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Can climate clubs speed up the development of next-generation climate risk technologies?

Joseph E. Aldy, Harvard Kennedy School

Kevin Wagner, Northwestern University

Eric Werker, Simon Fraser University

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Three decades of effort to reduce human-caused climate change have thus far not broken the unabated growth in carbon dioxide emissions. A broader portfolio of climate risk mitigation strategies – such as carbon dioxide removal and solar geoengineering, complementing decarbonization – will likely be necessary to avoid the most severe impacts of a changing climate. Yet market failures and political barriers have resulted in underinvestment in these emerging technologies. This paper considers the potential for a climate club to counteract the market failures and political barriers and accelerate the development and deployment of such technologies.

1. Introduction

Since the agreement on the 1992 United Nations Framework Convention on Climate Change (UNFCCC), policymakers and stakeholders at international negotiations as well as in national capitals have focused primarily on greenhouse gas abatement. Despite three decades of a policy emphasis on cutting emissions, the continued growth in greenhouse gas emissions and atmospheric concentrations, alongside the build-out of fossil fuel-reliant capital stock, have significantly reduced the likelihood that current approaches to climate policy will limit warming within 1.5–2°C as specified in the Paris Agreement (PA) (Fawcett et al. 2015; (Tong et al. 2019; (Raftery et al. 2017; Liu & Raftery 2021).

Instead of this singular focus, a broader portfolio of climate risk mitigation strategies designed to reduce emissions (abatement), temperature (amelioration), and impacts (adaptation) will likely be required. All three prongs of this portfolio depend on technological innovation, which both affects, and is affected by, economic growth and public policy (Aldy & Zeckhauser 2020). In this paper, we refer to the emerging technologies that address abatement, amelioration, and adaptation in foundational and transformative ways as next-generation climate risk technologies (NGCRTs).

In recent years, scholars, policymakers, and stakeholders have begun examining two NGCRTs: carbon dioxide removal (CDR) and solar geoengineering (SG). Combined, these two NGCRTs could prevent the worst impacts of climate change and effectively buy time for decarbonization (Long & Shepherd 2014; Belaia et al. 2021; Keith 2021; Smith 2022). Two key technologies within CDR and SG that provide the highest potential impact for reversing the current course of climate change are direct-air capture (DAC) and stratospheric aerosol injection (SAI).

DAC is a form of CDR that pulls CO_2 directly from the atmosphere, and either stores the gas in underground geological formations or repurposes for other applications such as fuel production and concrete. Compared to other CDR methods, DAC has a small footprint and a theoretically near limitless scalability. Bio-energy carbon capture and storage, for example, would require 7.2 million km^2 to remove 1,191 $GtCO_2$ to 2100 (Brack & King 2020), an area nearly the size of Australia. Another alternative, reforestation, requires 862 km^2 to remove 1 million tonnes of CO_2 (Cook-Patton et al. 2020); sequestering 1000$GtCO_2$, the upper limit imagined to limit temperature rise to 1.5°C (IPCC 2018), would thus utilize 862m km^2, larger than the surface of the earth.

With the IPCC noting high agreement that SAI could limit warming to below 1.5°C (de Coninck et al. 2018), it is the most promising SG proposal. SAI aims to emulate the aftermath of large volcanic eruptions where tiny reflective particles temporarily shift the earth's albedo. It would accomplish this using modified aircraft capable of injecting millions of tonnes of albedo-enhancing aerosol into the atmosphere. Usually, researchers suggest various forms of sulfur due to volcanic analogues, but other materials (e.g., calcium-based) are under consideration.

In spite of their potential to mitigate the risks of climate change, there is significant underinvestment in reducing the unit costs of CDR and developing and testing human-controlled SAI. This is especially notable given the pace of emissions reduction and the movement towards greener forms of energy, as we describe below. The architecture of the Paris Agreement does not provide obvious institutional contexts for DAC and SAI. Moreover, the evidence that the Paris Agreement may not deliver sufficiently fast, deep, and broad emissions cuts has motivated consideration of alternative (perhaps complementary) institutions. Climate clubs are one way around this logjam. In their broadest sense, they are smaller groups of states that operate outside the UN system to act on or discuss climate change. Nordhaus (2015) conceptualizes them as potential multilateral environmental agreements where participating countries that meet agreed-upon emission targets receive a club benefit (free trade) and non-participating countries are excluded or sanctioned (through tariffs).

