Well Under 2 Degrees Celsius:

Fast Action Policies to Protect People and the Planet from Extreme Climate Change

Report of the Committee to Prevent Extreme Climate Change
Chairs:
V. Ramanathan, M. L. Molina, and D. Zaelke

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The Committee to Prevent Extreme Climate Change (CPECC) Co-Chairs:
V. Ramanathan[1], M.J. Molina[2], D. Zaelke[3]

[1] Scripps Institution of Oceanography, University of California, San Diego; [2] University of California, San Diego; [3] Institute for Governance & Sustainable Development

Committee Members:

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2. **Max Auffhammer**, University of California, Berkeley
3. **Paul Bledsoe**, Bledsoe & Associates, Washington
4. **Nathan Borgford-Parnell**, Climate and Clean Air Coalition, Geneva, Switzerland
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25. **Mark Thiemens**, University of California, San Diego
26. **David W. Titley**, Center for Solutions to Weather and Climate Risk, Pennsylvania State University, State College
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28. **Sachi Tripathi**, Indian Institute of Technology, Kanpur, India
29. **David Victor**, University of California, San Diego
30. **Yangyang Xu**, Texas A&M University, College Station

Summary for Global Leaders

Climate change is becoming an existential threat with warming in excess of 2°C within the next three decades and 4°C to 6°C within the next several decades. Warming of such magnitudes will expose as many as 75% of the world's population to deadly heat stress in addition to disrupting the climate and weather worldwide. Climate change is an urgent problem requiring urgent solutions. This report lays out urgent and practical solutions that are ready for implementation now, will deliver benefits in the next few critical decades, and places the world on a path to achieving the long-term targets of the Paris Agreement and near-term sustainable development goals. The approach consists of four building blocks and 3 levers to implement ten scalable solutions described in this report by a team of climate scientists, policy makers, social and behavioral scientists, political scientists, legal experts, diplomats, and military experts from around the world. These solutions will enable society to decarbonize the global energy system by 2050 through efficiency and renewables, drastically reduce short-lived climate pollutants, and stabilize the climate well below 2°C both in the near term (before 2050) and in the long term (post 2050). It will also reduce premature mortalities by tens of millions by 2050. As an insurance against policy lapses, mitigation delays and faster than projected climate changes, the solutions include an Atmospheric Carbon Extraction lever to remove CO_2 from the air. The amount of CO_2 that must be removed ranges from negligible, if the emissions of CO_2 from the energy system and SLCPs start to decrease by 2020 and carbon neutrality is achieved by 2050, to a staggering one trillion tons if the carbon lever is not pulled and emissions of climate pollutants continue to increase until 2030.

There are numerous living laboratories including 53 cities, many universities around the world, the state of California, and the nation of Sweden, who have embarked on a carbon neutral pathway. These laboratories have already created 8 million jobs in the clean energy industry; they have also shown that emissions of greenhouse gases and air pollutants can be decoupled from economic growth. Another favorable sign is that growth rates of worldwide carbon emissions have reduced from 2.9% per year during the first decade of this century to 1.3% from 2011 to 2014 and near zero growth rates during the last few years. The carbon emission curve is bending, but we have a long way to go and very little time for achieving carbon neutrality. We need institutions and enterprises that can accelerate this bending by scaling-up the solutions that are being proven in the living laboratories. We have less than a decade to put these solutions in place around the world to preserve nature and our quality of life for generations to come. The time is now.

Foreword

Transition to a Safe Anthropocene

We are clearly living in the Anthropocene–but then, what exactly is the Anthropocene? Even after thinking about that for many years, it still is not really clear to me. We have not yet found a clean, quasi-mathematical definition, which is also reflected by the extensive discussions about what starting point to assign. The idea of the Anthropocene–the age of Humans–all started from the simple idea that humanity has moved out of the Holocene and taken over from nature in shaping the face of the planet. But then it quickly becomes more abstract than one might think at first. And it becomes more complicated and extensive than only the scientific discourse: the Anthropocene concept is being used socially and culturally, for example in Art, and even in the context of what it means for religions. A fun question to consider is: how would the world look if we had never brought about the Anthropocene? What if our global society had grown in a way that was built from the beginning on renewable energy, on circular economies and on environmentally and societally low-impact consumption? We rarely think about such an alternate present, but maybe that can give us insight into how we can go about pursuing the noble goal of Sustainable Development–which in many ways is just as abstract as the Anthropocene, maybe even more so.

Climate change, one of the main indicators of the Anthropocene, is also an abstract concept for many – something "out there", in the future predicted by complicated climate models. But sadly, it is becoming less abstract with every passing year, given the mounting evidence ranging from temperature records to melting glaciers and ice sheets to sea level rise. And within the Anthropocene, climate change is intricately linked to many of the other grand challenges that we face. For example, rising temperatures and shifting precipitation patterns can affect agriculture, animal husbandry, and fisheries, severely threatening food security. Climate change is also a challenging justice issue, since the poor and future generations are mostly the ones who will be worst affected. Furthermore, climate change can lead to immigration and conflicts or wars over borders and resources like water, which in turn can hinder international efforts towards disarmament and peace. Even education is affected by climate change, since in farming regions where the changing climate is leading to water scarcity, we are already seeing children not going to school because they have to spend hours a day helping the families carry water from far away. And in turn, issues like hunger, poverty, lack of education and cultural and national conflicts make it challenging to put the attention needed into transitioning to technologies and lifestyles that cause less emissions of CO_2 and other climate-forcing gases and particles. A viscious cycle can develop within these connections.

The enormity of these challenges is reflected in the first impression I got in looking through this report: it just feels as though it's too much, far beyond the simple, elegant, mathematics-based solution that I would like as a scientist. Probably many people feel this way when they first look at a report like this. But don't give up too easily! After I looked through it again, and another time, then found it actually got very easy to go through and get an overview, not only of the problems, but also of the pathways to solving them. The report is very nicely structured, with its four building blocks, three levers, and 10 scalable solutions. It creates an appetite for reading it, and at the same time, provides valuable food for thought. And one thought I had while reading the report is that in many ways, it's like reading about the Anthropocene, due to how it all fits together and its grand scope–even though it's really about climate change, and not much is explicitly said about the Anthropocene. But it doesn't really need to be mentioned much explicitly, since it's woven in the fabric of the report: the authors did not have on blinders, looking only at climate change and its physical, chemical, and biological basis, but kept their eyes on the broader humanistic and societal aspects that are so central to the Anthropocene.

Nevertheless, despite the best effort of the authors to make an understandable and convincing case, I'm very concerned that humanity collectively will not be wise enough to follow the straightforward solutions to the extent laid out here. Of course, it's not black and white: doing some is better than doing none. And in the course of this, it will be very important to continue to lay out this scientific basis, so that we know better and better how to apply the full constructive talents of human beings (which, sadly, are harder to apply than the destructive talents). In order to do this well, we're going to have to learn to make better use of that great gift we are given: the human brain. Supplied with the right conditions, a healthy human brain can think much better than under challenging conditions and massive stress. We still need to learn new and better ways to think, to apply our minds–especially to be able to really get our minds around such massive issue as climate change in the larger context of the Anthropocene. This may require taking a serious step back, and becoming more reflective about how our own thoughts work. If we can learn to do this, then not only will we be able to forecast a safe Anthropocene, but perhaps even more importantly: a beautiful Anthropocene.

Paul Crutzen

Nobel Laureate, Chemistry 1995 (shared with Mario J. Molina and F. Sherwood Rowland)

* I thank Mark Lawrence for his collaboration in this foreward

High Level Summary

The Paris Agreement is an historic achievement. For the first time, effectively all nations have committed to limiting their greenhouse gas emissions and taking other actions to limit global temperature change. Specifically, 197 nations agreed to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels," and achieve carbon neutrality in the second half of this century.

The climate has already warmed by 1°C. The problem is running ahead of us, and under current trends we will likely reach 1.5°C in the next fifteen years and surpass the 2°C guardrail by mid-century with a 50% probability of reaching 4°C by end of century. Warming in excess of 3°C is likely to be a global catastrophe for three major reasons:

- Warming in the range of 3°C to 5°C is suggested as the threshold for several tipping points in the physical and geochemical systems; a warming of about 3°C has a probability of over 40% to cross over multiple tipping points, while a warming close to 5°C increases it to nearly 90%, compared with a baseline warming of less than 1.5°C, which has only just over a 10% probability of exceeding any tipping point.
- Health effects of such warming are emerging as a major if not dominant source of concern. Warming of 4°C or more will expose more than 70% of the population, i.e. about 7 billion by the end of the century, to deadly heat stress and expose about 2.4 billion to vector borne diseases such as Dengue, Chikengunya, and Zika virus among others.
- Ecologists and paleontologists have proposed that warming in excess of 3°C, accompanied by increased acidity of the oceans by the buildup of CO_2, can become a major causal factor for exposing more than 50% of all species to extinction. 20% of species are in danger of extinction now due to population, habitat destruction, and climate change.

The good news is that there may still be time to avert such catastrophic changes. The Paris Agreement and supporting climate policies must be strengthened substantially within the next five years to bend the emissions curve down faster, stabilize climate, and prevent catastrophic warming. To the extent those efforts fall short, societies and ecosystems will be forced to contend with substantial needs for adaptation—a burden that will fall disproportionately on the poorest three billion who are least responsible for causing the climate change problem.

Here we propose a policy roadmap with a realistic and reasonable chance of limiting global temperature to safe levels and preventing unmanageable climate change—an outline of specific science-based policy pathways that serve as the building blocks for a three-lever strategy that could limit warming to well under 2°C. The projections and the emission pathways proposed in this summary are based on a combination of published recommendations and new model simulations conducted by the authors of this study (see Figure 1). We have framed the plan in terms of four building blocks and three levers, which are implemented through 10 solutions.

The first building block would be fully implementing the nationally determined mitigation pledges under the Paris Agreement of the UN

Framework Convention on Climate Change (UNFCCC). In addition, several sister agreements that provide targeted and efficient mitigation must be strengthened. Sister agreements include the Kigali Amendment to the Montreal Protocol to phase down HFCs, efforts to address aviation emissions through the International Civil Aviation Organization (ICAO), maritime black carbon emissions through the International Maritime Organization (IMO), and the commitment by the eight countries of the Arctic Council to reduce black carbon emissions by up to 33%. There are many other complementary processes that have drawn attention to specific actions on climate change, such as the Group of 20 (G20), which has emphasized reform of fossil fuel subsidies, and the Climate and Clean Air Coalition (CCAC). HFC measures, for example, can avoid as much as 0.5°C of warming by 2100 through the mandatory global phasedown of HFC refrigerants within the next few decades, and substantially more through parallel efforts to improve energy efficiency of air conditioners and other cooling equipment potentially doubling this climate benefit.

For the second building block, numerous sub-national and city scale climate action plans have to be scaled up. One prominent example is California's Under 2 Coalition signed by over 177 jurisdictions from 37 countries in six continents covering a third of world economy. The goal of this Memorandum of Understanding is to catalyze efforts in many jurisdictions that are comparable with California's target of 40% reductions in CO_2 emissions by 2030 and 80% reductions by 2050—emission cuts that, if achieved globally, would be consistent with stopping warming at about 2°C above pre-industrial levels. Another prominent example is the climate action plans by over 52 cities and 65 businesses around the world aiming to cut emissions by 30% by 2030 and 80% to 100% by 2050. There are concerns that the carbon neutral goal will hinder economic progress; however, real world examples from California and Sweden since 2005 offer evidence that economic growth can be decoupled from carbon emissions and the data for CO_2 emissions and GDP reveal that growth in fact prospers with a green economy.

The third building block consists of two levers that we need to pull as hard as we can: one for drastically reducing emissions of short-lived climate pollutants (SLCPs) beginning now and completing by 2030, and the other for decarbonizing the global energy system by 2050 through efficiency and renewables. Pulling both levers simultaneously can keep global temperature rise below 2°C through the end of the century. If we bend the CO_2 emissions curve through decarbonization of the energy system such that global emissions peak in 2020 and decrease steadily thereafter until reaching zero in 2050, there is less than a 20% probability of exceeding 2°C. This call for bending the CO_2 curve by 2020 is one key way in which this report's proposal differs from the Paris Agreement and it is perhaps the most difficult task of all those envisioned here. Many cities and jurisdictions are already on this pathway, thus demonstrating its scalability. Achieving carbon neutrality and reducing emissions of SLCPs would also drastically reduce air pollution globally, including all major cities, thus saving millions of lives and over 100 million tons of crops lost to air pollution each year. In addition, these steps would provide clean energy access to the world's poorest three billion who are still forced to resort to 18th century technologies to meet basic needs such as cooking.

