accessible offtakes for modular DAC systems could be thought of as strictly higher than larger-scale conventional CCS, given DAC's relative flexibility in siting and its smaller minimum viable offtake agreement size.

21 Leakage data to date is limited. Approximately 1.5 billion tons of carbon dioxide has been stored in the United States, largely for enhanced oil recovery, with little evidence of significant leakage (Conniff 2018), though leakage has occurred due to poorly maintained wells elsewhere globally (IEA 2016).

22 Iceland's government-sponsored demonstration "CarbFix" CCS mineralization project is one such example. There, 95 to 98 percent of injected carbon dioxide, dissolved in water, has been measured as mineralizing to rock within two years of injection in the presence of alkaline formation waters (Matter et al. 2016).

23 Another consideration for any CCS project is a potential limiting maximum rate at which a large volume of carbon dioxide could flow through the subsurface at a single injection site (Baik et al. 2018), though that constraint might be mitigated for relatively smaller and more distributed modular DAC installations.

24 For a simple comparison, at an average capacity factor of 28 percent (EIA 2018), US utility-scale solar installations produce approximately 123 gigawatt-hours per square kilometer annually. This then represents an average carbon dioxide savings of about 54,000 metric tons per square kilometer annually, or five to twelve times less dense than with DAC (assuming a 2017 average carbon dioxide intensity of US power generation of 439 kilograms per megawatt-hour [Schivley and Samaras 2018] and solar land-use figures from Arent et al. 2013, which places utility-scale PV land intensity at 50-megawatt capacity per square kilometer).

25 To cite some recent examples, regulated utilities and third-party rooftop solar installers regularly skirmish in US state legislatures and before utility commissions over the proper value and compensation for their products (e.g., net-energy metering rates); oil suppliers have contested biofuel blending requirements, while agricultural associations promote them; even energy efficiency standards can pit various manufactures against each other.

Policy makers have at times even intentionally co-opted industry political might to help achieve their goals—the California Low Carbon Fuel Standard, for example, consciously included a mechanism whereby the state's electricity utilities could generate revenues through participation in a new trading market to counterbalance potential lobbying efforts against the measure by the state's politically engaged oil distributors.

26 The incumbent most threatened by DAC would conceivably be refiners who currently manufacture high-grade carbon dioxide for use in the food industry or as a chemical feedstock. As discussed below, however, most envision that widespread DAC deployment, due to scale, would entail explicit expansion of existing markets for carbon dioxide feedstocks rather than a simple displacement.

27 One could imagine a variety of potential justifications for such views: if negative-emissions technologies were available, then less political support in the form of mandates and subsidies might be given to existing low-carbon technologies like renewables (an apparent motivator of one of the few groups opposing the 45Q tax credit—the US solar industry lobby); were significant leakage of stored carbon dioxide to occur, then climate benefits could be blunted; or any technology that effectively extended the future lifetime of the fossil fuel industry from a carbon budget perspective could (charitably) exacerbate local air pollution problems, which indeed remain a significantly more costly human health issue than climate change, or (more cynically) perpetuate an often-targeted political constituency.

28 Emission baseline problems are one reason that clean-energy legislation is often discussed not in terms of impact on actual emission levels, and rather in terms of proxies for emission reductions, such as the share of renewables in electricity generation—there are too many confounding factors to credibly attribute changes in emission levels to any one measure or any one investment.

29 Potential caveats to this are (a) the potential offsetting emissions intensity of the power and heat sources supplying a DAC installation; (b) if a DAC system were capturing carbon dioxide for sale as an industrial feedstock in such a way that it is not displacing existing produced carbon dioxide and that new product is not storing that new carbon input (e.g., if DAC were to dramatically expand the global market for fizzy sodas); or (c) somewhat more existentially, the extent to which carbon dioxide geologically sequestered from DAC for enhanced oil recovery were to increase the ultimate use of fossil fuels. These are all important concerns but, even in the worst case, are of a smaller magnitude than similar ones that regularly affect the emissions reduction efficacy of other current or envisioned low-carbon technologies.

30 A more recent example of this dynamic is the mining of digital cryptocurrencies such as bitcoin or ethereum in remote data centers through intensive computation. Cryptocurrency mining extends the analogy most fully given the global fungibility and discreet unit characteristics of the digital product being created and transacted. It is perhaps unsurprising, then, that remote Iceland, which now consumes more electricity for cryptocurrency mining in data centers than it does for its own domestic residential population (benefitting from the country's natural cheap and low-carbon renewable energy supplies), has also become an early demonstration center for DAC plus sequestration.

31 Softening of aggregate demand has arguably already affected some higher-cost regional coal producers in the eastern United States, who have witnessed a wave of consolidation and bankruptcies as natural gas has displaced coal-fired power generation, for a variety of reasons.

32 For context, these most recent observed DAC costs are still about eight to ten times more expensive than the large-scale Petra Nova CCS demonstration project in Texas, which captures a more concentrated post-combustion carbon dioxide stream from a conventional thermal coal power plant and uses it for enhanced oil-recovery projects in the surrounding region.

33 This proposed manufacturing efficiency-based approach evokes the cost savings path realized in Chinese supply chains of polysilicon photovoltaic solar panels over the past five to ten years.