Building on more than a decade of academic research, leading think tanks have proposed clubs (Shaia & Colgan 2020) (Tagliapietra & Wolff 2021), mainstream media outlets profile it positively ("Carbon Border Taxes Are Defensible but Bring Great Risks" 2021) (Mufson 2021) (Coy 2021), and perhaps most importantly, politicians include climate clubs in their platforms. In a speech at the World Economic Forum, Federal Chancellor of Germany Olaf Scholz stated that "[Germany] will use our presidency of the G7 to turn that group into the nucleus of an international climate club" (Scholz 2022). The IMF's international carbon price floor proposal could also serve as a key condition for participating in a climate club (Parry 2021).

What could be the potential for climate clubs to promote a broader portfolio of climate risk mitigation strategies, including the need to increase R&D spending for NGCRTs? In the rest of this paper we characterize a potential role for climate clubs in accelerating the development discovery and deployment of these technologies. Section 2 describes the current state of DAC and SG technologies, as well as the reasons why investment in these NGCRTs remains underfunded. Section 3 highlights the lessons from efforts to build climate clubs to promote technology investment and diffusion. Section 4 sketches a simple model of a climate club focused on NGCRT research, development, and deployment. In section 5, we conclude with a discussion of policy implications and next steps for research.

2. The state of the technologies

In this section, for both DAC and SAI, we summarize the current level of technological development, the sources and magnitudes of investment, as well as the limitations to adequate R&D and deployment under the status quo. Both DAC and SAI require significant ramping up of investment to be commercially viable (in the case of DAC) or deployable (in the case of SAI).

Globally, 19 DAC projects operate and capture about 0.01 $MMTCO_2$/year. By 2025, new plants expected to come online will likely capture an additional 2 $MMTCCO_2$/year (International Energy Agency 2021a). To put this technology growth in context, annual direct air capture needs to withdraw about 85 $MMTCO_2$ from the atmosphere by 2030, and nearly 1,000 $MMTCO_2$ by 2050 (International Energy Agency 2021b). Such scale suggests the need for significantly more funding for development and deployment. Moreover, the current technology costs do not enable DAC to compete with renewables.

In 2018, for example, leading European DAC plant producer Climeworks stated that capturing one tonne of CO_2 cost approximately $600 (Tollefson 2018). At this cost, the market for investing in carbon capture – and securing associated offset credits – is limited to large progressive, technology companies such as Microsoft and Stripe that are implementing their own net-zero plans.

Consistent with the energy innovation literature, the commercial viability of DAC depends on the use of public policy to stimulate market demand. This could occur through technology-neutral policies, such as pricing carbon through a cap-and-trade program or a carbon tax, or through direct government support of specific early-stage technologies. In their review of a broad innovation and public policy literature, Henderson and Newell (2010) suggest that combining these two strategies would provide the greatest boost to energy innovation rates. For carbon pricing to drive DAC adoption, the cost of removing CO_2 would need to fall considerably, perhaps decreasing to $100 per tonne (Royal Society (Great Britain) 2018). Public spending on R&D and deployment could facilitate cost reductions. The National Academies of Sciences, Engineering, and Medicine recommend between $1.8 and $2.4 billion in investments over the next 10 to 20 years with funding at all stages of innovation—basic science, development, demonstration, and deployment (National Academies of Sciences, Engineering, and Medicine 2019). Until recently, public spending fell orders of magnitudes below this recommendation: annual U.S. government appropriations for DAC technology averaged less than $20 million in recent years. This changed with the 2021 Infrastructure Investment and Jobs Act, which earmarked $3.5 billion to build four DAC hubs across the country. Alongside that funding, the same bill provides $6 billion for carbon capture, utilization, and storage, which will have some spillover into the DAC space (DeFazio 2021).