For the fourth and the final building block, we are adding a third lever, ACE (Atmospheric Carbon Extraction, also known as Carbon Dioxide Removal, or "CDR"). This lever is added as an insurance against surprises (due to policy lapses, mitigation delays, or non-linear climate changes) and would require development of scalable measures for removing the CO_2 already in the atmosphere. The amount of CO_2 that must be removed will range from negligible, if the emissions of CO_2 from the energy system and SLCPs start to decrease by 2020 and carbon

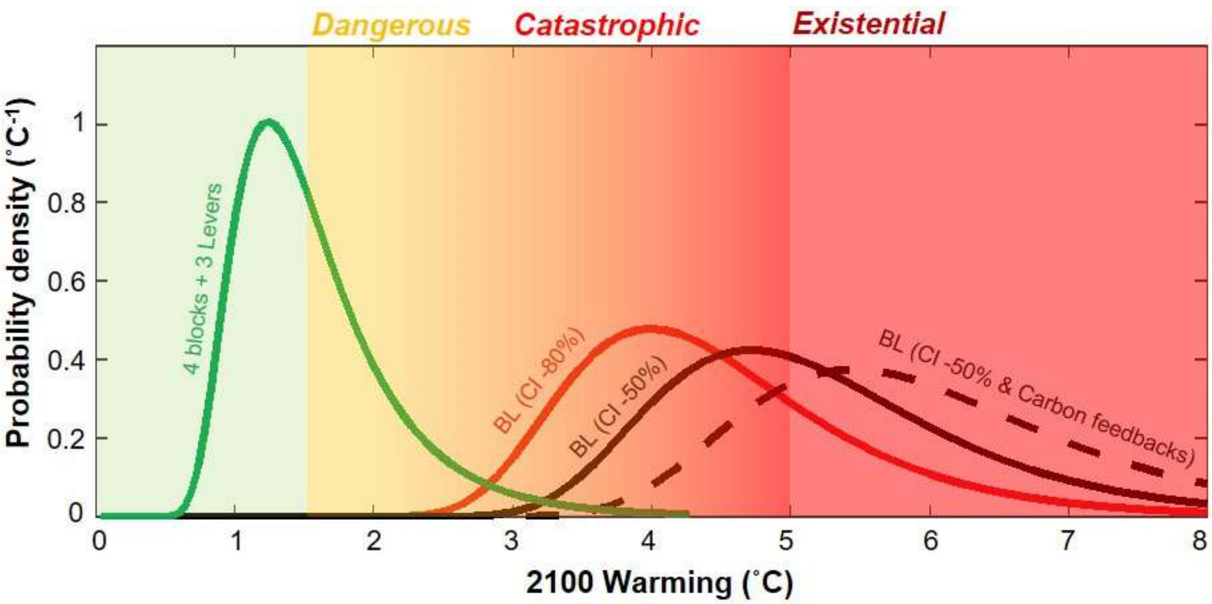

Figure 1: Projected warming for 4 different scenarios from pre-industrial to 2100 as adopted from Xu and Ramanathan (2017). The warming is given in terms of probability distribution instead of a single value, because of uncertainties in climate feedbacks, which could make the warming larger or smaller than the central value shown by the peak probability density value. The three curves on the right side indicated by BL (for baseline), denote projected warming in the absence of climate policies. The BL (CI-80%) is for the scenario for which the energy intensity (the ratio of energy use to economic output) of the economy decreases by 80% compared with its value for 2010. For the BL (CI-50%), the energy intensity decreases by only 50%. These scenarios bound the energy growth scenarios considered by IPCC–WGIII (2014). The right extreme curve, BL (CI-50% & C feedback), includes the carbon cycle feedback due to the warming caused by the BL (CI-50%) case. The carbon cycle feedback adopts IPCC recommended values for the reduction in CO_2 uptake by the oceans as a result of the warming; the release of CO_2 by melting permafrost; and the release of methane by wetlands.

The green curve adopts the 4 building blocks and the 3 levers proposed in this report. There are four mitigation steps:

1. Improve the energy efficiency and decrease the energy intensity of the economy by as much as 80% from its 2010 value. This step alone will decrease the warming by 0.9ºC (1.6ºF) by 2100.
2. Bend the Carbon emission curve further by switching to renewables before 2030 and achieving carbon neutrality in 3 decades. This step will decrease the warming by 1.5ºC (2.7ºF) by 2100.
3. Bend the Short-Lived Climate Pollutants curve, beginning 2020, following the actions California has demonstrated. This step will decrease the warming by as much as 1.2ºC (2.2ºF) by 2100.
4. In addition, extract as much as 1 trillion tons (about half of what we have emitted so far) from the atmosphere by 2100. This step will decrease the warming by as much as 0.3ºC to 0.6ºC (0.5ºF to 1ºF).

The 50% probable warming for the 4 scenarios are respectively from left to right: 1.4ºC (2.5ºF); 4.1ºC (7.4ºF); 5ºC (9ºF); 5.8ºC (10.4ºF). There is a 5% probability, the warming for the 4 scenarios can exceed respectively (left to right): 2.2ºC (4ºF); 5.9ºC (10.6ºF); 6.8ºC (12.2ºF); 7.7ºC (14ºF).

The risk categories shown at the top largely follow Xu and Ramanathan (2017) with slight modifications. Following IPCC and Xu and Ramanathan (2017), we denote warming in excess of 1.5°C as *Dangerous*. Following the burning embers diagram of IPCC as updated by Oneill et al. (2017), warming in excess of 3°C is denoted as *Catastrophic*. We invoke recent literature on health effects of warming >4°C, impacts on mass extinction of warming >5°C and projected collapse of natural systems for warming in excess of 3°C, to denote warming >5°C as exposing the global population to *Existential* threats.

neutrality is achieved by 2050, to a staggering one trillion tons, if CO_2 emissions continue to increase until 2030, and the carbon lever is not pulled until after 2030. This issue is raised because the NDCs (Nationally Determined Contributions) accompanying the Paris Agreement would allow CO_2 emissions to increase until 2030. We call on economists and experts in political and administrative systems to assess the feasibility and cost-effectiveness of reducing carbon and SLCPs emissions beginning in 2020 compared with delaying it by ten years and then being forced to pull the third lever to extract one trillion tons of CO_2.

The fast mitigation plan of requiring emissions reductions to begin by 2020, which means that many countries need to cut now, is urgently needed to limit the warming to well under 2°C. Climate change is not a linear problem. Instead, we are facing non-linear climate tipping points that can lead to self-reinforcing and cascading climate change impacts. Tipping points and self-reinforcing feedbacks are wild cards that are more likely with increased temperatures, and many of the potential abrupt climate shifts could happen as warming goes from 1.5°C in 15 years to 2°C by 2050, with the potential to push us well beyond the Paris Agreement goals.

Box 1: Aggressive mitigation actions have already begun

The four building blocks to be implemented through the 10 solutions may appear ambitious and formidable, but there are numerous living laboratories ranging from cities such as Stockholm to a large state like California, the sixth largest economy in the world, already embarked on mitigation actions such as 40% reductions in CO_2 emissions by 2030 and 50% to 80% reductions in SLCPs. CO_2 emissions curves in the U.S. and E.U. have already started to bend since 2005. G7 and G20 countries have agreed to accelerate access to renewables. The world now adds more renewable power capacity annually than it adds (net) capacity from all fossil fuels combined. By the end of 2015, there was enough installed renewable capacity in place to supply an estimated 23.7% of global electricity demand, with hydropower providing about 16.6%. In part due to these advances and innovations, worldwide CO_2 emissions, which grew at a rate of 2.9% per year from 2000 to 2011, slowed to 1.3% per year from 2012 to 2014 and was down at near zero growth for 2015 and into 2016. While these are encouraging signs, aggressive policies still needed to achieve carbon neutrality and climate stability by mid-century.

The progress of the past several years can be accelerated by immediately ending all fossil fuel subsidies and expanding incentives for renewables as has been called for by the G20 and others. Global energy efficiency gains are accelerating. In 2015, global energy intensity improved 1.8%, three times the annual average of the last decade and investment in energy efficiency increased by 6%. Quickly ratifying and implementing the Kigali Amendment to the Montreal Protocol to phase down HFCs while pursuing parallel efforts to improve affordable appliance efficiency by at least 30% is an immediate opportunity to drive global energy efficiency improvements even farther. There is also more hope for increased public support due to religious declarations—including the Pope's sustainability encyclical, 'Laudato Si', as well as inter-faith declarations on climate change—calling on their billions of followers to commit to a low-carbon future through renewable energy. Businesses are also stepping up. Twenty-five worldwide business networks speaking for 6.5 million companies from over 130 countries have pledged to help foster a low-carbon and climate resilient economy. We are not starting from a blank page. The climate change mitigation train has already left the station. What we must do is scale up what is already happening in many parts of the world.

Box 2: Climatological Pearl Harbor

Walter Munk, Centenarian Oceanographer

Walter Munk, fourth from the left

I recall a previous time when academics from three campuses of the University of California system joined forces to combat a global crisis.

It was 1940 and we were losing the war. My homeland, Austria, had been taken over by Germany in 1938 and the Axis-powers had overrun much of Europe. It appeared that U.S. military action was imminent, so I enlisted in the newly formed Ski Troops at Fort Lewis, WA.

Our Allies were desperate for help. We were shipping food and arms in merchant ships sailing in protected convoys, but German U-boats were very effective in sinking them. In response, the U.C. Regents directed President Sproul to form the University of California Division of War Research (UCDWR). Scripps Director Harald Sverdrup and recent SIO graduate Lt.(jg) Roger Revelle arranged for my discharge from the Army. I had served eighteen months and there had been no military action, so I was anxious to join the UC effort. One week later on 7 December 1941, the Japanese attacked Pearl Harbor; all Army discharges were canceled. My unit was dispatched to Papua New Guinea and virtually wiped out.

There was no initial grand solution on the horizon of how to respond to the German submarine attacks (like in the present challenge for Carbon Neutrality). As it turned out, many of today's concepts about operations on and under the sea go back to that early effort. I think back to this period with great satisfaction; we worked purposefully together to do a job that had to be done.

Three and a half years later on D-Day, 6 June 1944, at spring low tide, our troops came ashore on Omaha Beach.

The combined resources of our University have proven a formidable resource in times of national needs. I welcome this opportunity to participate in the effort towards protecting our planet, before we are faced with a climatological Pearl Harbor.

Where Do We Go from Here?

A massive effort will be needed to stop warming at 2°C, and time is of the essence. With unchecked business-as-usual emissions, global warming has a 50% likelihood of exceeding 4ºC and a 5% probability of exceeding 6ºC in this century, raising existential questions for most, but especially the poorest three billion people. A 4ºC warming is likely to expose as many as 75% of the global population to deadly heat. Dangerous to catastrophic impacts on the health of people including generations yet to be born, on the health of ecosystems, and on species extinction have emerged as major justifications for mitigating climate change well below 2ºC, although we must recognize that the uncertainties intrinsic in climate and social systems make it hard to pin down exactly the level of warming that will trigger possibly catastrophic impacts. To avoid these consequences, we must act now, and we must act fast and effectively. This report sets out a specific plan for reducing climate change in both the near- and long-term. With aggressive urgent actions, we can protect ourselves. Acting quickly to prevent catastrophic climate change by decarbonization will save millions of lives, trillions of dollars in economic costs, and massive suffering and dislocation to people around the world. This is a global security imperative, as it can avoid the migration and destabilization of entire societies and countries and reduce the likelihood of environmentally driven civil wars and other conflicts.

Staying well under 2°C will require a concerted global effort. We must address everything from our energy systems to our personal choices to reduce emissions to the greatest extent possible. We must redouble our efforts to invent, test, and perfect systems of governance so that the large measure of international cooperation needed to achieve these goals can be realized in practice. The health of people for generations to come and the health of ecosystems crucially depend on an energy revolution beginning now that will take us away from fossil fuels and toward the clean renewable energy sources of the future. It will be nearly impossible to obtain other critical social goals, including for example the UN agenda 2030 with the Sustainable Development Goals, if we do not make immediate and profound progress stabilizing climate, as we are outlining here.

10 Scalable Solutions to Bend the Curve

Achieving success will require the global mobilization of human, financial, and technical resources. For the global economy and society to achieve such rapid reductions in SLCPs by 2030 and carbon neutrality and climate stability by 2050, we will need multi-dimensional and multi-sectoral changes and modification, which are grouped under Ten Scalable Solutions in the table below. We have adapted the solutions with some modifications from the report: Bending the Curve written by fifty researchers from the University of California system. These solutions, which often overlap, were in turn distilled from numerous publications and reports.

Table 1: Ten Scalable Solutions

Science Solutions

1. Show that we can bend the warming curve immediately by reducing SLCPs, and long-term by replacing current fossil fuel energy systems with carbon neutral technologies.

Societal Transformation Solutions

2. Foster a global culture of climate action through coordinated public communication and education at local to global scales.
3. Build an alliance among science, religion, health care, and policy to change behavior and garner public support for drastic mitigation actions.

Governance Solutions

4. Build upon and strengthen the Paris Agreement. Strengthen sister agreements like the Montreal Protocol's Kigali Amendment to reduce HFCs.
5. Scale up subnational models of governance and collaboration around the world to embolden and energize national and international action. California's Under 2 Coalition and climate action plans by over 50 cities are prime examples.

Market- and Regulation-Based Solutions

6. Adopt market-based instruments to create efficient incentives for businesses and individuals to reduce CO_2 emissions.
7. Target direct regulatory measures—such as rebates and efficiency and renewable energy portfolio standards—for high emissions sectors not covered by market-based policies.

Technology-Based Solutions

8. Promote immediate widespread use of mature technologies such as photovoltaics, wind turbines, biogas, geothermal, batteries, hydrogen fuel cells, electric light-duty vehicles, and more efficient end-use devices, especially in lighting, air conditioning and other appliances, and industrial processes. Aggressively support and promote innovations to accelerate the complete electrification of energy and transportation systems and improve building efficiency.
9. Immediately make maximum use of available technologies combined with regulations to reduce methane emissions by 50%, reduce black carbon emissions by 90%, and eliminate high-GWP HFCs ahead of the schedule in the Kigali Amendment while fostering energy efficiency.

Atmospheric Carbon Extraction Solutions

10. Regenerate damaged natural ecosystems and restore soil organic carbon. Urgently expand research and development for atmospheric carbon extraction, along with CCUS.

* *Adapted from Ramanathan et al. (2016) and modified by authors of this report.*

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Technical Summary

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1. The Building Blocks Approach

The 2015 Paris Agreement, which went into effect November 2016, is a remarkable, historic achievement. For the first time, essentially all nations have committed to limit their greenhouse gas emissions and take other actions to limit global temperature and adapt to unavoidable climate change. Nations agreed to hold "the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels" and "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (UNFCCC, 2015). Nevertheless, the initial Paris Agreement has to be strengthened substantially within five years if we are to prevent catastrophic warming; current pledges place the world on track for up to 3.4°C by 2100 (UNEP, 2016b).

Until now, no specific policy roadmap exists that provides a realistic and reasonable chance of limiting global temperatures to safe levels and preventing unmanageable climate change. This report is our attempt to provide such a plan—an outline of specific solutions that serve as the building blocks for a comprehensive strategy for limiting the warming to well under 2°C and avoiding dangerous climate change (Figure 1).

