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Technologies for a Stable Future Climate

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Executive Summary

Technological progress has played a large role in bringing about anthropogenic climate change. That fact notwithstanding, we will have to rely upon technological progress to help solve the climate problem too. Technology will have a significant role to play in both mitigation and adaptation: the two most appropriate pillars of climate change policy. But mitigation and adaptation will most likely not be enough to avoid all climatic harms. In order to meet our climate goals, we will almost certainly have to look beyond mitigation and adaptation towards a third pillar of policy – negative emissions technologies – and perhaps even towards a fourth – solar radiation management. The point of this brief is to shed some light on specific technologies that are relevant to each of the four potential policy responses to climate change.

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Introduction

Across the past couple of centuries, advancements in technology have aided impressive human progress along many metrics. For example, the average individual born in the United Kingdom in 1850 had a life expectancy of about 40 years; today, that number is above 80.[1] Or consider agricultural output as an example. Average output for a hectare of land in the UK in 1850 was around 2 tons (depending upon the crop); today, each hectare of land can produce somewhere between 5 and 8 tons of food. Even greater progress is shown in energy output. In 1850, we as a global community produced about 7 terawatt-hours of energy; today, global energy output is 20 times higher.

The vast majority of this progress has been due to advancements in technology. Unfortunately, in making such unprecedented technological advancements, we have simultaneously engaged in environmental degradation on a scale never before seen. Since the industrial revolution, we have emitted over 600 billion tons of carbon.[2] This has resulted in the atmospheric concentration of carbon dioxide rising from 275 ppm to a concentration of over 400 ppm today.[3] Accompanying this increase in atmospheric concentration of carbon dioxide has been an increase in global surface temperature as well. On average, global surface temperature has risen by nearly a full degree Celsius (the equivalent of roughly 1.6 degrees F) since the industrial revolution.[4] And these increases in atmospheric concentrations of greenhouse gases and global surface temperature are bringing about unprecedented changes to our global climate, changes that will carry with them severe climatic harms for both present and future generations.

Fortunately for both present and future generations, we have the Paris Agreement. Nearly two years ago, 195 signatories representing almost every person on the globe made a collective commitment to limit warming to 2 degrees Celsius and to make serious efforts to keep warming below 1.5 degrees Celsius.[5] Unfortunately, given current national pledges, Paris would be insufficient to limit warming to below 2 degrees Celsius. Pledges from national governments around the world are going to have to get more ambitious, and we are going to have to hope the "pledge and review" process proves successful.[6] Still, Paris represents a great achievement in international collaboration, and the flexibility built into the agreement provides a good framework from which to address climate change in the near and distant future.

There have traditionally been two main categories of policy available for fighting climate change: mitigation and adaptation. Mitigation refers to a net reduction in our emissions of greenhouse gases (achieved through both reducing emissions at their source and enhancing/protecting natural

[1] https://ourworldindata.org/life-expectancy/
[2] http://www.trillionthtonne.org/
[3] https://www.co2.earth/annual-ghg-index-aggi
[4] https://data.giss.nasa.gov/gistemp/
[5] http://unfccc.int/paris_agreement/items/9485.php
[6] http://climateparis.org/pledge-and-review

greenhouse-gas sinks),[7] whereas adaptation refers to anticipating adverse climatic effects that aren't or can't be prevented and taking appropriate measures to minimize the expected harms. It is generally recognized that mitigation and adaptation are our two best policy responses to anthropogenic climate change. But, with each year that passes, it is becoming clearer and clearer that they alone may prove insufficient to avoid many of the harmful effects of delayed action.

Over the past decade, there has been increased discussion around two other potential pillars of climate policy: negative emission technologies (NETs) and solar radiation management (SRM). NETs refer to different ways in which we could actually suck greenhouse gases out of the atmosphere, whereas SRM refers to different proposals that would all reflect a certain amount of incoming solar radiation, thus limiting global warming. Again, mitigation and adaptation should be our primary focus, but there is almost necessarily a large role for NETs to play if we want to limit warming to 2 degrees, and there may even come a point in the future in which SRM technologies are seriously considered. The point of this brief is to shed some light on specific technologies that are relevant to each of the four potential policy responses to climate change.