In addition to public spending, the United States employs tax expenditures to subsidize corporate investment in DAC. In 2018, the Bipartisan Budget Act rewrote section 45Q of the Internal Revenue Code, the carbon oxide sequestration tax credit. In the updated code, the tax credit for direct capture will rise to $50/tCO$_2$ by 2026 and the minimum removal requirement will decrease to 100,000t (House of Representatives 2011). The use of these tax credits is becoming an increasingly popular policy instrument. For example, Rep. Tim Ryan (D-Ohio) led a bipartisan coalition in 2021 that introduced the Coordinated Action to Capture Harmful (CATCH) Emissions Act, which would increase the credit from $50 to $85/tCO$_2$ for capture and storage (S&P Global 2021).

The major players in the DAC space are raising increasing levels of private funding (PwC 2021). The three largest DAC plant producers, Climeworks, Global Thermostat, and Carbon Engineering, raised $750 million, $70 million, and $68 million respectively. Additionally, newcomer Heirloom Carbon Technologies raised $53 million in series A funding in March 2022. To put this recent private investment interest in DAC in perspective, about $260 million of the $60 billion in climate technology private investment in the first half of 2021 focused on any form of carbon capture, utilization, and storage (i.e., including but not exclusively DAC). The investment in carbon capture is miniscule compared to other climate technology funding areas, such as mobility and transport ($36 billion raised); food, agriculture, and land use ($7 billion); or energy ($5 billion).

In contrast to DAC, private investors have not focused on SAI. The technology likely has more in common with a public infrastructure project than a commercially-oriented enterprise. Moreover, SAI has not been deployed at any scale in practice; instead, its promise reflects scientific understanding of the cooling effects of natural experiments, such as volcanic eruptions, and the technical prospects of engineering airplanes to fly high-altitude missions that inject light-reflecting particles into the stratosphere.

From 2008 to 2018, SG received government funding of just $31 million while private sources added another $24 million in capital (Necheles et al. 2018). The largest donors are eco-conscious technology billionaires: Bill Gates has provided about $8 million in research support and Dustin Moskovitz's (billionaire co-founder of Facebook) *Open Philanthropy Project* provided $6 million to several SG projects. Several foundations have also supported SG research, including the Pritzker Innovation Fund, VK Rasmussen Foundation, and the Alfred P. Sloan Foundation (Surprise & Sapinski 2021).

Compared to other climate change mitigation and adaptation strategies, SAI is an inexpensive option. Annual engineering cost estimates for SAI range from about $2 billion in the early years of deployment (Smith & Wagner 2018) to as much as $20 billion over long-term deployment (Smith 2020). Additional costs could include further backup deployment capacity, observation equipment, and modeling of impacts (Reynolds et al. 2016). In short, SAI could be far cheaper – by multiple orders of magnitude – than adaptation and rapid decarbonization, and cost far less than the damages from a changing climate (Aldy & Zeckhauser 2020).

To continue to develop SG, NASEM recommends public spending on SG R&D of $100–$200 million over five years (National Academies of Sciences, Engineering, and Medicine 2021). In 2021, the U.S. Congress appropriated an additional $5 million in funds for U.S. National Oceanic and Atmospheric Administration to use on SG-related research, building on a previous $4 million appropriation. Instead of a traditional applied science R&D-first approach, the Academy identified three integrated research clusters. They are context and goals for SG research (20% suggested funding allocation), impacts and technical dimensions (35%), and social dimensions (20%) with 25% of funding allocated dynamically as learning progresses. As NASEM outlines, research into SG cannot afford to be pure applied science R&D. The integration of other disciplines including international relations, behavioral science, sociology, anthropology, and others are needed to better inform approaches to SG governance and to engage the public (Aldy et al. 2021).

In summer 2021, the test of the Stratospheric Controlled Perturbation Experiment (SCoPEx) – intended to demonstrate experimental equipment for measuring the impacts of high-altitude particle injection – was cancelled in response to public criticism (Fountain & Flavelle 2021). In 2019, the Climate Action Network, a group of over 1,300 environmental NGOs, issued a statement opposing SG deployment and real-world experiments, although several U.S. environmental NGOs notably endorsed small-scale field experiments (Climate Action Network 2019).