The first building block is the full implementation of the nationally determined mitigation pledges under the Paris Agreement of the UN Framework Convention on Climate Change (UNFCCC) and strengthening global sister agreements, such as the Kigali Amendment to the Montreal Protocol to phase down HFCs, which can provide additional targeted, fast action mitigation at scale. For the second building block, numerous sub-national and city scale climate action plans have to be scaled up such as California's Under 2 Coalition signed by 177 jurisdictions from 37 countries on six continents. The third building block is targeted measures to reduce emissions of short-lived climate pollutants (SLCPs), beginning now and fully implemented by 2030, along with major measures to fully decarbonize the global economy, causing the overall emissions growth rate to stop in 2020-2030 and reach carbon neutrality by 2050. Such a deep decarbonization would require an energy revolution similar to the Industrial Revolution that was based on fossil fuels. The final building block includes scalable and reversible carbon dioxide (CO_2) removal measures, which can begin removing CO_2 already emitted into the atmosphere.

Such a plan is urgently needed. Climate change is not a linear problem. Instead, climate tipping points can lead to self-reinforcing, cascading climate change impacts (Lenton et al., 2008). Tipping points are more likely with increased temperatures, and many of the potential abrupt climate shifts could happen as warming goes from 1.5°C to 2°C, with the potential to push us well beyond the Paris Agreement goals (Drijfhout et al., 2015).

In order to avoid dangerous climate change, we must address these concerns. We must act now, and we must act fast. Reduction of SLCPs will result in fast, near-term reductions in warming, while present-day reductions of CO_2 will result in long-term climate benefits. This two-lever approach—aggressively cutting both SLCPs and CO_2–-will slow warming in the coming decades when it is most crucial to avoid impacts from climate change as well as maintain a safe climate many decades from now. To achieve the near-term goals, we have outlined solutions to be implemented immediately. These solutions to bend down the rising emissions curve and thus bend the warming trajectory curve follow a 2015 assessment by the University of California under its Carbon Neutrality Initiative (Ramanathan et al., 2016). The solutions are clustered into categories of social transformation, governance improvement, market- and regulation-based solutions, technological innovation and transformation, and natural and ecosystem management.

Additionally, we need to intensely investigate and pursue a third lever—ACE (Atmospheric Carbon Extraction). While many potential technologies exist, we do not know the extent to which they could be scaled up to remove the requisite amount of carbon from the atmosphere in order to achieve the Paris Agreement goals, and any delay in mitigation will demand increasing reliance on these technologies.

Yet, there is still hope. Humanity can come together, as we have done in the past, to collaborate towards a common goal. We have no choice but to tackle the challenge of climate change. We only have the choice of when and how: either now, through the ambitious plan outlined here, or later, through radical adaptation and societal transformations in response to an ever-deteriorating climate system that will unleash devastating impacts—some of which may be beyond our capacity to fully adapt to or reverse for thousands of years.

Figure 1: Four building blocks to achieve climate policy success.

2. Major Climate Disruptions: How Soon and How Fast?

"Without adequate mitigation and adaptation, climate change poses unacceptable risks to global public health."

(WHO, 2016)

The planet has already witnessed nearly 1°C of warming, and another 0.6°C of additional warming is currently stored in the ocean to be released over the next two to four decades, if climate warming emissions are not radically reduced during that time (IPCC, 2013). The impacts of this warming on extreme weather, droughts, and floods are being felt by society worldwide to the extent that many think of this no longer as climate change but as climate disruption. Consider the business as usual scenario:

15 years from now: In 15 years, planetary warming will reach 1.5°C above pre-industrial global mean temperature (Ramanathan and Xu, 2010; Shindell et al., 2012). This exceeds the 0.5°C to 1°C of warming during the Eemian period, 115,000–130,000 years ago, when sea-levels reached 6-9 meters (20-30 feet) higher than today (Hansen et al., 2016b). The impacts of this warming will affect us all yet will disproportionately affect the Earth's poorest three billion people, who are primarily subsistence farmers that still rely on 18th century technologies and have the least capacity to adapt (IPCC, 2014a; Dasgupta et al., 2015). They thus may be forced to resort to mass migration into city slums and push across international borders (U.S. DOD, 2015). The existential fate of low-lying small islands and coastal communities will also need to be addressed, as they are primarily vulnerable to sea-level rise, diminishing freshwater resources, and more intense storms. In addition, many depend on fisheries for protein, and these are likely to be affected by ocean acidification and climate change. Climate injustice could start causing visible regional and international conflicts. All of this will be exacerbated as the

risk of passing tipping points increases (Lenton et al., 2008).

30 years from now: By mid-century, warming is expected to exceed 2°C, which would be unprecedented with respect to historical records of at least the last one million years (IPCC, 2014c). Such a warming through this century could result in sea-level rise of as much as 2 meters by 2100, with greater sea-level rise to follow. A group of tipping points are clustered between 1.5°C and 2°C (Figure 2) (Drijfhout et al., 2015). The melting of most mountain glaciers, including those in the Tibetan-Himalayas, combined with mega-droughts, heat waves, storms, and floods, would adversely affect nearly everyone on the planet.

80 years from now: In 80 years, warming is expected to exceed 4°C, increasing the likelihood of irreversible and catastrophic change (World Bank, 2013b). 4ºC warming is likely to expose as much as 75% of the global population to deadly heat (Mora et al., 2017). The 2°C and 4°C values quoted above and in other reports, however, are merely the central values with a 50% probability of occurrence (Ramanathan and Feng, 2008). There is a 5% probability the warming could be as high as 6°C due to uncertainties in the magnitude of amplifying feedbacks (see Section 4). This in turn could lead to major disruptions to natural and social systems, threatening food security, water security, and national security and fundamentally affecting the great majority of the projected 11.2 billion inhabitants of the planet in 2100 (UN DESA, 2015).

3. What Are the Wild Cards for Climate Disruption?

Increasing the concentrations of greenhouse gases in the atmosphere increases radiative forcing (the difference between the amount of energy entering the atmosphere and leaving) and thus increases the global temperature (IPCC, 2013). However, climate wild cards exist that can alter the linear connection with warming and anthropogenic emissions by triggering abrupt changes in the climate (Lenton et al., 2008). Some of these wild cards have not been thoroughly captured by the models that policymakers rely on the most. These abrupt shifts are irreversible on a human time scale (<100 years) and will create a notable disruption to the climate system, condemning the world to warming beyond that which we have previously projected. These climate disruptions would divert resources from needed mitigation and upset mitigation strategies that we have already put in place.

1. Unmasking Aerosol Cooling: The first such wild card is the unmasking of an estimated 0.7°C (with an uncertainty range of 0.3°C to 1.2°C) of the warming in addition to mitigating other aerosol effects such as disrupting rainfall patterns, by reducing emissions of aerosols such as sulfates and nitrates as part of air pollution regulations (Wigley, 1991; Ramanathan and Feng, 2008). Aerosol air pollution is a major health hazard with massive costs to public health and society, including contributing to about 7 million deaths (from household and ambient exposure) each year (WHO, 2014). While some aerosols, such as black carbon and brown carbon, strongly absorb sunlight and warm the climate, others reflect sunlight back into space, which cools the climate (Ramanathan and Carmichael, 2008). The net impact of all manmade aerosols is negative, meaning that about 30% of the warming from greenhouse gases is being masked by co-emitted air pollution particles (Ramanathan and Carmichael, 2008). As we reduce greenhouse gas emissions and implement policies to eliminate air pollution, we

are also reducing the concentration of aerosols in the air. Aerosols last in the atmosphere for about a week, so if we eliminate air pollution without reducing emissions of the greenhouse gases, the unmasking alone would lead to an estimated 0.7°C of warming within a matter of decades (Ramanathan and Feng, 2008). We must eliminate all aerosol emissions due to their health effects, but we must simultaneously mitigate emissions of CO_2, other greenhouse gases, and black carbon and co-pollutants to avoid an abrupt and very large jump in the near-term warming beyond 2°C (Brasseur and Roeckner, 2005).

2. Tipping Points: It is likely that as we cross the 1.5°C to 2°C thresholds we will trigger so called "tipping points" for abrupt and nonlinear changes in the climate system with catastrophic consequences for humanity and the environment (Lenton, 2008; Drijfhout et al., 2015). Once the tipping points are passed, the resulting impacts will range in timescales from: disruption of monsoon systems (transition in a year), loss of sea ice (approximately a decade for transition), dieback of major forests (nearly half a century for transition), reorganization of ocean circulation (approximately a century for transition), to loss of ice sheets and subsequent sea-level rise (transition over hundreds of years) (Lenton et al., 2008). Regardless of timescale, once underway many of these changes would be irreversible (Lontzek et al., 2015). There is also a likelihood of crossing over multiple tipping points simultaneously. Warming of close to 3°C would subject the system to a 46% probability of crossing multiple tipping points, while warming of close to 5°C would increase the risk to 87% (Cai et al., 2016).

Recent modeling work shows a "cluster" of these tipping points could be triggered between 1.5°C and 2°C warming (Figure 2), including

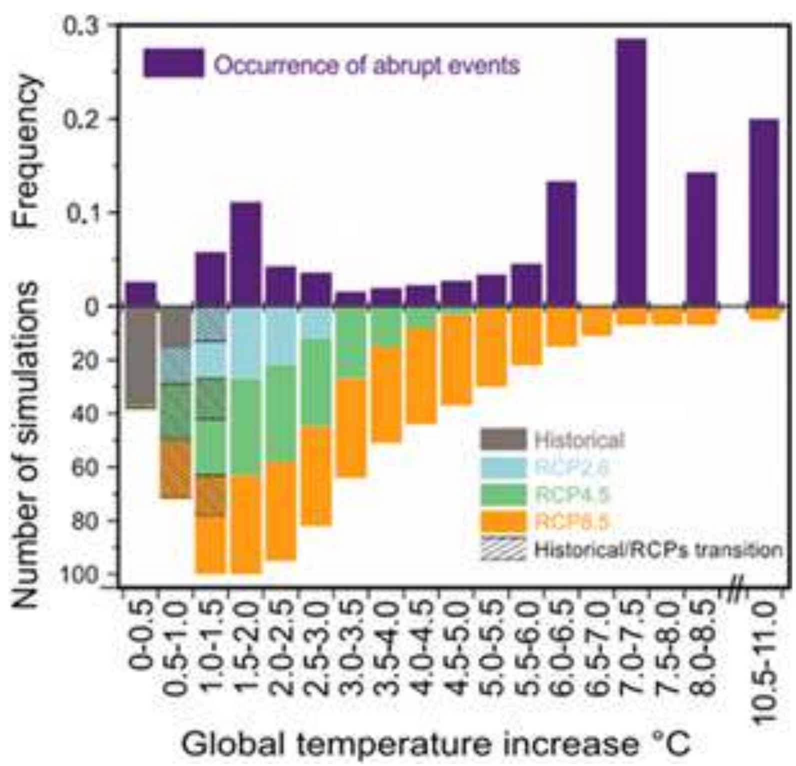

Figure 2: The occurrences of abrupt events (purple bars) show a cluster between 1.5°C and 2°C global temperature increase and again above 6°C (Drijfhout et al., 2015).

melting of land and sea ice and changes in high-latitude ocean circulation (deep convection) (Drijfhout et al., 2015). This is consistent with existing observations and understanding that the polar regions are particularly sensitive to global warming and have several potentially imminent tipping points. The Arctic is warming nearly twice as quickly as the global average, which makes the abrupt changes in the Arctic more likely at a lower level of global warming (IPCC, 2013). Similarly, the Himalayas are warming at roughly the same rate as the Arctic and are thus also more susceptible to incremental changes in temperature (UNEP-WMO, 2011). This gives further justification for limiting warming to no more than 1.5°C.

While all climate tipping points have the potential to rapidly destabilize climate, social, and economic systems, some are also self-amplifying feedbacks that once set in motion increase warming in such a way that they perpetuate yet even more warming. Declining Arctic sea ice, thawing permafrost, and the poleward migration of cloud systems are all examples of self-amplifying feedback mechanisms, where initial warming feeds upon itself to cause still more warming acting as a force multiplier (Schuur et al., 2015).

3. Unstable Melting of Marine-Based Sectors of Ice Sheets: During the Eemian period (115,000 to 130,000 years ago), the earth was approximately 0.5°C to 1°C warmer than present temperatures (Hansen et al., 2016b). This caused significant portions of the Greenland ice sheet and most of the marine-based portions of the west Antarctic ice sheet to melt, resulting in 6 to 9 meters of sea-level rise (Hansen et al., 2016b). This rise in sea-level is staggering, but this paleo-record along with the recent discovery of unstable melting of the Amundsen sector of west Antarctic and the melting of Greenland glaciers has raised concern about the probability of a 2-meter sea-level rise by the end of this century (Joughin et al., 2014; Rignot et al., 2014).

4. Himalayan and Tibetan Glaciers and the Asian Monsoon: More than 80% of the glaciers in this region are retreating (Liu et al., 2006; Neckel et al., 2014). A primary source of water for these glaciers is precipitation from the South Asian monsoon, which has decreased by about 7% during the last fifty years (Sinha et al., 2015). Many studies have attributed the weakening monsoon to the reduction of solar radiation, known as "global dimming," due to aerosol pollution (Ramanathan and Carmichael, 2008; Ramanathan et al., 2001). Further, the deposition of black carbon (from diesel combustion and biomass cooking among other sources) on glaciers and snowpack is decreasing the snow's albedo, causing surface warming and melting (Yasunari et al., 2010; Xu et al., 2016). The combination of warming by greenhouse gases, weakening monsoons due to aerosol dimming, and surface melting driven by black carbon deposition is creating an unstable situation for this so-called "Water Tower of Asia," which provides headwaters for most of the major river systems in Asia.