Mitigation

There may have been a time in the recent past in which we could have perhaps hit the temperature goals outlined in the Paris Agreement through reduced energy consumption alone. However, a rapidly growing population coupled with an increase in demand for energy in developing economies means that reduced energy consumption is no longer sufficient to limit dangerous temperature rise. Energy output is going to have to increase, and it is going to have to increase while associated emissions fall. The only way for this to happen is through the development and dispersion of cleaner, more renewable technologies. And one of the most promising technologies currently available that is capable of both allowing energy output to increase while having emissions fall is solar energy.

Solar energy technologies generally fall into two main categories: Concentrating Solar Power (CSP) and Photovoltaics (PV). CSP relies upon sophisticated mirrors and lenses to concentrate solar radiation at a fixed point, where it uses this concentrated solar radiation to produce electricity through more traditional steam-driven turbines. PV, on the other hand, converts solar radiation directly to electrical current using a photovoltaic cell.

Despite its rapid growth, solar energy currently only makes up about 1% of global energy supply. There are reasons for this. First, both CSP and PV require significant upfront investments. Second, both CSP and PV have difficulties in consistently providing energy. At night time or on significantly cloudy days, supply of energy is limited, often requiring a more conventional backup energy supply. This problem of fluctuating energy production is somewhat mitigated by two factors. First, energy demands generally peak around midday, a time at which solar energy performs the best. Second, our ability to store the energy solar systems produce is improving, as evinced by Elon Musk's installation of a 100-megawatt storage facility in Australia – a feat that has been promised to take no more than 100 days' time.[8]

[7] http://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_summary-for-policymakers.pdf

[8] https://www.bloomberg.com/news/articles/2017-09-29/musk-s-100-day-race-to-biggest-battery-starts-in-south-australia

There are a number of reasons to be optimistic about the role for solar energy in the near and distant future. First, solar energy's potential is unparalleled. PV alone has the technical potential to deliver 1.5 to 50 times the projected demand for energy in 2050.[9] Second, solar energy's carbon footprint is miniscule in comparison to conventional fossil fuels. For instance, the median CO2 equivalent lifecycle emissions from a PV utility is a mere 17% of that from a coal-fired power plant.[10] And one of the major attractions of solar energy is its ability to supply electricity to remote locations where the energy grid has yet to reach.

In 2010 the International Energy Agency (IEA) predicted that PV alone could account for up to 11% of global energy supply by 2050.[11] But there are reasons to think the IEA prediction is significantly underestimating solar's potential. For instance, between the years 1998 and 2015, the IEA regularly predicted annual growth of the cumulative installed capacity of PV on the order of 16-30%, whereas the *actual* growth the technology achieved averaged out to 38% per year. Relying upon these more optimistic numbers, some researchers predict solar PV alone could account for 30-50% of global electricity supply by 2050, making it the dominant energy technology.[12] But this optimistic prediction about the future role of solar energy is anything but a guarantee. It is highly unlikely that solar technologies will experience the kind of growth needed to hit our warming targets without appropriate carbon pricing and other significant policy measures.[13]

In sum, the mitigation challenge for 2 degrees Celsius is daunting, but not impossible. It will require great upscaling of solar technologies. But it should be said that solar energy is only one horse in the renewable energy race. Renewable energy refers to a broad category of technologies comprising not only solar, but also bioenergy, geothermal energy, hydropower, ocean energy, and wind energy. There will most likely be an expanding role for each of these technologies as our energy portfolio broadens and becomes more decarbonized across the next century. But, to repeat, such upscaling won't happen autonomously -- it will require suitable policy to create the appropriate incentives for research and development.