Research on the public's opinion of SG is inconclusive. In the first international survey on perceptions of SG (then classified as solar radiation management), 72% of participants replied that they either "somewhat agreed" or "strongly agreed" that "scientists should study solar radiation management" (Mercer et al. 2011). Comparatively, a Pew Research Centre report from 2021 states that the public hold negative views of SG. Their research indicates that in the United States, 53% of adults believe that it would not successfully reduce the effects of climate change. Additionally, it appears that while only 32% of adults label themselves as "very concerned" about SG, that percentage increases to 72% among "those who have heard a lot about [SG]" (Johnson & Kennedy 2021). Since knowledge of SG among the public is low, these varying results may be a function of its framing.

In summary, both DAC and SAI have near-term promise to reduce the risks posed by climate change, but each requires significant increases in R&D support to play a meaningful role in mitigating these risks. For DAC, private funding has increased recently, but driving the necessary innovation to make it a viable strategy will likely require a blend of push and pull policies – public spending to demonstrate and advance the technology, and carbon pricing as well as offsets markets to draw the technology into larger commercial scale. For SAI, public R&D spending across nations must continue to grow if it is to be a viable risk mitigation strategy. Given the public infrastructure nature of SAI, it's not clear that carbon pricing or regulatory standards on private firms would induce meaningful private investment in SAI.

Beyond the limited funding into R&D, each NGCRT that we have analyzed suffers from opposition, often from environmental groups that perceive the application of such technologies may undermine political will and public support for deeper emissions reductions. While the technologies do have champions, they do not yet have the political clout to bring about the transformational change of pace of research and deployment that the planet may require. Climate clubs, focused on research and development of next-generation climate technologies, may address some of these challenges.

3. R&D-focused climate clubs

NGCRTs are not the only technologies to potentially benefit from climate clubs, and indeed the current potential for emission reductions has been driven in large part by the research and development of new and cheaper ways to provide renewable energy, hydrocarbon-free transportation, and efficient electricity grids, among other proven technologies. In this section we examine how climate clubs have emerged previously to encourage R&D and uptake of this earlier generation of clean tech.

A climate club in Nordhaus's view has two key elements: 1) it must provide a public good to members that outweigh the cost of membership; 2) it must be able to exclude or penalize non-members at low or no cost to members (Nordhaus 2015). In effect, the European Union could represent such a club, although it obviously addresses much more than climate change and is insufficiently large to bend the global emissions trajectory (Ellerman 2010). While the Nordhaus model is the most discussed variation, scholars have expanded the typology to include other structures. Falkner et al. (2021) identify three potential forms of climate clubs: 1) normative clubs that set standards on climate change mitigation commitments; 2) bargaining clubs where powerful states negotiate objectives and targets; 3) transformational clubs, which operate according to Nordhaus's principles. To put this typology in real-world context, consider three examples of such clubs focused on decarbonizing the energy system: the Major Economies Forum on Energy and Climate (MEF), Clean Energy Ministerial (CEM), and Mission Innovation (MI).

The MEF is a semi-annual gathering of the largest developed and developing countries (effectively the G20 minus Argentina, Saudi Arabia, and Turkey) launched by the Obama Administration in 2009. In addition to its role facilitating progress in UN climate talks, the MEF aims to "advance the exploration of concrete initiatives and joint ventures that increase the supply of clean energy while cutting greenhouse gas emissions" (U.S. Department of State 2009). In 2009, the leaders of MEF nations agreed to double R&D investment in "low-carbon, climate-friendly technology" by participating nations (The White House 2009). In practice, many MEF countries, including the United States, fell short of this goal.

To inform coordination and strategy on next steps in promoting research on climate-friendly technologies, the MEF tasked the IEA to develop *Global Gaps in Clean Energy Research, Development, and Demonstration.* Based on this gap analysis, participating countries worked together on a series of ten technology action plans—one for each area identified by the MEF as key for the future of addressing climate change. Under Falkner's typology, this represents a bargaining climate club. Powerful states have created plans that identify key areas of research and innovation.