5. Loss of Arctic Summer Sea Ice: Arctic summer sea ice, which has already retreated by 40%, could disappear abruptly when the 1.5°C threshold is crossed in 15 years (Overland and Wang, 2013). Recent analysis indicates that the threshold for an ice-free Arctic may be slightly higher than 1.5°C, but that "the 2°C target may be insufficient to prevent an ice-free Arctic" (Screen and Williamson, 2017). As the Arctic warms, the sea-ice melts and exposes the darker ocean water beneath, which allows for greater absorption of solar radiation, increasing the ocean's temperature and acting as a force multiplier. Furthermore, the persistently warmer water hinders significant ice growth in winter, which can also impact the amount of sea ice that melts during the summer. The increased climate forcing from the loss of Arctic summer sea ice between 1979 and 2011, if averaged globally, is equivalent to 25% of the forcing from CO_2 over the same period (Pistone et al., 2014).

6. Collapse of Arctic Permafrost and Other Soil Carbon Stores: Permafrost is soil that stays below freezing temperatures for at least two consecutive years. Arctic permafrost contains three times as much carbon as there is in the atmosphere, and the thawing of the permafrost over land and subsea has the potential to release large quantities of this trapped carbon as both CO_2 and methane (Schuur et al., 2015; WB and ICCI, 2013). The thawing of permafrost will not necessarily result in an abrupt shift in the climate, but even a release of 1% of the carbon stored in permafrost could double current rates of warming (WB and ICCI, 2013). By the end of the century carbon release from permafrost could add an estimated 0.1°C to 0.3°C of warming and even greater and irreversible increases for centuries to come (Schuur et al., 2015). While the Arctic region contains the largest stores of soil carbon on earth, warming temperatures are also expected to deplete soil carbon stocks outside of permafrost regions. By 2050, increasing temperatures could trigger global soil carbon losses equivalent to 12 to 17% of expected emissions under a BAU scenario (Crowther et al., 2016).

7. Poleward Retreat of Extra-Tropical Cloud Systems: Though clouds enhance the greenhouse effect by trapping heat, they also reflect an enormous amount of solar radiation and nearly double the albedo of the planet. Their albedo effect dominates over their greenhouse effect, balancing out to a net cooling of about -25 Wm^{-2} (compared with the 1.6 Wm^{-2} forcing from CO_2 and total current forcing of 3 Wm^{-2}) (IPCC, 2013). More than two-thirds of this cooling is from the extensive extratropical cloud systems, which are found poleward of about 40° and are associated with jet streams and storm tracks (IPCC, 2013). Satellite data reveal that these cloud systems are retreating poleward in both hemispheres, which has led to an increase in the solar radiation reaching the extratropics, further amplifying warming (Bender et al., 2012; Norris et al., 2016). Thus, the Arctic warming is amplified by two large feedbacks: first is the decrease in albedo from the retreating sea ice, which is then further amplified by the decrease in albedo from the shrinking storm track clouds.

4. Dealing with Uncertainty and the Problem of the 'Fat Tail'

Climate change projections are quantified on their likelihoods of occurrence. Our understanding of the climate system is more refined in some areas than in others, but this does not detract from the overall assessments and projections for future changes to the climate. Climate models will continue to improve their treatment of many physical, dynamical, and chemical processes, particularly those dealing with clouds, aerosols, ice sheet dynamics, and the carbon cycle. But the complexity and interconnectedness of climate and human systems means that humanity will never fully dispel all uncertainties about the exact rate, magnitude, or implications of the changes we are affecting on our world through climate change.

Despite these uncertainties, the observed changes in our climate system and the ability of the climate models to simulate these changes and even predict the changes in many instances give us more than enough certainty to act. As warned by a team of retired admirals and generals from the U.S. in a report on climate change:

> *"Speaking as a soldier, we never have 100 percent certainty. If you wait until you have 100 percent certainty, something bad is going to happen on the battlefield."* (CNA, 2014)

However, the uncertainties cut both ways, and there is one type of climate uncertainly that should inspire us to act with incredible urgency: the uncertainty of the "fat tail." The feedbacks mentioned in the above section, and others not discussed here, give rise to a wide spread probability distribution of warming for a given forcing from increased CO_2 and other climate pollutants. For example, a doubling of CO_2 has a projected central value of warming of 3°C (IPCC, 2013). The 90% probability distribution, however, includes warming as low as

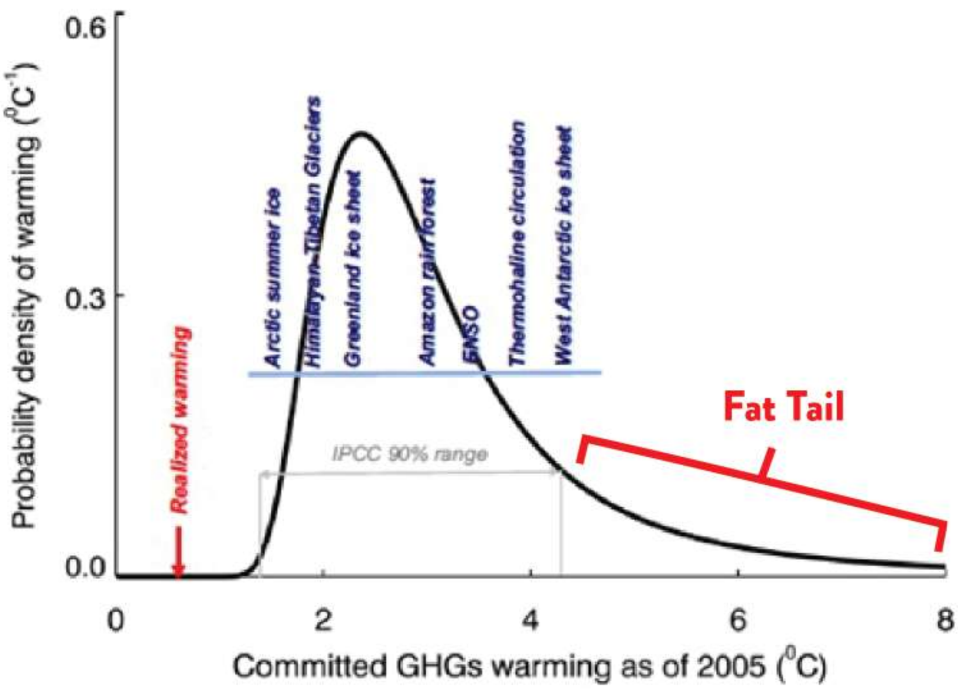

Figure 3: The figure shows a central estimate of warming of about 2°C with a 20% probability of being more than 3°C and a 5% chance of being more than 4°C. The results shown above were estimated by keeping the concentrations of GHGs fixed at their 2005 levels and zeroing out emissions of all human produced aerosols. Such a scenario could result if stringent air pollution regulations were enacted to clean the air of particulates immediately and emissions of GHGs were allowed to decrease slowly to zero by 2100. For the end of the century projection of 4°C warming, there is a non-trivial 1% to 5% probability the warming could be as large as 6°C to 8°C (Ramanathan and Feng, 2008).

2°C and as large as 4.5°C. On the lower side, there is a less than 1% chance that the warming seen under a doubling of CO_2 will be less than 1.5°C. However, on the upper limit, there is a 1% to 5% probability the warming could be as large as 6°C to 8ºC (Figure 3) (Ramanathan and Feng, 2008). Such low probability and high-risk probability distribution is referred to as "fat tail" (Weitzman, 2011). Warming magnitudes of 6°C or more would pose an existential threat to most of the global population and expose nearly 90% of the species to extinction (Mora et al., 2017; Barnosky, 2014).

In the context of warming and greenhouse gases, the "fat tail" indicates there exists a larger range of possible temperatures far warmer than 2°C compared to the range of possible temperatures cooler than 2°C. With each incremental increase in temperature, this central value gets shifted farther towards the warmer temperature range, and with it the "fat tail" shifts in the same manner, which means that even greater temperatures exist within the realm of possibility, even if it is a small chance.

Put in perspective, how many people would choose to buckle into an airplane seat if they knew there was as much as a 1 in 20 chance, or even a 1 in 100 chance, of the plane crashing? Most of us would undoubtedly stay home. The calculated odds of dying in a plane crash are closer to 1 in 11 million, which is why it is such a popular and safe form of transportation. If a 1 in 100 chance of dying in a plane crash would be enough to end air travel shouldn't it also be enough to end the use of fossil fuels and slow climate change?

5. What Are the Impacts on Social Systems?

Damages due to climate change have already been detected and, in the future, are expected to disproportionately affect the poorest and most vulnerable. Coastal archaeology provides us with some understanding of how past societies have responded to the impacts of rapid climate change and can serve as analogues for our present-day societal responses to anthropogenic global warming. A number of studies of coastal societies that existed more than 4,000 years ago indicate that there are climatic thresholds to cultural tolerances, and that abrupt, unpredictable climate change can have devastating consequences on human populations by disrupting food production, forcing repeated human dispersal, and causing conflict and realignment of social and trade networks, particularly for structurally complex societies (Kennett et al., 2007; Haberle and David, 2004; Liu, 2000).

Limiting global average temperature rise to well under 2°C, aiming for no more than 1.5°C, over pre-industrial temperatures will not eliminate the negative impacts of anthropogenic climate change, but it would significantly reduce the rate of temperature increase, the intensity of climate impacts, and the risks to society (Schleussner et al., 2016b). This is critical for both providing societies time to adapt to changes and slowing, if not avoiding, the worst predicted impacts of climate change. Actions that would bring immediate relief to the rapidly changing climate are vital for survival. With mounting evidence of past impacts, we still have a good deal to learn about how climate change will affect communities. What follows is a list of issues being discussed among social scientists, policy experts, and political leaders.

National and International Security: Climate change poses security risks "because it degrades living conditions, human security, and the ability of governments to meet the basic needs of their populations" (U.S. DOD, 2015). Climate change is a direct cause of resource conflicts in countries with weak capacities and governance challenges. The conflicts in Syria and Darfur are partially attributed to droughts that caused massive agriculture failures, which in turn led to mass displacements and migration (Kelley et al., 2015). One estimate suggests that sea-level rise of one meter could displace almost 50% of Bangladeshi citizens.

Sustainable Development: The 17 Sustainable Development Goals (SDGs) and their 169 targets strive to eliminate poverty and hunger, improve health, expand access to clean modern energy, protect the planet, and ensure all people enjoy peace and prosperity (UN, 2016). The current and near-term impacts of climate change will cause multiple complex impacts on human health, infrastructure, society, and the environment, and thereby threaten to undermine the success of the SDGs if not put them entirely out of reach. Climate change is a multiplier of the obstacles faced in achieving the SDGs.

For example, increased extreme weather events combined with reduced crop production due to climate change can put entire food systems at risk (Wheeler, 2015). This threatens the SDGs related to food security, health (through increased malnutrition), and poverty (due to losses of traditional livelihood). Agricultural failures can also lead to massive impacts on social systems (Kelley et al., 2015).

In 2015, extreme weather-related events were reported to have displaced just over 19 million people, with an average of approximately 25 million people displaced each year since 2008 (IDMC, 2016). While the impacts of extreme, individual climate-driven disasters are relatively clear, the "cumulative impacts from small, recurrent disasters over time can equal or even exceed those from larger catastrophes" (World Bank, 2013a). In addition to the direct impacts described above and the indirect impacts such as increased food prices and food insecurity, these smaller climate-related hazards tend to exacerbate other stressors, reinforce poverty, and compound the hardships endured by poor communities (Kreft et al., 2015).

Public Health: Between the millions of premature deaths resulting from fossil fuel combustion—directly from air pollution and indirectly from increases in climate change-related extremes such as heat waves, droughts, floods, and forest fires—there is good evidence that "without adequate mitigation and adaptation, climate change poses unacceptable risks to global public health" (WHO, 2016). Morbidity and mortality due to heat stress alone is now common all over the world, and extreme heat events are responsible for more deaths annually than hurricanes, lightning, tornadoes, floods, and earthquakes, combined (Luber and McGeehin, 2008). By end of century, climate change together with population growth and demographic change could lead to: 3 billion additional events of elderly people exposed to extreme heat annually; 1.4 billion additional events of people exposed to droughts; and 2 billion additional events of people exposed to extreme rainfall annually (Watts et al., 2015). A more recent study estimates that without mitigation nearly three-quarters of the global population will be exposed to deadly heat events by 2100 (Mora et al., 2017).

Climate Justice:

"We have to realize that a true ecological approach always becomes a social approach; it must integrate questions of justice in debates on the environment, to hear both the cry of the earth and the cry of the poor."

(Pope Francis, Laudato Si, 2015)

Roughly 50% of the climate warming pollution is from the wealthiest one billion of humanity while the poorest three billion contribute 5% or less (Dasgupta et al., 2015). Yet these poorest three billion will suffer the worst consequences of climate change since they are forced by poverty to rely on 18th century technologies for meeting basic needs such as cooking (Dasgupta et al., 2015). The World Bank estimates that more than 100 million people could be forced into extreme poverty within 15 years when the warming reaches 1.5°C (Hallegate et al., 2016). About 10% of the global population is at risk of forced displacement due to climate change. The impacts on mass migration, trafficking, and breakdown of social structure among the poorest three billion must be assessed urgently, and preventive measures must be put into place. The poorest three billion will be significantly more impacted by the climate change impacts occurring over the next 30 years than those in the long term, for the simple reason that they may not survive to see those long-term effects (Dasgupta et al., 2015). In this context, speed is essential for achieving climate justice, as justice delayed is justice denied.

Box 1: Health co-benefits of climate change mitigation policies

Well-designed policies to reduce the emissions of GHGs and the SLCP black carbon can also improve human health by reducing air pollution as well as increases in physical activity (through increased walking and cycling) and dietary change. A recent study of the sources of $PM_{2.5}$ worldwide suggests that 25% of urban ambient air pollution from $PM_{2.5}$ is contributed by traffic, 15% by industrial activities, 20% by domestic fuel burning, 22% from unspecified sources of human origin, and the remainder from dust and natural sources (Karagulian et al., 2015).