Adaptation

Even if we engage in significant mitigation efforts, and even if we are successful in reducing our emissions close to zero across the next century, there will still be significant harms to both human and natural systems due to climate change. This is due both to the inertia of the climate system – the fact that global temperatures will continue to rise even after we reduce our emissions – and the long lifespan of atmospheric carbon dioxide – most carbon dioxide emitted into the atmosphere is absorbed by the oceans within a couple hundred years, but some molecules can remain the atmosphere for thousands of years.[14] There is, of course, a strong relation between mitigation and adaptation. The less we engage in mitigation, the more heavily we will have to engage in adaptation measures. And, vice versa, the more aggressively we mitigate our emissions now, the less adaptation there will have to be in the future. But again, it is impossible at this point to avoid all of the harms of climate change through mitigation alone.

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9 https://www.nature.com/articles/nenergy2017140
10 https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_annex-iii.pdf
11 http://www.iea.org/publications/freepublications/publication/pv_roadmap_foldout.pdf
12 https://www.nature.com/articles/nenergy2017140
13 https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_annex-iii.pdf
14 https://www.theguardian.com/environment/2012/jan/16/greenhouse-gases-remain-air

This is why the second main pillar of climate policy is that of adaptation: taking appropriate measures to reduce the climatic harms associated with any given amount of climate change. Typical adaptation proposals can be simple and straightforward. Take adaptation to rising sea levels, for example. The UN estimates that our current emissions trajectory has us on a path towards a warming of 3 degrees Celsius.[15] A warming of 3 degrees Celsius could displace hundreds of millions of people living in cities like Miami, Shanghai, Rio de Janeiro, and Osaka.[16] Through building and reinforcing seawalls, elevating roadways, or raising the height of dykes, we can adapt to some (though, not all) change in sea-level rise.

But some adaptation proposals are more bombastic. Climate change will also have significant effects on different plant and animal species and there are ways that we can help or hinder these species adapt to the coming changes. For example, certain mosquitoes – such as *Aedes aegypti* – will be able to thrive in seasons and areas where they previously could not have.[17] The *Aedes aegypti* mosquito is the primary driver of various viral diseases. This expansion of suitable environments for the mosquito may also carry with it adverse effects on human health, such as an increased risk of outbreaks of Dengue – a disease that, according to the World Health Organization, is infecting close to 400 million people per year, causing severe flu-like symptoms and even death.[18]

There are a number of different ways to control the populations of *Aedes aegypti* mosquitoes, such as the use of chemical insecticides to target adults or the use of “artificial breeding grounds” that are stocked with larvae-eating fish. However, there has been increasing attention and even a number of small field trials focusing on genetically engineering the problem away.[19]

Through the use of cutting-edge gene editing techniques, scientists can inject mosquito larvae with “lethal genes.” These lethal genes would make it impossible for the offspring of mosquitoes carrying such genes to survive. By releasing large numbers of (non-biting) male mosquitoes carrying these lab-injected lethal genes and having them mate with wild females, we could dramatically reduce mosquito populations. Field trails in Brazil, for example, reduced populations by as much as 82% in 8 months.[20] Intuitively, a significant reduction in mosquito populations should radically reduce instances of the viral diseases they transmit.

But there are serious questions that remain. First, the relation between mosquito population and instances of infection is not perfect, nor perfectly understood. It may be that a reduction of only 80 or 90% of a population will prove insufficient to eliminate the spread of certain viruses.[21] And, perhaps more importantly, there are always risks associated with genetic manipulation. What if the gene alteration makes the mosquitoes more aggressive or immune to other environmental controls? What about the negative side-effects we

15 https://www.unenvironment.org/resources/emissions-gap-report

16 https://www.theguardian.com/cities/2017/nov/03/miami-shanghai-3c-warming-cities-underwater

17 http://www.sciencedirect.com/science/article/pii/S2352396416301335

18 http://www.who.int/mediacentre/factsheets/fs117/en/

19 https://www.scientificamerican.com/article/genetically-engineered-mosquitoes/

20 https://www.theatlantic.com/technology/archive/2016/04/genetically-modified-mosquitoes-zika/479793/

21 https://www.theatlantic.com/technology/archive/2016/04/genetically-modified-mosquitoes-zika/479793/

are not yet aware of – so-called, "unknown unknowns?" And, finally, there are ethical concerns relating to the intentional killing off of an entire species. Are we permitted to intentionally eliminate a species – a species that has developed over the past 80 million years? Some might think this a perfect instantiation of hubris; of our species overstepping our proper domain.