The Clean Energy Ministerial (CEM), announced at the 2009 Copenhagen climate summit, is a group of more than 20 countries that account for more than 90% of the world's clean power. Their stated goals are to bring together clean energy leaders, improve policy and expand deployment of clean energy, foster clean energy leadership globally, fill a gap in the international clean energy conversation, and engage key private-sector partners (Clean Energy Ministerial n.d.).

The CEM has proven successful in providing support toward the development of energy efficiency standards, providing clean energy transition advice, and on global clean-energy capacity building (Sandalow 2016). Its interventions have proven to be low-cost and efficient with continued backing from a strong coalition (Yu 2019).

Again, though, the CEM acts largely as a bargaining club—a space where nations gather to determine priorities and clarify standards which they then provide to both members and non-members alike. While decarbonization is a club outcome through the support of clean energy transitions, the CEM succeeds because of the low cost to members and the prospect of economic gain through clean energy collaboration (Tosun & Rinscheid 2021).

The final club we will examine is MI, which includes 22 of the largest developed and developing countries. At launch, the stated goal of Mission Innovation was to have each member country double its clean energy R&D budget within five years—the same goal suggested in the initial mandate of the CEM (Mission Innovation 2015). If successful, this would lead to a global increase in spending from $14.5 billion to $28.9 billion.

2020 was the five-year mark for MI and the initiative did not reach its targets. Some countries did succeed (E.g., China: $4 billion to $8 billion), but total clean energy R&D spending by member states only increased by 38% (Myslikova & Gallagher 2020). Following the original five-year term, MI created a new mission statement and new focuses. As Anna Krzyzanowska, MI adviser to the European Commission states, "scaling up both private and public RD&D investments will remain crucial," (Mission Innovation 2021) but defined investment targets no longer seem to be a key aspect of MI's vision.

Of these climate clubs, the original vision of MI comes the closest to a transformational club. It featured clear commitments from members and provided a club good in the form of information sharing and collaboration on clean energy issues. However, it struggles for the same reason that the Paris Agreement does—the structure of the club does not overcome the free-riding problem.

Despite this experience of R&D-focused climate clubs, not all international actions have been cooperative when it comes to promoting the development and diffusion of clean tech. Utilizing anti-dumping measures in international trade law to protest domestic subsidies, both the EU and the United States imposed tariffs on Chinese solar panels, likely penalizing customers and slowing the adoption of solar power (Blenkinsop 2018, Houde and Wang 2021). As we consider climate club models for promoting NGCRTs, it is worth keeping producer interests in mind.

4. A model climate club for next-generation climate risk technologies?

In this section we sketch out the parameters of a climate club with the potential to accelerate the deployment of cost-effective NGCRTs. The club would have two tasks: (1) increasing expenditure on R&D and with it, accelerating the development of feasible and economical NGCRTs, and (2) accelerating the uptake of successful technologies, as appropriate for climate change risk mitigation alongside continued deep greenhouse gas mitigation.

Previous research on R&D and climate change mitigation suggests that this specific combination may increase both the profitability and the stability of environmental agreements. Under the assumption that R&D benefits can be fully excluded from non-participating countries, collaboration on R&D alone is enough to overcome the free-riding problem (Carraro & Siniscalco 1997). Allowing for some spillovers of technological benefits, and a climate club can still remain profitable and stable (Carraro & Marchiori 2002). However, Barrett (2005) questions whether it would even be in countries' best interest to exclude non-participants from the clean energy fruits of their R&D labor.

Market failures. This paper has argued that there is current underinvestment in NGCRT R&D, as well as its eventual takeup, from both public and private actors. It has demonstrated that there are several sources of market failure: a failure to correctly price the *externalities* that contribute to climate change, namely carbon emissions, which results in underspending on climate change mitigation activities; and a failure of *property rights* guarantees common across all innovation, that innovators are unable to fully appropriate the returns to innovation, which is all the more present given the government-reliant nature of potential markets for NGCRTs.