A growing number of studies have quantified the air pollution benefits of climate change mitigation policies. The recent report of the International Energy Agency projects that under a "central scenario," "premature deaths attributable to outdoor air pollution increase to 4.5 million in 2040 (from around 3 million today), while premature deaths due to household air pollution fall to 2.9 million (from 3.5 million today)" due to reducing use of solid biomass as a cooking fuel (IEA, 2016). Under a "Clean Air Scenario" maximizing deployment of existing air pollution reduction technologies, annual outdoor air pollution deaths declined to 2.8 million and deaths due to household air pollution to 1.3 million by 2040 with the largest benefits in developing economies, notably China and India (IEA, 2016). Although a 7% increase in investment is required between 2016 and 2040, amounting to about USD $5 trillion, these costs are offset by the resulting health and other co-benefits (IEA, 2016).

Policies (particularly in urban areas) to increase the uptake of low carbon transport, including petrol/electric hybrids and electric vehicles and investment in public transport, can reduce fine particulate air pollution and increased active travel (walking and cycling), bringing additional benefits of increased physical activity. The balance of health co-benefits depends on background levels of air pollution, physical activity patterns, and the risk of road traffic injuries. In the case of London, the health co-benefits are likely to result particularly from increased physical activity and greatly outweigh the increased risks of injury and death (Tainio et al., 2016). In a city like Delhi the benefits of reduced air pollution may be relatively larger. There is the potential to reduce costs to the health system due to common conditions related to sedentary lifestyle such as diabetes, heart disease, and stroke (Jarrett et al., 2012). The benefits of active travel also exceed the increased risks of air pollution exposure in all but the most heavily polluted cities. Better design of transport infrastructure can reduce injury risks and increase walking and cycling (Jarrett et al., 2012).

The food and agriculture sectors are major contributors to GHG emissions and are responsible for up to 30% of emissions if land use change is included (Flynn and Smith, 2010). They are also a major driver for land use and freshwater demands. At the same time, poor diets are responsible for a large disease burden worldwide including by increased risks of a range of common non-communicable diseases. A recent systematic review has shown how dietary change can potentially provide benefits for both the environment and health, particularly in Western countries where most studies have been located. The systematic review outlined 14 common dietary patterns, which aimed to be more sustainable than comparison diets, with resulting reductions as high as 70±80% of GHG emissions and land use, and 50% of water use (with medians of about 20±30% for these indicators across all studies) (Aleksandrowicz et al., 2016). The environmental benefits were generally proportional to the magnitude of reduction of livestock-based foods. Dietary shifts also yielded modest benefits in all-cause mortality risk (Aleksandrowicz et al., 2016).

6. How Much Time Do We Have to Protect Nature and Humanity?

At what warming level does climate change become catastrophic? Is it at 1.5°C, 2°C, 3°C, or 4°C? A correlated question is: How do we define "catastrophic"? Even a one-meter sea-level rise (which is assured given the current atmospheric concentrations of pollutant gases) would be catastrophic for small island nations like the Federated States of Micronesia and the Maldives and low-lying coastal nations such as Bangladesh (IPCC, 2013). The sort of multiyear drought that recently impacted California would be catastrophic for much of the poorest three billion (Dasgupta et al., 2015). Heat waves and floods that have become more frequent over the last few decades are already killing thousands in many nations, including in developed nations (Meehl and Tebaldi, 2004). We are fully aware of such limitations of defining "catastrophic."

In what follows, we will build upon the Paris Agreement and discuss the time we have left to mitigate climate change to well below 2°C. We assume this to mean limiting the warming to a range between 1.5°C to 2°C. In addition, we are making a proposal of "Well Under 2 Celsius." The climate forcing of CO_2 and all other anthropogenic greenhouse gases as of 2010, however, is 3 Wm^{-2}, which is sufficient to warm the planet by 2°C or more (Figure 3). We have not seen such a large warming, in large part due to two off-setting factors: the cooling by aerosols may have masked about 0.7°C of the warming and about 0.6°C is stored in the ocean to be released in the coming decades. If and when we clean the atmosphere of all particulate pollutants, the 0.7°C warming will be unmasked. So how can we keep the warming well under 2°C?

There is one way to get out of this quandary. Of the 3 Wm^{-2} greenhouse forcing, about 1.2 Wm^{-2} is from gases with atmospheric lifetimes of approximately one decade or less (methane, tropospheric ozone, and HFCs) (IPCC, 2013). These gases are collectively known as short-lived climate pollutants (SLCPs). In addition, black carbon, which has a lifetime of only one week, has a net positive forcing of 0.4 Wm^{-2} after accounting for the cooling effects of co-emitted organic carbon particles (IPCC, 2013).

The short atmospheric lifetimes of SLCPs means that reducing them will reduce their forcing within a decade. If we mitigate the emissions of these SLCPs making maximum use of available technologies, we can reduce their positive forcing by as much as 0.8 Wm^{-2} and reduce the warming by as much as 0.6°C by 2050 (Hu et al., 2013).

This could cut the rate of global average warming in half by 2050, and the rate of Arctic warming by two-thirds, as well as reduce total warming in the high-altitude Himalayan-Tibetan Plateau by at least half (UNEP-WMO, 2011; Shindell et al., 2012).

Beyond 2050, further warming can be mitigated by making the planet carbon neutral (net zero emissions of CO_2) but only if actions are taken by 2020 to aggressively reduce CO_2 emissions. The Paris Agreement, on the other hand, allows CO_2 emissions to increase until 2030 and decline afterwards. A substantial portion (20–40%) of emitted CO_2 remains in the atmosphere for centuries to millennia (Matthews and Caldiera, 2008). This long lifetime combined with ocean thermal inertia means that cutting CO_2 emissions will not produce considerable climate benefits for several decades (Solomon et al., 2009). As of 2010, we have emitted 2 trillion tons of CO_2.

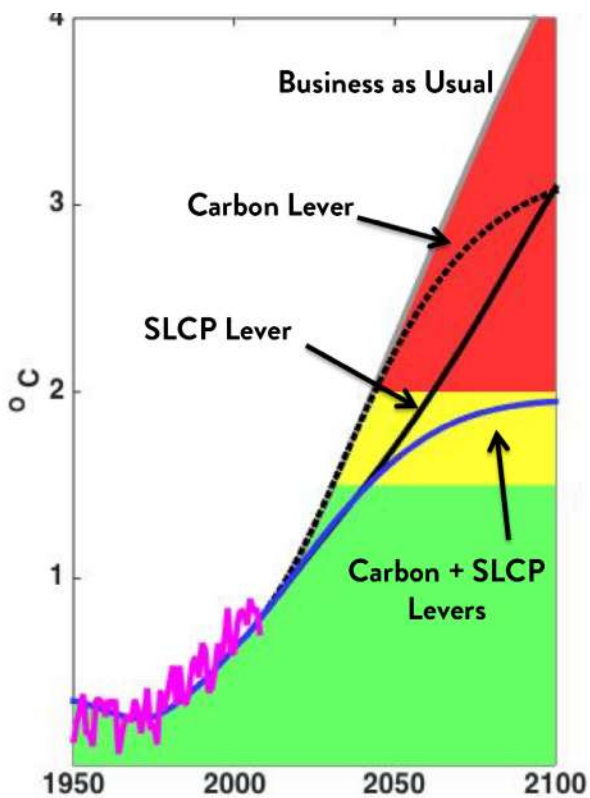

Figure 4: Possible warming trajectories under different mitigation strategies: BAU, mitigation of only CO_2 (Carbon Lever), mitigation of only SLCPs (SLCP Lever), and mitigation of both CO_2 and SLCPs (Carbon + SLCP Levers). The temperature estimates shown are anomalies relative to the 1900–1910 mean and are based on the central value of climate sensitivity. The purple line represents observations from 1900 to 2011 (Ramanathan and Xu, 2010 & Hu et al., 2013).

At BAU emission rates, we will have emitted the third trillionth ton by 2035 (IPCC, 2014c). That would commit the planet to 2°C warming by 2035 from CO_2 alone (assuming it will take about 40 years to reduce the emissions to zero from 2035), meaning that if we wait until 2035 to act, we will have already committed the planet to more than 2°C warming. If we continue with BAU until we witness 2°C warming in 2050, we will emit the fourth trillionth ton by 2055 (IPCC, 2014c). By then the warming would be locked in at more than 3°C. These estimates of warming are only 50% probability events. The 10% to 20% probability would project warming double the 50% probability warming values. The bottom line is that we must decarbonize as fast as possible.

In sum, long-lived CO_2 and SLCPs are key levers for slowing climate change that can and must both be pulled immediately to achieve our climate goals. The climate impact of each of the two levers operates on fundamentally different timescales. By mitigating the emissions of SLCPs by 2030 and by beginning the carbon neutrality pathway in 2030 and completing it by 2050, we may be able to bend down the warming curve to keep warming below 2°C throughout the rest of the century. However, Figure 4 shows only a 50% probability of achieving this goal. There is still a 10–20% probability of the warming exceeding 3°C by 2100. To decrease the probability of exceeding 2°C to less than 20%, we have to start on the carbon neutrality pathway by 2020, i.e., emissions of CO_2 begin to decrease by 2020. A 10-year delay in beginning carbon neutrality as envisioned in the Paris Agreement would necessitate the removal of as much as one trillion tons of CO_2 from the air during the second half of this century.

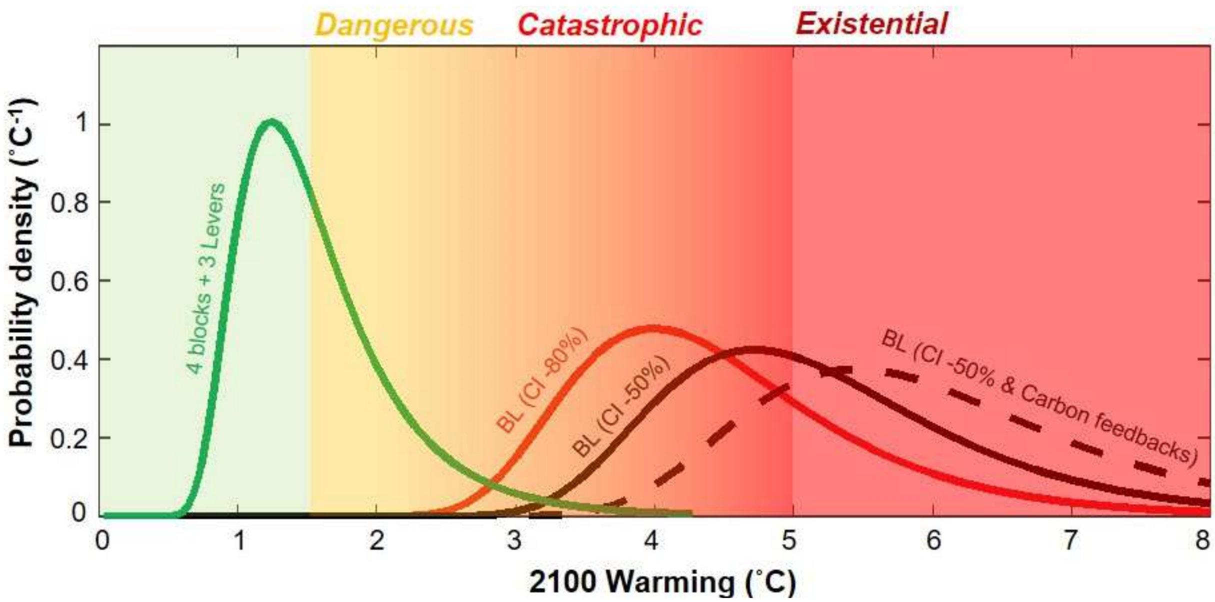

Figure 5: Projected warming for 4 different scenarios from pre-industrial to 2100 as adopted from Xu and Ramanathan (2017). The warming is given in terms of probability distribution instead of a single value, because of uncertainties in climate feedbacks, which could make the warming larger or smaller than the central value shown by the peak probability density value. The three curves on the right side indicated by BL (for baseline), denote projected warming in the absence of climate policies. The BL (CI-80%) is for the scenario for which the energy intensity (the ratio of energy use to economic output) of the economy decreases by 80% compared with its value for 2010. For the BL (CI-50%), the energy intensity decreases by only 50%. These scenarios bound the energy growth scenarios considered by IPCC–WGIII (2014). The right extreme curve, BL (CI-50% & C feedback), includes the carbon cycle feedback due to the warming caused by the BL (CI-50%) case. The carbon cycle feedback adopts IPCC recommended values for the reduction in CO_2 uptake by the oceans as a result of the warming; the release of CO_2 by melting permafrost; and the release of methane by wetlands.

The green curve adopts the 4 building blocks and the 3 levers proposed in this report. There are four mitigation steps:

1. Improve the energy efficiency and decrease the energy intensity of the economy by as much as 80% from its 2010 value. This step alone will decrease the warming by 0.9°C (1.6°F) by 2100.
2. Bend the Carbon emission curve further by switching to renewables before 2030 and achieving carbon neutrality in 3 decades. This step will decrease the warming by 1.5°C (2.7°F) by 2100.
3. Bend the Short-Lived Climate Pollutants curve, beginning 2020, following the actions California has demonstrated. This step will decrease the warming by as much as 1.2°C (2.2°F) by 2100.
4. In addition, extract as much as 1 trillion tons (about half of what we have emitted so far) from the atmosphere by 2100. This step will decrease the warming by as much as 0.3ºC to 0.6ºC (0.5ºF to 1ºF).

The 50% probable warming for the 4 scenarios are respectively from left to right: 1.4°C (2.5°F); 4.1°C (7.4°F); 5°C (9°F); 5.8°C (10.4°F). There is a 5% probability, the warming for the 4 scenarios can exceed respectively (left to right): 2.2°C (4°F); 5.9°C (10.6°F); 6.8°C (12.2°F); 7.7°C (14°F).