There is undoubtedly a role for technology to play when it comes to adapting to climate change. Whether or not that will include genetically modifying plant and animal species is still uncertain. Though, whether or not we choose to rely upon some of these more aggressive technological interventions will almost certainly be influenced by the effort we put into curbing climate change in the first place.

Negative Emissions

A perhaps necessary third pillar of climate change policy is that of negative emissions technologies. Negative emissions technologies (NETs) support conventional mitigation by removing carbon from the atmosphere. However, particular NETs remove carbon in very different ways, raising the prospect of correspondingly different potential benefits, costs, and risks.

One option is Bioenergy with Carbon Capture and Storage (BECCS), which removes atmospheric carbon through the growth of biomass, which is then combusted to produce power, and carbon capture technology is then used to prevent combustion from re-releasing carbon. A second, more familiar option is Afforestation and Reforestation (AR), an ancient technology. A third group of options, classified as Enhanced Weathering (EW), increase the carbon storage of soils or the sea via the dispersal of crushed carbonate or silicate materials. A fourth option is Ocean Fertilization (OF), using iron particles to increase the drawdown of CO2 into the ocean. A fifth option is Soil Carbon Sequestration (SCS), involving restoration of soils previously degraded by agricultural production. And sixth, there are Direct Air Capture (DAC) techniques, which directly remove carbon from the atmosphere and sequester it underground.
With the exception of OF, each of these options is now considered to have significant carbon removal potential. For instance, BECCS and DAC may remove between 0.5-5 gigatones of CO2 per year if deployed at sufficient scales, depending upon how much geological storage is available. AR may remove between 0.5-3.6 gigatones of carbon per year, SCS may achieve between 3-6 gigatones per year, and EW techniques may achieve between 2-4 gigatones per year. To put these figures into perspective, the annual emissions of the USA are around 1.5 gigatones per year, while China's are now around 2.7.[22]

However, upscaling most of these techniques presents significant challenges. In some cases, there is doubt about whether upscaling will even be possible, given the estimated costs of doing so, and the resource requirements. This has been particularly concerning in the case of BECCS, which has very large land requirements and may compete with agriculture for arable land, pushing up food prices and further diminishing planetary biodiversity. EW at very large scales would require the creation of a mineral extraction industry larger than all current mining activity combined. DAC requires cheap and abundant sources of renewable energy, along with ample geological reservoirs – a problem shared with BECCS. Another storage-based problem with CCS technologies such as BECCS and DAC is with the permanence of carbon stored in geological reservoirs, along with the potential for such actions to trigger seismic events, or contaminate aquifers.

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[22] https://www.earth-syst-sci-data.net/8/605/2016/essd-8-605-2016.pdf

Public consultation is clearly important for any such proposals. Along with conventional mitigation technologies, the sites chosen for NETs may also be contested by local communities and others who do not wish to live next to them. This seems to be especially important for proposed CCS sites, which have already proved to be controversial in some places. For instance, anti-CCS protests in Germany have likened carbon storage to the dumping of nuclear waste.

Other options may be more benign, and may even provide additional benefits. AR could increase biodiversity, and could produce other social, cultural and economic co-benefits associated with forests. And SCS increases soil fertility, improving agricultural output, reducing pollution, and improving soil, water, and air quality. More impressive still, SCS is very inexpensive. Indeed, it may even be cost-negative.[23]

Like renewables, NETs will not be capable of achieving large-scale carbon removal without the right policy incentives for research, development, and implementation. NETs currently feature prominently in emissions scenarios consistent with the Paris goals. This is especially so for the more stringent 1.5 degree Celsius target, which is now seemingly impossible without NETs. But even for limiting warming to 2 degrees Celsius by the end of the century, NETs are very likely to be essential, given the political and economic difficulties of rapidly phasing out fossil fuels. Thus, NETs are at best complements to mitigation technologies such as wind and solar, rather than direct replacements.