Political barriers. The near-singular focus on emission cuts to mitigate climate change risk reflects the initial political economy characterizing the climate policy debate in the 1980s and 1990s. Environmental groups led the civil society charge to prevent climate change from occurring by advocating for deep emission cuts. While such reduction effort has not materialized, many of these advocates have been wary of supporting adaptation and amelioration strategies for managing climate change risks. The resulting pressure by lobby groups to stigmatize the role of NGCRTs in reducing the impact of climate change-causing activity represents another cost or hurdle that these technologies must overcome to become viable risk mitigation strategies.

Welfare maximization. To respond to these market failures, an optimizing social planner would set the carbon price equal to the marginal social damage resulting from greenhouse gas emissions. Furthermore, she would subsidize private innovation to offset the innovator's inability to appropriate the benefits from innovation. Finally, she would attempt to legitimize the technologies through the dissemination of information or signalling.

As the paper has demonstrated, there is some degree of public policy action along all three of these dimensions at the national or regional level. There is a carbon price or an emission trading scheme in many jurisdictions; there is public R&D spending as well as quasi carbon tax credits (in the case of DAC in the United States); and legislators have engaged in virtue signalling through the introduction of bipartisan bills to promote carbon capture and appropriate modest funds for SAI. However, the paper has also argued that this activity is insufficient to eliminate the market failures. To investigate this insufficiency further, next we model the political economy of NGCRT policy and subsidy.

A national market for public action to promote NGCRTs. First, consider demand for public action, which may be in the form of subsidies or regulation. We assume that private firms and stakeholders have some influence in capturing the state (e.g., Dal Bó 2006) through the process of legislated R&D subsidies. This will likely result in R&D support that is not technologically neutral, but instead supports the specific technologies favoured by incumbent firms and stakeholders. It would also tend to favour technologies that are closer to the commercial stage since firms would be more incentivized to lobby the more appropriable the rents are from further innovation. We also assume that individual citizens prefer to free ride off the efforts of others to reduce their own emissions. Next, consider the supply side of public action. We assume that there is a convex cost function driven by spending constraints due to distortionary taxation in the case of subsidies, and by increasing costs on disfavoured interest groups in the case of regulation. Political finance also drives the supply side of public action, reflecting the interest group arguments on the demand side as described above.

Combining the demand and supply functions of public action generates several predictions that are consistent with our findings in the paper as well as the general observation above that policy makers at the national level will underinvest in NGCRT R&D. First, social returns for NGCRT R&D still exceed the marginal cost of R&D activity. Second, public support for reducing climate risk through new technologies will be technology focused, e.g. with budget line items for nuclear, or carbon capture in specific carbon-intensive processes, or energy efficiency, which fairly describes much of the U.S. Department of Energy R&D program (Gallagher and Anadon 2019). Third, the subsidies and rebates that do exist will target near-commercial technologies—clearly a challenge for some of the early-stage NGCRTs like SAI that lack a powerful incumbent firm or user. Fourth, public action will shy away from promoting stigmatized technologies like SG even when the technical benefits outweigh the costs.

Designing an international climate club to solve national under-provision. We now consider a set of countries, each with these key fundamentals. They underprice emissions. They under-subsidize climate innovation, especially in controversial applications, and the innovation they support is technology-focused and near-commercial. In each country, we assume that the policymaker aspires to set welfare-maximizing policies.

We consider two designs in which climate clubs may both increase net social benefits while providing incentives for individual countries to join in promoting NGCRT innovation and take-up.

Design 1: A portfolio of innovation

Due to the technology-specificity of domestic innovation political economy, design 1 proposes that countries coordinate to reduce duplication of technology while supporting national firms in a specific NGCRT. At the national level, the policymaker can embrace technology-specific lobbying ties and the emergence of real incumbent firms. (This will bring about an additional benefit as suppliers and workers congregate to produce a higher-productivity "cluster" in the specific technology, e.g. Jackson 2011.) At the international level, R&D benefits will spill over to other countries, both members and non-members alike, as successful technologies emerge into bankable assets and reduce the risk of climate change. However, the original national champion firms are likely to have a leg up on the competition through their initial development of commercial capabilities, thus providing incentives for countries to join.