The risk categories shown at the top largely follow Xu and Ramanathan (2017) with slight modifications. Following IPCC and Xu and Ramanathan (2017), we denote warming in excess of 1.5°C as *Dangerous*. Following the burning embers diagram of IPCC as updated by Oneill et al. (2017), warming in excess of 3°C is denoted as *Catastrophic*. We invoke recent literature on health effects of warming >4°C, impacts on mass extinction of warming >5°C and projected collapse of natural systems for warming in excess of 3°C, to denote warming >5°C as exposing the global population to *Existential* threats.

7. The Two Lever Approach: What Do We Need to Do and When?

Bending the Curve: We need to bend the rising curve of projected emissions of pollutants. As explained earlier, we have two key levers to pull: the SLCP lever and the carbon lever. The SLCP lever is essential for slowing near-term warming (the next three decades), and slowing the self-amplifying feedbacks, especially in the Arctic. Both levers are essential for slowing long-term warming (beyond 2050) (Shoemaker et al., 2013; Bowerman et al., 2013). This two-lever strategy is also justified by ethical and equity considerations.

The SLCP lever: In addition to slowing the self-reinforcing feedbacks, the SLCP lever addresses the ethical/equity issue of intra-generational equity. This concerns primarily the fate of the poorest three billion who until now had very little to do with climate pollution. The poorest three billion are often the most vulnerable to the impacts of climate change and the least capable of adaptation (IPCC, 2014a; Dasgupta et al., 2015). As explained in the previous section, we need measures that can be deployed and scaled within a matter of years and provide climate relief within decades or less (Molina et al., 2009).

In 2011, the UNEP-WMO Assessment identified 16 technical and policy measures which, if deployed at scale by 2030, can reduce black carbon emissions by ~77% and methane emissions by ~38% (Table 3). Most of the control measures for reducing black carbon and methane can be implemented today with existing technologies and often with existing laws and institutions, including through enhancement and enforcement of existing air quality regulations. HFCs are now being phased down under the Montreal Protocol as a result of the landmark Kigali Amendment in 2016 (Box 2). The Montreal Protocol could potentially avoid up to 0.5°C by 2100 as the control mechanisms are strengthened in the next decade, and potentially avoid significantly more through parallel efforts to improve energy efficiency of air conditioners and other cooling equipment (Xu et al., 2013b; Shah et al., 2015; Zaelke et al., 2012).

Together, these SLCP measures would avoid up to 0.6°C of projected warming by 2050 and 1.2°C by 2100 (Ramanathan and Xu, 2010; Hu et al., 2013). SLCP measures would cut the rate of warming in 2050 in half, giving societies and natural systems—including glaciers, ecosystems such as coral reefs and the Amazon, managed agriculture, and rivers—urgently needed time to adapt to unavoidable changes (UNEP-WMO, 2011; Shindell et al., 2012).

In addition to climate benefits, reducing SLCPs provides strong collateral benefits for public health and food security. For example, black carbon is a component of aerosol particles, a harmful air pollutant, so the reduction of sources of particulate matter and black carbon will reduce their climate impact as well as improve air quality. Cutting emissions of SLCPs could save an estimated 2.4 million lives per year currently lost to outdoor air pollution and likely millions more from indoor air pollution. In addition, it would cut global crop losses by around 52 (30–140) million tons a year, which represents an increase of up to 4% of the total annual crop production (Shindell et al., 2012).

The Carbon Lever: The effects of CO_2 on climate and ecosystems last thousands of years, affecting generations yet to be born (IPCC, 2013; Solomon et al., 2009). Thus, the rationale for pulling this lever is based on intergenerational equity, which is at the core of the sustainability of nature and sustainability of humanity. It has been estimated that cumulative emission of 3.7 trillion tons of CO_2 (or one trillion tons of carbon) will result

Box 2: The Kigali Amendment to the Montreal Protocol – The SLCP Lever in Action

The 2016 Kigali Amendment to the Montreal Protocol will essentially eliminate the warming caused by HFCs, one of the six main greenhouse gases, using a treaty with the experience and expertise to ensure a fast, effective, and efficient phasedown. The Montreal Protocol fully implements the principle of 'common but differentiated responsibilities' by having developed countries undertake their control measures first and then pay the full incremental cost of compliance for developing countries through the Multilateral Fund. It is the only treaty in the world with universal membership, including for its four previous amendments.

Under the Kigali Amendment, most developed countries start in 2019 with a freeze in HFC consumption, which caps future growth, and an immediate 10% reduction. The progressive group of developing countries, which includes China, freeze in 2024, with India, the Gulf States, and a few other countries freezing in 2028 (UNEP, 2016a). The early action by developed countries and the ambitious group of developing countries ensures a fast market transition, which means that the transition of those in the last group almost certainly will be much faster than their formal date. Even on the original phase down schedule, the Kigali Amendment will avoid ~90% of the warming HFCs otherwise would have caused by 2100.

Historically, the market for new environmentally friendly substitutes has moved ahead of the Montreal Protocol control schedules, and recent studies calculate that countries can reduce their HFC emissions by as much as 99% by 2030 by simultaneously transitioning to already available low-GWP alternatives and super-efficient appliances. A simultaneous transition to super-efficient air conditioners could double the climate benefit of either action alone and would avoid (or free up for other uses) an amount of electricity equal to the production of between 680 and 1,587 medium-sized peak-load coal power plants by 2030 and between 1,090 and 2,540 by 2050 (Shah et al., 2015).

in a warming of 2°C (50% probability) (IPCC, 2014c). Since we have already emitted 2 trillion tons of CO_2 by 2010, we have to limit cumulative CO_2 emissions from 2010 through the rest of the century to 1.7 trillion tons of CO_2 (IPCC, 2014c). The current annual rate of emissions is 38 billion tons of CO_2 or 50 billion tons of CO_2e (if we include other greenhouse gases). These emission rates imply that we must immediately work to bend the emissions curve (i.e., negative emission trends) by 2020 and achieve carbon neutrality by 2050.

However, making rapid changes in total CO_2 emissions will be challenging because most

Box 3: Economic Instruments

Worldwide two types of policy instruments are being implemented to meet the mitigation challenge—command and control and market-based regulations. Both help internalize the cost of climate pollution, which is otherwise born by the public. Command and control regulations can dictate emissions limits, specific technologies, inputs to production and/or technologies to be used by economic sector and sometimes by facility. These approaches are ubiquitous and preferred by many policy makers as they are easy to understand and implement, and often easier to enforce. They also can be more certain in achieving their objective. Further, the cost of reducing emissions this way is largely invisible. Economists have shown that command and control strategies often are a more expensive way of achieving emission reductions, although some command-and-control regimes have achieved their objectives at low cost, such as the Montreal Protocol's controls that have phased out nearly 100 chemicals that damage the stratospheric ozone layer and also warm the climate with nearly 100% compliance.

In addition to command and control, incentive based policies, such as GHG taxes and cap-and-trade systems, are also being used to limit climate pollutants. Both taxes and cap-and-trade systems place a price on carbon, which requires firms to start internalizing the damage their climate pollution is imposing on the global environment. A carbon tax sets a price per ton of GHG, which has the advantage that firms have perfect price certainty, but has the disadvantage that the exact amount of emissions reductions is uncertain as it depends on the firm response. A cap-and-trade system has the advantage that it sets the "allowed" amount of GHG emissions and hence can meet a mitigation goal exactly, yet firms face price uncertainty. Countries have followed different strategies and some have chosen carbon taxes of up to US$150 per ton (Sweden) and others have chosen cap-and-trade systems, where permits have traded at relatively low prices (California's price is near $14 per ton, while the European ETS is around $7).

California uses a cap-and-trade system to achieve about 20 percent of its GHG emission reductions. The California cap-and-trade is designed to reduce GHGs from multiple sources. The cap declines approximately 3 percent each year. The price on carbon creates incentives to reduce GHGs below allowable levels through investments in clean technologies. These market forces spur technological innovation and investments in clean energy. California has linked its market with Quebec and Ontario and has just extended the market's operating timeline through the year 2030. California is also working with China and other jurisdictions around the world to help establish similar market and carbon pricing mechanisms that promote GHG reduction.

Given the fat tail probability of catastrophic damage from BAU climate pollution, some economists suggest that an insurance perspective is the corrective approach, rather than a cost benefit approach. Martin Weitzman at Harvard is a leading proponent of this view.

CO_2 emissions come from energy infrastructure and technologies that have long replacement timescales (e.g., power plants) (Erickson et al., 2015). Significantly reducing emissions from these sources is achievable in the near-term but in some cases, would require early sunsetting of existing facilities that would strand assets (Jacobson and Delucchi, 2009). It would also require significantly increasing investments in deployment of clean energy technologies and supporting infrastructure such as long-distance transmission.

Research from many quarters—including the massive review of existing studies in the 2014 IPCC Report—shows that there are many different options for decarbonizing energy systems. Many studies have focused on renewable power options. Theoretically, at least 80%, and perhaps up to 90 or 100%, of global energy can come from available renewable technologies by mid-century–notably solar, wind and water power. Such technologies have currently been deployed at limited scales in China, California, Denmark, Germany, and elsewhere. In addition, 40 cities in the United States and dozens more worldwide, many with populations ranging from 100,000 to 13 million, over 100 businesses, and several universities have become living laboratories for ambitious climate mitigation programs that include carbon neutrality goals. Use of renewables and other low carbon energy sources are increasing rapidly. Catalyzed by falling prices and continued policy support, renewables accounted for about 50% of all new power generation capacity in the world (primarily in China, Japan, Germany, and the United States) in 2014, representing an investment of about $270 billion (IEA, 2015). Scaling up from these levels will require a substantial commitment as well as many new technologies and markets—for example, systems that can integrate large amounts of renewable power into electric grids while assuring high levels of reliability.

Global carbon emissions seem to be responding to these favorable developments. Worldwide CO_2 emissions, which grew at a rate of 2.9% per year from 2000 to 2011, slowed to 1.3% per year from 2012 to 2014, and was down at near zero growth (-0.2% per year) for 2015 and 2016 (IEA, 2016). The low to near-zero growth rate since 2012 is due to a combination of several factors: switching from coal to oil and natural gas; increased production from no or low-carbon sources such as nuclear (1.3%), hydro (1%), wind and solar (15%); and reduction in carbon intensity of the global economy (IEA, 2016). Negative emissions growth rates in the U.S. (-2.6%) and China (-0.7%) contributed the largest share of the recent bending of the emissions curve (IEA, 2016).

In addition to renewables, there are a few other options. Some include use of existing nuclear reactors. In China, United Arab Emirates, and perhaps other countries, expansion of nuclear power is being considered through heavy government support, and with proper attention to operational safety, design, and control over fissile materials, this can play a role in decarbonization, but the plants being built today are mostly only offsetting the plants closed in Japan, the U.S., Europe, and elsewhere. Another option involves using fossil fuels but finding ways to decarbonize the fuels. One avenue involves combusting coal or natural gas and capturing the CO_2 pollution before it goes into the atmosphere—known as carbon capture and storage (CCS) or, when the CO_2 is used for industrial purposes rather than just sequestered underground, carbon capture, utilization and storage (CCUS). Many pilot projects around CCS and CCUS have been developed or planned, and there is growing attention to strategies that would allow this technology to be deployed more widely, but the costs of the process are currently limiting their deployment.

There are concerns that the carbon neutral goal will hinder economic progress. Numerous examples contradict such claims and show that decoupling of emissions from economic growth can be achieved over reasonable time periods and with the right policy instruments. Between 2000 and 2014, 35 countries reduced their annual greenhouse gas emissions while simultaneously growing GDP (Yeo and Evans, 2016). And recent analysis by the Brookings Institution found that 33 U.S. states and the District of Columbia had similarly decoupled economic growth from carbon emissions since 2000 (Saha and Muro, 2016). The evidence is growing that economic growth can be decoupled from carbon emissions. Other concerns have been raised about carbon neutral goals potentially harming the poor by limiting their access to energy. There are about three billion who still lack access to sufficient energy to meet their basic needs, often because the infrastructure to support expanded energy access is lacking (Dasgupta et al., 2015). For these poorest three billion, decentralized power through, for example, village scale micro-grids relying on solar power, wind, and biogas is often far more effective for providing access to modern forms of energy. It is also important to keep in mind that providing energy services to low income households has almost no effect on the global level of CO_2 emissions.

A key central message is that there are no obvious "silver bullet" technologies for decarbonization, and different societies will make different choices to achieve decarbonization. However, it is clear that we need to move to 100% clean energy as soon as possible, that we already have technologies and practical examples that can achieve significant decarbonization, and that a growing number of governments are committing to achieve this ambitious goal in the next few critical decades. For example, in May 2017, more than 250 U.S. mayors, committed to run their cities 100% on renewable energy by 2035 (USCM, 2017).

8. Adding a Third Lever

The two-lever strategy assumes a central value of climate sensitivity of 3°C warming for a doubling of CO_2 (Hu et al., 2013). What does that mean? To reduce the probability of exceeding the 2°C warming from 50%, to less than 20%, we must employ a third lever: managing CO_2 after it has been emitted, for example, by capturing, utilizing, and storing it, and by removing it from the ambient atmosphere, known as atmospheric carbon extraction (ACE), or Carbon Dioxide Removal (CDR) (IPCC, 2013).

The main ACE measures under consideration are afforestation (including urban forestry), capturing, utilizing, and storing CO_2, bioenergy combined with carbon capture and sequestration (BECCS), soil organic carbon management, biochar, direct air capture, enhanced weathering and ocean liming, and ocean fertilization with iron (Fuss et al., 2014). It is very likely that one or more of these techniques could eventually be used to significantly reduce the amount of anthropogenic CO_2 in the atmosphere (i.e., removing a cumulative amount of up to hundreds of $GtCO_2$), although the development of the necessary technologies and vast infrastructures would likely take several decades (Fuss et al., 2014). Furthermore, BECCS, other than from waste biomass, is not carbon neutral in the critical near-term period when we are at risk of accelerating the self-amplifying feedback mechanisms and passing critical tipping points (Fuss et al., 2014). Immediate analysis needs to be done to determine which BECCS technologies are carbon neutral or negative in the critical near-term period and which are only neutral or negative in the longer term.