[23] http://www.interfacecutthefluff.com/wp-content/uploads/2012/09/Stranded-Carbon-Assets-and-NETs-06.02.15.pdf

Solar Radiation Management

In addition to reducing our emissions, adapting to climatic changes, and deploying NETs, there is a fourth possible response to minimize the expected harm from a changing climate. By reducing the amount of solar radiation that makes it to the earth's surface or by increasing the amount of solar radiation that is reflected back out into space, we can limit the effect of the heat-trapping gasses within the atmosphere. There are a number of different solar radiation management (SRM) proposals, which range from the quotidian to the more grandiose.

Towards the more quotidian end of the range is what is known as "cool roof" technology. By painting roof materials in lighter, more heat-reflecting colors, we could enhance the reflectivity of human settlements. This enhanced reflectivity of roof materials would increase the amount of radiation that is sent back out towards space as opposed to being absorbed by heat-trapping darker materials. Of course, the effectiveness of this proposal is limited significantly due to the small surface area of the globe to which it could actually be applied.[24]

Towards the more grandiose end of the spectrum lies the proposal to place mirrors in low-earth orbit. Once in orbit, these mirrors could deflect solar radiation before it reaches the lower atmosphere. The cooling potential of such a proposal is, theoretically, immense. Depending upon the number and positioning of the mirrors, we could potentially deflect significant portions of incoming solar radiation. Of course, there are a number of side-effects that would accompany significant

[24] Royal Society, Geoengineering the Climate: Science, Governance and Uncertainty, 25.

deflection of incoming solar radiation, and the cost of such a project is essentially prohibitive.[25]

Somewhere between the quotidian proposal of painting our roofs white and the grandiose proposal of putting mirrors into orbit – though, probably closer to the grandiose – lies the technology known as stratospheric aerosol injection. By injecting tiny particles known as aerosols into the stratosphere, we could create a semi-permeable layer that would shield the earth from a small percentage of incoming sunlight. The less solar radiation that makes it to the earth's surface, the cooler the planet will be.

We have a relatively good idea about how such a technology would work because we have a natural analog in volcanoes. When volcanoes erupt, the often eject large quantities of sulfur into the lower atmosphere. For instance, the eruption of Mount Pinatubo in 1991 released somewhere between 10-20 million tons of sulfur, resulting in a global cooling effect of roughly 0.5 degrees C for the year. Injecting sulfate aerosols into the stratosphere would attempt to mimic this volcanic effect.

There are merits of such a "technological fix" to the problem of climate change. For one, the technology is relatively cheap compared to NETs and emissions mitigation – though, it is not by any means a perfect substitute for either. Second, if it were to be deployed, it would have a rapid effect, bringing about its associated cooling effect in a matter of weeks. But, like most "quick fixes," there are also serious worries associated with using such a technology. For starters, SRM technologies in general are merely masking the problem of warming, and are doing nothing to address the root problem of climate change. Negative side-effects associated with GHG emissions (like the acidification of our oceans) will continue unabated. Furthermore, controlling temperature and controlling climate are two very different things. The potential for stratospheric aerosol injection to cause disruption to important precipitation patterns even while it is adequately controlling temperature is well recognized. But perhaps the most concerning untoward side-effects are those we haven't yet discovered. Finally, the power that such a technology promises has significant political implications. How should such a power be regulated and distributed? Who should get to have a say over how such a technology is developed and deployed, and how should we distribute its potential benefits and burdens?

While SRM technologies like stratospheric aerosol injection seem to have the potential to alleviate some of the harms associated with climate change, the hope is that technologies within the other three pillars will prove sufficient, and that we will not need to engage in such a risky intervention into the climate system. Technological progress played a momentous role in bringing about the climate change problem, and it will have to play a momentous role in solving it as well.

[25] Royal Society, *Geoengineering the Climate: Science, Governance and Uncertainty*, 33.

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