Design 2: Pooled resources for innovation

Some technologies, such as nuclear fusion, have potentially high fixed costs or barriers to innovators being able to appropriate the returns to their invention due to the distance of the technology from commercial application. Others, such as SG, face limited commercial market application as well as domestic legitimacy gaps due to the political power of certain stakeholders. To overcome those obstacles, design 2 pools resources to invest in basic science in for some NGCRTs while generating domestic legitimacy for other NGCRTs by establishing international cooperative R&D groups. Indeed, states have often sought out the legitimizing support of international organizations to convince a skeptical public that a proposed course of action is acceptable (Chapman 2012). Individual countries are incentivized to join as R&D costs in non-appropriable or early-stage technology can be spread out among members, while stigma for otherwise smart domestic policy is reduced through the international collaboration.

5. Policy implications and next steps

A defining characteristic of the Nordhaus climate club proposal is the use of trade measures to penalize countries outside of the club. Indeed, as we mentioned above, the EU could be considered a version of such a climate club, and the European Commission proposed carbon tariffs through a carbon border adjustment mechanism (CBAM) in 2021. Under this proposal, EU importers would have to buy special import carbon emission allowances that reflect the carbon intensity of the imported good and the going price for emission allowances for European firms covered by the EU Emissions Trading System (European Commission 2021a). If a country already imposes a comparable carbon price on its manufacturers, then its government may apply for an exemption to the CBAM. This raises three interesting possibilities for NGCRT clubs.

First, given the modest public funding to date for DAC and SAI, carbon tariffs could serve as a financing mechanism for these (and other climate-related) technologies. Over 2026–2030, the EU CBAM is estimated to generate €1 billion per year in revenue (European Commission 2021b). Such revenues will likely have many claims on them, so there may be political barriers to securing their use for clean tech R&D.

Second, carbon tariffs could be used as a stick to penalize members of the club for failing to spend monies on technology R&D consistent with their commitments. For example, the largest developed and developing countries in the world agreed to double their clean energy R&D over five years in the 2009 Major Economies Forum Leaders' Declaration. In 2015, the leaders of the countries in Mission Innovation – including virtually all MEF countries and a few new entrants to the clean energy R&D club – likewise agreed to double their clean energy R&D over five years. In both cases, many countries failed to deliver on their commitments, but they bore no adverse consequences. Securing agreement among the club to impose carbon tariffs on those falling short on their R&D commitments, alongside a failure to tax carbon emissions, may increase the likelihood of greater spending on these technologies.

Third, the eventual deployment of DAC and SAI technologies may influence how countries engage with each other on the potential application of carbon tariffs. For example, suppose that a country opts to pursue aggressive deployment of DAC as a part of implementing a net-zero emissions goal. If this country can credibly demonstrate that its economy-wide emissions are zero on net, then it may argue that its manufactured exports should not be subject to carbon tariffs in other economies because they originate from a net-zero economy. Likewise, a country may argue that its deployment of SAI offsets the damages associated with the emissions that still occur in its economy. In this case, they could argue that their economy is climate-neutral, and thus their manufactured exports merit exceptions under carbon tariffs. The prospect of either scenario could create stronger incentives and greater political will for DAC and SAI innovation spending.

The potential integration of NGCRT goals into climate clubs, potentially alongside primary mitigation measures like CBAMs, shows a potential pathway to increase R&D spending as well as deployment of the technologies. Far from being a new idea, the linkage of mitigation and technological innovation has been present since the earliest discussions of the Kyoto Accord. The present paper builds on these earlier works by establishing a clear pathway and structure for an R&D-focused climate club. We find that, at present trends, R&D spending on NGCRTs is insufficient to create the technological readiness to have these tools deployed to limit the risk of climate change, in the event that mitigation efforts fall short of what is necessary to limit global temperature rise to 1.5 or 2°C. We put forward a model of supply and demand for subsidies and regulations, and find that political economy considerations at the national level generate barriers to optimal investments. Climate clubs offer a potential solution to harness and overcome those barriers.

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