Given the short-timescales to keep global warming well below 2°C and aiming for 1.5°C, it is not clear how much ACE will be able to contribute in the near term. However, given the very real chance of a substantial overshoot of the Paris Agreement goals and the incumbent impacts, not pursuing ACE options may result in policymakers eventually considering radical geoengineering options such as injecting particles into the stratosphere or other forms of large-scale solar radiation management (also known as planetary albedo modification) (Schäfer et al., 2015). While these proposed techniques may be able to reduce climate risks in some regions, they are very poorly understood and could introduce novel climate and environmental risks, including a rapid temperature increase if such techniques were to be implemented and then stopped over a short timescale at a future time (McNutt et al., 2015a; 2015b). Furthermore, given their regionally heterogeneous impacts they would present an extremely large governance challenge.

Given the urgency, it is critical to support ongoing research and staged deployment of CO_2 removal techniques and to deepen our scientific understanding of albedo modification techniques to support informed decision-making in the future. This research needs to include technical, engineering and natural as well as social science aspects in order to be most effective in guiding policy development. This research should also address aspects ranging from development of effective governance and regulation, to our societal perspective on the relationships between humans and their environments, to more concrete economic aspects, particularly considering the investments needed to scale up any of the CO_2 removal techniques and whether it would be more prudent to make the same investment directly in decarbonizing energy and production.

9. Building Blocks for the Three Lever Approach

Achieving climate success will require the mobilization of human, financial, and technical resources at a global scale. Some of the building blocks for this are already available using existing treaties, regulations, and technologies, including the four building blocks for the Three Lever Approach.

Building Block 1: Fully implement the pledged Nationally Determined Contributions (NDCs) under the Paris Agreement and strengthen sister agreements.

The 2015 Paris Agreement was a landmark achievement, with 190 countries submitting intended NDCs by the end of 2016, in which each committed to greenhouse gas reductions, indicating a significant level of interest and expectation that this Agreement will produce tangible results. However, recent analysis indicates that even if all unconditional and conditional NDC pledges are achieved, projections indicate only a 66% probability of maintaining global temperatures at 3°C over pre-industrial temperatures by the end of the century (UNEP, 2016b).

The commitments of the Paris Agreement can be immediately strengthened and supported by addressing specific emissions and emissions sectors through targeted multilateral sister agreements (see Table 1) and by expanding subnational models of governance and collaboration around the world to embolden and energize national and international action. (Bottom up efforts will be especially important in countries in which the governments no longer actively support or consider pulling out of the universally signed Paris Agreement.) Scaling up these initiatives can drive greater ambition and provide a down payment for climate mitigation using targeted tools and expertise.

Table 1: Selected Sister Agreements

Kigali HFC Amendment to the Montreal Protocol	The Kigali Amendment to the Montreal Protocol, passed in October 2016, will phase down consumption and production of HFCs and will help avoid most of the 0.5°C of warming that would occur if HFC production continued as currently projected (UNEP, 2016a).
International Civil Aviation Organization Ruling on Aircraft Emissions	In October 2016, ICAO agreed to cap net CO_2 emissions from the aviation industry by 2035 to 2020 levels. Any emissions growth after 2020 needs to be offset (ICAO, 2016).
International Maritime Organization Ruling on Shipping Emissions	IMO is beginning to act on reducing black carbon emissions from the maritime shipping industry. In early 2015, the organization published a report assessing abatement technologies to reduce emissions. IMO also has passed mandatory measures regarding the fuel efficiency of ships, which will reduce both CO_2 and black carbon emissions (IMO, 2015).
Arctic Council	On 11 May 2017, the eight countries of the Arctic Council adopted the first Pan-Arctic report to achieve collective progress to reduce black carbon and methane emissions by both Arctic and Observer States and set as a goal to drastically reduce black carbon emissions by 25-33% below 2013 levels by 2025 (Arctic Council, 2017a; Arctic Council, 2017b).

Strengthening the ambition of current and pending sister agreements over time can achieve even greater climate benefits. Some examples include:

- The current HFC phasedown could be accelerated for quicker elimination of HFCs and thus lesser warming impact from the pollutants. Fast implementation and parallel efforts to improve energy efficiency of air conditioners and other cooling equipment could potentially double available climate mitigation.
- Eliminate use of heavy fuel oil (HFO) in the Arctic through the International Maritime Organization.
- Develop new, targeted agreements to address specific emissions or sectors such as regional emissions of black carbon and PFCs from the aluminum sector.

Building Block 2: Scale up subnational models of governance

State- and city-level jurisdictions can set the standards and the pace for national actions by serving as living laboratories for renewable technologies, regulatory-based ("command and control") strategies, and market-based solutions. California, for example, has many successful strategies other state- and city-level jurisdictions can emulate. Building cross-sector collaborations among urban stakeholders is critical because creating sustainable cities is a key to global change. One example is the Under 2 Coalition, which brings together 177 jurisdictions from 37 countries on 6 continents, that have "commit[ted] to either reducing their greenhouse gas emissions 80–95% below 1990 levels by 2050 or achieving a per capita emissions target of less than 2 metric tons by 2050" (Under2MOU, 2017). National and subnational leaders must promote international action and cooperation for unilateral climate policies, such as California's climate mitigation mandate under the Global Warming Solutions Act of 2006 (also known as AB 32), the American Clean Energy and Security Act of 2009, the Short-Lived Climate Pollutants Act of 2016 (SB 1383), and the proposed Buy Clean California Act (AB-262). State-level climate policy should also encourage innovation and commercialization of technologies and solutions that can replace fossil fuels and concurrently enable the poorer nations of the world to achieve economic growth with zero- and low-carbon technologies.

One option is to accelerate the impact of cities on climate mitigation through: municipal and regional Climate Action Plans; green infrastructure projects such as urban forestry and localized microgrids of renewable energy; smart mobility planning and improved mass transit systems to encourage cities to be less auto-centric; incentivizing passive house developments, including photovoltaic retrofits and net-zero energy technology for buildings, and super-efficient cooling appliances and equipment

Building Block 3: Pull the decarbonized energy and SLCP levers

Immediately begin decarbonizing the global economy with mature renewables, low- or no-carbon technologies, and aggressively support and promote innovation. Options for achieving rapid decarbonization include:

- Promote immediate and widespread use of mature clean technologies such as photovoltaics, wind turbines, nuclear in appropriate settings, biogas, geothermal, batteries, hydrogen fuel cells, electric light-duty vehicles, and more efficient end-use devices, especially in lighting, air conditioning and other appliances, and industrial processes; this could achieve a 30% to 40% reduction in fossil fuel CO_2 emissions by 2030 relative to BAU.
- Create efficient incentives to businesses and individuals to reduce CO_2 and SLCPs through market-based instruments, such as cap and trade or emission pricing. This will require high-quality emissions inventories and monitoring and enforcement mechanisms. Economic theory and empirical evidence (such as the experience with European, California, and New England carbon markets) tell us that market approaches may be the most cost-effective in specific circumstances. A central market mechanism should be to remove subsidies for fossil fuels and other emissions-intensive activities while simultaneously expanding subsidies for low-emissions technologies. Current subsidies provide carbon-intensive fuels an economic advantage over low-carbon fuels and thereby promote carbon pollution. Direct regulatory measures—such as rebates, efficiency standards, and renewable energy portfolio mandates—may be most effective for high-emissions sectors not covered by market-based policies. Regulatory measures are historically the choice for air pollution, including black carbon and tropospheric ozone.
- Promote innovations to accelerate the complete electrification of energy and transportation systems and improve building efficiency. Smart grid and microgrid technologies make possible the increasing penetration of intermittent solar and wind generation resources, the emergence and integration of plug-in electric vehicles into the grid infrastructure, and a proactive response to the increasing demand for enhanced grid resiliency. The evolution of this technology represents a paradigm shift to meet the challenging environmental goals associated with climate change, air quality, and water consumption. In addition, energy storage is a vital enabling technology that holds the key to both transitioning away from fossil fuels for our vehicular needs and managing the intermittency of renewables on the electric power grid. Over the past five years, electric vehicles have been entering the market, and storage technologies are being tested now on various grid applications, mainly

driven by innovations in lithium-ion batteries and hydrogen.

- Some specific options for decarbonization are described in Table 2 below.

Table 2: Select Decarbonization Measures

Energy System	
Electric Grid	Achieve a more reliable and resilient electric grid with at least 90% of all new generation capacity by 2030 from distributed and renewable technologies, such as those listed above.
End-use Devices	Expand electrification of highly efficient end-use devices, especially lighting, electric vehicles, machinery, and plug-load appliances.
Storage	Support development of lower cost energy storage for applications in transportation, resilient large-scale and distributed micro-scale grids, and residential uses.
Storage	Support research and development of a portfolio of new energy storage technologies, including batteries, super-capacitors, compressed air, and hydrogen and thermal storage, as well as advances in heat pumps, efficient lighting, fuel cells, and smart buildings and systems integration. These innovative technologies are essential for meeting the target of an 80% reduction in CO_2 emissions by 2050.
Transport System	
Electrification	Transition from fossil to zero-carbon, locally-sourced transportation fuels-such as hydrogen to power fuel cell-powered electric vehicles and low-carbon grid electricity to power battery electric vehicles-to meet the carbon reduction required from the light-duty and goods movement transportation sectors (medium- and heavy-duty vehicles, locomotives and ships).
Fuels	Support research and development of environmentally friendly renewable fuel solutions for heavy-duty transport, such as algal-based biofuels.
Building Efficiency	
Lighting	Replace all incandescent, metal halide, and fluorescent lighting fixtures with LED lighting. This can reduce energy consumption from lighting by 40%.
Lighting	Support investments, research, and development with next-generation intelligent and more efficient 200 lumens per Watt LED lighting products.
Cooling and Heating	Replace existing residential and commercial air conditioning units with super-efficient systems using low-GWP refrigerants while improving building design to keep cool, such as white roofs
Cooling and Heating	Deploy heat pumps and systems coupled with solar thermal and solar power generation. Residential natural gas consumption can be reduced by 50% or more. To accelerate this goal, we recommend deploying an incentive program of rebates comparable to those for energy efficiency appliances.

Sustainable agricultural practices and maintaining natural ecosystems are an essential component of decarbonizing the global economy and are also vital to global food security, and human health. Agriculture accounts for 10 to 15% of global GHG emissions (60% of nitrous oxide and 50% of methane emissions) (IPCC, 2013). Agriculture and residues from natural ecosystems can contribute to renewable energy production through the conversion of organic waste streams to bio-based products and fuels. Globally, food waste reduction programs that recover energy from food that is not consumed has the potential to reduce 20% of the current 50 billion tons of emissions of CO_2 and other greenhouse gases and, in addition, meet the recently approved sustainable development goals by creating wealth for the poorest 3 billion.

- The over-use of nitrogen fertilizers is estimated to be the largest portion of direct agricultural soil management-related nitrous oxide emissions in most countries. Global agricultural nitrous oxide emissions are expected to increase by 35 to 60% by 2030 in association with increased fertilizer nitrogen use and manure production (IPCC, 2013). Therefore, the efficient application of nitrogen-based fertilizers should be encouraged worldwide to mitigate GHG emissions. Appropriate fertilizer nitrogen use also increases crop biomass to help restore, maintain, and increase soil organic carbon.

Immediately make maximum use of available technologies combined with regulations to eliminate high-GWP HFCs, reduce methane emissions by 50%, and reduce black carbon emissions by 90% by 2030 (Shindell et al., 2012). Immediately implementing and globally scaling-up technology and policy solutions to address SLCPs will avoid up to 0.6°C of warming by 2050 and 1.2°C by 2100 (Hu et al., 2013). In addition to the climate and health benefits, this solution will provide access to clean cooking for the poorest 3 billion people who spend hours each day collecting solid biomass fuels and burning them indoors for cooking (Dasgupta et al., 2015).

- HFCs will be phased down under the Montreal Protocol under the Kigali Amendment of October 2016. Moreover, several recent studies have shown that emissions of HFCs could be quickly phased out and their warming virtually eliminated by 2030 by using low-GWP alternatives already available on the market. With a rapid transition away from high-GWP HFCs, an additional 39–64 Gt CO_2e can be avoided from future buildup of HFC banks (Velders et al., 2014). The climate benefits of phasing out HFCs could be more than doubled in some sectors through parallel efforts to increase energy efficiency of air conditioners and other appliances and equipment during this switch in refrigerants.
- The specific technological measures for reducing methane and black carbon are described in Table 3 below. These measures were developed by an international panel and reported in a UNEP-WMO Report, 2011.

Building Block 4: Pull the third lever of atmospheric carbon extraction

Regenerate damaged natural ecosystems and restore soil organic carbon to improve natural sinks for carbon through afforestation, reduced deforestation, sustainable grazing strategies, and efficient application of fertilizer, including through the use of organic amendments, such as biochar or compost. The potential for carbon mitigation from afforestation, reduced deforestation, and restoration of soil organic carbon is about 8 to 12 Gt per year (Ramanathan et al., 2016). Other strategies to extract CO_2 from the air include biochar, enhanced weathering and ocean liming, ocean fertilization with iron, and direct air capture. Because they are scalable and reversible, these strategies are sometimes described as "soft-geoengineering." In addition, other strategies include carbon capture, utilization, and storage, or CCUS, such as the process for capturing CO_2 at the smoke stack of power plants

Table 3: Select Measures for Curbing Black Carbon and Methane Emissions

Methane Measures	
Extraction and transport of fossil fuels	Extend pre-mine degasification and recovery and oxidation of CH_4 from ventilation air from coal mines.
	Extend recovery and utilization, rather than venting, of associated gas and improved control of unintended fugitive emissions from production of oil and natural gas.
	Reduce gas leakage from long-distance transmission pipelines.
Waste Management	Separate and treat biodegradable municipal waste through recycling, composting and anaerobic digestion, and landfill gas collection with combustion/utilization.
	Upgrade primary wastewater treatment to secondary/tertiary treatment with gas recovery and overflow control.
Agriculture	Control methane emissions from livestock, mainly through farm-scale anaerobic digestion of manure from cattle and pigs, but also researching methods to reduce methane from enteric fermentation.
	Promote healthy low-meat diets.
Black Carbon Measures (affecting BC and other co-emitted compounds)	
Transport	Require diesel particle filters for road and off-road vehicles.
	Eliminate high-emitting vehicles in road and off-road transport.
	Promote active transport.
Residential	Replace coal with coal briquettes in cooking and heating stoves.
	Replace current wood-burning technologies with pellet stoves and boilers, using fuel made from recycled wood waste or sawdust, in the residential sector in industrialized countries.
	Introduce clean-burning biomass stoves for cooking and heating in developing countries.
	Leapfrog to inexpensive portable induction cookstoves.
Industry	Replace traditional brick kilns with vertical shaft kilns and Hoffman kilns.
	Replace traditional coke ovens with modern recovery ovens, including the improvement of end-of-pipe abatement measures in developing countries.
Agriculture	Ban open field burning of agricultural waste.

and cement plants and turning it into calcium carbonate to use as building materials.