34 One strategy that has been suggested to reduce overall DAC costs is opportunistic dispatch—running the capture facilities only when electricity is as cheap as possible, at night in wind energy-prevalent regions like Texas

or at noontime in solar-heavy areas like California. But today's DAC firms report that capital costs represent more than half of overall costs, making opportunistic dispatch likely uneconomic—units are currently assumed to instead operate at 90 percent capacity factors.

35 It should nonetheless be acknowledged that many climate or clean-energy policies today in fact result in effective emission reduction costs on the order of today's DAC systems—well over $250 per ton in some cases—but are otherwise favored politically or socially for adjacent attributes; see retrospective federal analysis of costs in Nordhaus, Merrill, and Beaton 2013 or forward-looking state-level cost evaluations in CARB 2017B.

36 Experience with carbon dioxide EOR has been largely limited to the United States.

37 It is possible that DAC's added costs over conventional carbon capture for this application could be reduced in certain applications by reducing fixed costs. For example, in remote locations DAC would have less need to build costly long-distance carbon dioxide transmission pipelines from point emitters. A DAC unit could simply be built on top of the field, given power availability at the site, and heat inputs could even be supplemented by any associated natural gas that would otherwise be flared. The supply of carbon dioxide for oil field needs could also be better balanced through the use of smaller-scale modular capture units, potentially even shifting units around a production area as needed over time.

38 Importantly, solar geoengineering is not a complete offset to carbon dioxide emissions in the way that DAC plus sequestration or other forms of CCS are: both approaches described here could themselves introduce potentially undesirable environmental interactions, and neither would address deleterious nonheating impacts of higher carbon dioxide concentrations such as ocean acidification.

39 See Carl and Fedor 2017 for a discussion of US public attitudes and low knowledge about nuclear power generation.

40 Returning to the sources of potential fat-tail climate risk outlined at the start of this essay, another reasonable backstop trigger might be if scientists were to observe that the climate sensitivity—that is, the climatic and weather response to a given level of atmospheric carbon dioxide concentration—was significantly more responsive than today's damages models expect. For example, if the sensitivity were observed to be double our current expectations (currently about 2.8 degrees Celsius for a doubling of atmospheric concentrations over preindustrial levels; Cox, Huntingford, and Williamson 2018), then that would increase the risk of experiencing dangerous fat-tail climate risk and potentially justify a step change in emission reduction responses. Given the importance of this scalar, the climate sensitivity range has been a matter of substantive scientific and political debate in recent years (Otto et al. 2013, Knutti, Rugenstein, and Hegerl 2017).

41 Existing anthropogenic warming has led to global average sea level rise of 19 centimeters since 1900 and now continues to rise at an average 3.2 millimeters per year; some regions have experienced sea level rise at twice that rate (Church et al. 2013). Warming oceans are thought to have increased the frequency of coral bleaching events and subsequent coral reef deaths (Hughes et al. 2018), with local ecosystem implications. The spread of infectious diseases is theorized to already have been exacerbated by the climate change–induced increasing range of their hosts and vectors (Boyce et al. 2016, Caminade, McIntyre, and Jones 2016), though the overall prevalence of life-threatening vector-borne diseases has marginally decreased in the past decade (Gautret, Parola, and Raoult 2017). Some have even used statistical evidence to argue that regional droughts and forest fires may already have increased in frequency versus historical expectations (Williams et al. 2015, Diffenbaugh, Swain, and Touma 2016), though other studies have failed to find such weather links (Herring et al. 2014). Similar debates have occurred around storm intensity (GCRP 2014, GCRP 2017).

42 To put that in the context of global warming emissions, just the local damages of non–carbon dioxide pollutants from fossil fuel combustion today are equal to about $30–65 per ton of concurrently emitted carbon dioxide (Fawcett et al 2018).

43 The question of international cooperation also prompts the matter of valuing domestic versus total international climate damages (see Fraas et al. 2016 or Kotchen 2016). Whereas most emission reduction

costs are fully borne by the implementing party, the benefits of avoiding climate change are spread globally. A common estimate of the global social cost of carbon—which can alternatively be described as the social benefit of reducing carbon emissions—may be on the order of $48 per ton (to use a former US government estimate in 2010 dollars). But that benefit would fall to just $7 per ton considering only those climate change avoidance benefits directly experienced by Americans domestically (EPA 2017). This dynamic provides the basic rationale for coordinated emission reduction activities as described above and arguably becomes more salient if attempting to credibly justify these potentially very high cost-per-ton (but highly scalable) insurance-policy technologies.

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## *Shultz-Stephenson Task Force on Energy Policy*

The Hoover Institution's Shultz-Stephenson Task Force on Energy Policy addresses energy policy in the United States and its effects on our domestic and international political priorities, particularly our national security.

As a result of volatile and rising energy prices and increasing global concern about climate change, two related and compelling issues—threats to national security and adverse effects of energy usage on global climate—have emerged as key adjuncts to America's energy policy; the task force will explore these subjects in detail. The task force's goals are to gather comprehensive information on current scientific and technological developments, survey the contingent policy actions, and offer a range of prescriptive policies to address our varied energy challenges. The task force will focus on public policy at all levels, from individual to global. It will then recommend policy initiatives, large and small, that can be undertaken to the advantage of both private enterprises and governments acting individually and in concert.

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