Supporting the Building Blocks with a Global Strategic Campaign

The building blocks are there, but how do we create the political and social momentum to support the substantial changes needed to achieve them? To successfully deploy these building blocks and create strong public support for these technology and policy solutions, we will also need a comprehensive strategy that engages and mobilizes all of society's resources to achieve this momentous task. A global strategic campaign must support the four building blocks. Some elements of this strategy should include:

Engagement with strategic constituents and a broad ally base to foster a deeper global culture of climate collaboration, as action will be difficult to implement without buy-in from key stakeholders. A diverse support base sends a strong message that all communities have something to lose from climate change and are willing to work together to tackle this challenge. These stakeholders include:

- The military is an important constituency that can help mobilize both public and political action; it was instrumental in the U.S. in convincing the administration to require agencies to develop short-term mitigation and long-term mitigation plans. Further, the military needs to both build infrastructure and plan for operations to last for at least 30 years, so it has a vested interest in climate mitigation and adaptation (U.S. DOD, 2015).
- The medical community can similarly influence both public and political action. There is a growing recognition in the medical community of the imminent threat climate change and air pollution pose to public health. For example, in 2015 the Lancet Commission concluded, "the effects of climate change are being felt today, and future projections represent an unacceptably high and potentially catastrophic risk to human health" (Watts et al., 2015).
- Industry, particularly the energy industry.
- The world's top carbon emitters, both individuals and institutions, contribute about 60% of the world's greenhouse gas emissions. This target audience is easy to reach as they have readily available access to information technologies, and we must work to engage them in these issues.

To bring these diverse communities together, it is important to design venues where stakeholders, community and religious leaders, and researchers and scholars from all academic disciplines can converge around concrete problems. These will provide safe spaces for collaboration, instigating collective action to mitigate climate disruption. Within these venues, collaborators can outline policies and projects that are likely to lead to success. This includes building upon and learning from past successes like the Montreal Protocol and the California programs (Table 5), as well as smaller scale ideas that are ready to be taken to the next level.

Coordinated public communication and education at local and global scales to foster a global culture of climate action. Public support and awareness of the need and tools for taking heroic actions are still lacking. Major initiatives are needed to both foster that public support and change social attitudes and behavior. This will require, for example:

- A stronger education and communication strategy, working to educate policymakers, corporate CEOs, civil society leaders, and citizens around the world. Top-down action will be difficult to implement without substantial support from the general public.
- Integrated curricula at all levels of education, from kindergarten to graduate levels, to educate a new generation about climate change impacts and solutions. Following this education, the fundamental transformation is a change in our attitudes and a willingness to change some of our behaviors towards each other and towards nature, understanding how our social systems intersect with our natural systems.
- A global citizen movement is a crucial element needed to force governments and private industry to restrict warming to well below 2°C. To protect our climate and prevent catastrophe, people must become advocates of fast climate action.

The actions that underpin the building blocks described in this section can be distilled into 10 Scalable Solutions which we have adapted from the pioneering work of more than 50 researchers in the Bending the Curve report and earlier research, which are listed in the table and figure below.

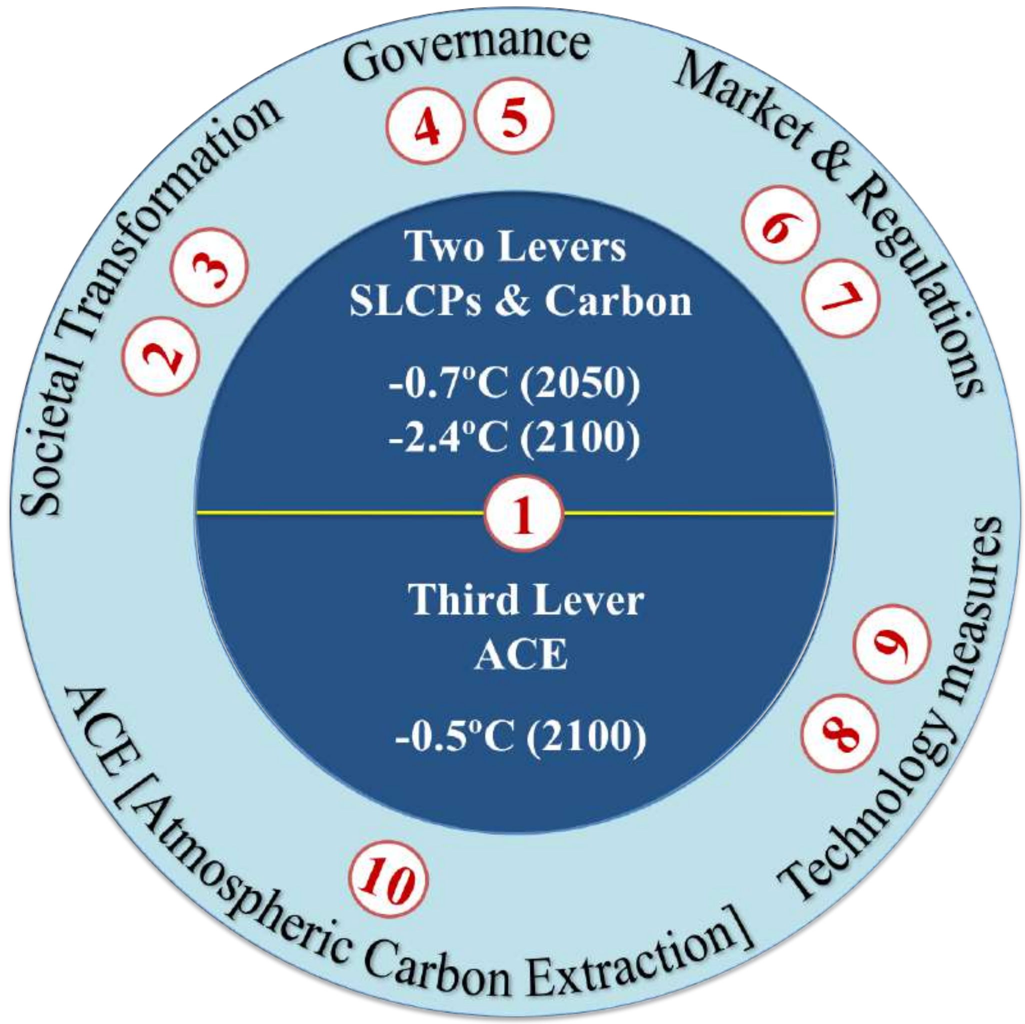

Figure 6: Scalable solutions for climate policy success highlighting the climate benefits from carbon neutrality (Carbon Lever), SLCPs (SLCP Lever), and Atmospheric Carbon Extraction (ACE Lever) mitigation. Adapted with modifications from Ramanathan et al., 2016.

Table 4: Ten Scalable Solutions

Science Solutions
1. Show that we can bend the warming curve immediately by reducing SLCPs, and long-term by replacing current fossil fuel energy systems with carbon neutral technologies.
Societal Transformation Solutions
2. Foster a global culture of climate action through coordinated public communication and education at local to global scales.
3. Build an alliance among science, religion, health care, and policy to change behavior and garner public support for drastic mitigation actions.
Governance Solutions
4. Build upon and strengthen the Paris Agreement. Strengthen sister agreements like the Montreal Protocol's Kigali Amendment to reduce HFCs.
5. Scale up subnational models of governance and collaboration around the world to embolden and energize national and international action. California's Under 2 Coalition and climate action plans by over 50 cities are prime examples.
Market- and Regulations-Based Solutions
6. Adopt market-based instruments to create efficient incentives for businesses and individuals to reduce CO_2 emissions.
7. Target direct regulatory measures—such as rebates and efficiency and renewable energy portfolio standards—for high emissions sectors not covered by market-based policies.
Technology-Based Solutions
8. Promote immediate widespread use of mature technologies such as photovoltaics, wind turbines, biogas, geothermal, batteries, hydrogen fuel cells, electric light-duty vehicles, and more efficient end-use devices, especially in lighting, air conditioning and other appliances, and industrial processes. Aggressively support and promote innovations to accelerate the complete electrification of energy and transportation systems and improve building efficiency.
9. Immediately make maximum use of available technologies combined with regulations to reduce methane emissions by 50%, reduce black carbon emissions by 90%, and eliminate high-GWP HFCs ahead of the schedule in the Kigali Amendment while fostering energy efficiency.
Atmospheric Carbon Extraction Solutions
10. Regenerate damaged natural ecosystems and restore soil organic carbon. Urgently expand research and development for atmospheric carbon extraction, along with CCUS.

10. In Pursuit of the Common Good: Where Do We Go from Here?

We conclude by considering the fundamental question: will society rise to the climate challenge or give up hope before it is too late? Given the existential threats BAU emissions present to many ecosystems, jurisdictions, and societies, it is imperative that we accept the challenge and effectively address climate change this century. We are quickly running out of time to prevent hugely dangerous, expensive, and perhaps unmanageable climate change. That is a central conclusion of this report.

Yet political leaders, corporations, civil society, and the general public for the most part are acting as if we do have plenty of time, not yet aware of the urgency of the climate crisis.

Climate change is an extremely urgent challenge and we need to act now to accelerate our solutions to reach global scale as fast as possible.

The good news is that it is still not too late to prevent disastrous climate change.

This report sets out a specific plan for limiting climate change in both the near- and long-term. With aggressive, urgent action, we can still protect ourselves. We also have many examples in our recent past proving that humanity can mobilize to achieve collective environmental objectives (Table 5).

As discussed above, staying well under 2°C will require a concerted global effort. We must address everything from our energy systems to our personal choices in order to reduce emissions to the greatest extent possible. Decarbonization must happen immediately and rapidly for our best chance to stay well under 2°C, and even with heroic action, removing existing carbon from the atmosphere will almost certainly be necessary to achieve this goal.

This report describes a detailed plan to restrict warming to well under 2°C and provides a path toward true climate protection, with the possibility, although difficult, of limiting warming to 1.5°C. Acting quickly, by 2020, to prevent catastrophic climate change will save millions of lives, trillions of dollars in economic costs, and massive suffering and dislocation to people around the world. Acting quickly to slow self-amplifying feedbacks and prevent runaway climate change is a global security imperative that can avoid the destabilization of entire societies and countries and reduce the likelihood of environmentally driven civil wars and other conflicts.

Table 5: Examples of Environmental Successes

Montreal Protocol	In the mid-1980s, scientists realized the ozone layer above Antarctica was disappearing due to the rapid rise in the production and usage of CFCs (chlorofluorocarbons). Recognizing the threat to human health, countries signed the Montreal Protocol to phase out these chemicals in 1987. Today the Montreal Protocol has phased out nearly 100 ozone-depleting substances by nearly 99% and has set the ozone layer on a path to recovery by 2065. In the U.S., the treaty will prevent over 280 million cases of skin cancer, 1.5 million skin cancer deaths, and 45 million cataracts (U.S. EPA, 2015). Because ozone-depleting substances are also powerful greenhouse gases, the Montreal Protocol also avoided the equivalent of 135 billion tons of CO_2 between 1990 and 2010, earning recognition as the most successful environmental treaty in history. When early boycotts against CFCs and early national measures are included, the avoided warming is equal to the warming currently caused by CO_2 today (UNEP, 2012). Absent the 2016 Kigali Amendment and parallel control measures at national and regional level, the carbon budget associated with a 66% probability of limiting warming to 2°C would have been reduced by 30 to 60% (Rogelj et al., 2015b).
Air Quality Improvements in California, New York City, and London	Recognizing the harmful effects of air pollution, particularly to human health, various cities and states have taken on air quality control measures over the last few decades. Since the 1960s, California has been highly successful in reducing air pollution, cutting emissions of ozone precursor gases, $PM_{2.5}$, air toxics, and black carbon by as much as 90% despite large increases in population, number of vehicles, and diesel fuel consumption (Ramanathan et al., 2016). In New York City from 2008 to 2014, annual averages of $PM_{2.5}$, NO_2, and NO levels, all of which threaten public health, declined by 16–24%, and SO_2 declined by nearly 70% (Kheirbek et al., 2016). In London, NOx emissions fell by 7.5% from 2008 to 2013 (GLA, 2015). Across the U.S., the Clean Air Act (passed in 1970 and amended in 1990) has led to $10-95 in health benefits for each $1 spent on pollution control measures (U.S. EPA, 2011).
The Convention on Long-range Transboundary Air Pollution (LRTAP)	LRTAP has resulted in drastic reductions of air pollutants in the United Nations Economic Commission for Europe region (Europe, the U.S., Canada, the Central Asian republics, and Israel). From 1990 to 2006, SO_2 and NOx emissions, both of which contribute to acid rain, fell by 70% and 35% in the E.U., respectively and 36% and approximately 25% in the U.S., respectively. PM_{10}, which is a public health threat, levels declined by nearly 30% in the EU (UNECE, 2009).

11. References

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