Bending The Curve: Ten Scalable Solutions For Carbon Neutrality And Climate Stability

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ABSTRACT:

We are living in a world of over seven billion people, with annual greenhouse gas emissions of approximately 50 billion tons a year and rising steadily. If continued unabated, the world is on target to warm by about 2^0C in less than 40 years, pushing the climate to a regime unlike any that has been witnessed in the last million years. Nonetheless, we still have time to avert such a catastrophic scenario, or delay its occurrence by several decades to provide human societies and the ecosystem with the time to adjust. In order to mitigate the possibility of climate disruption, we need to recognize that fossil fuel based technologies have become outdated and transform the energy system to that of low-carbon, sustainable and secure energy systems. In addition, we have to mitigate emissions of the four short-lived climate pollutants to bring immediate relief from climate change and protect vulnerable societies. Stability of the climate system involves not only the centrality of scientific and technological advancements and investments, but also necessary shifts in social structure and behavior by individuals, communities and societies worldwide as well as market based instruments, sub-national collaborations and governance structure. Fortunately, living laboratories—such as the State of California and the University of California system, which has pledged to become carbon neutral by 2025—provide demonstrable solutions which hold promise in alleviating the climate warming in the next generation. These jurisdictions are tiny emitters in the global picture, but they offer the potential for leverage through demonstrating new technologies as well as workable institutions that cut emissions. We outline 10 pragmatic solutions—a "kit of parts" rooted in California but scalable to the world—that taken together, can “bend the curve” of the upward trajectory of human-caused warming trends. Wholesale transformation of our current fossil fuel based energy systems towards sustainable energy is among the greatest of societal challenges—and opportunities-- faced in the 21st century.

1. INTRODUCTION

1.1 SEIZING THE MOMENT

Climate change is scientifically incontrovertible and has become a defining problem for the current as well as future generations. The Paris agreement to mitigate climate change [1] was a truly historic agreement that signaled to the entire world that mitigation of climate change is an urgent priority among leaders of the nations of the world. What the world urgently needs now are scalable solutions for bending the curve — flattening the upward trajectory of human-caused greenhouse gas emissions and consequent global climate change (Figure 1). The overall targets for stabilizing climate change are rather straightforward and have been prescribed in numerous studies [2]. Basically energy consumption has to become carbon neutral as soon as possible and in addition we have to drastically mitigate emissions of numerous other climate warming pollutants within few decades [3, 4]. However, the specific pathways or solutions to reach these targets are complex and require behavioral, institutional, technological and governance changes, and these have not been prioritized nor synthesized into one logical framework. Furthermore the solutions have to be based upon real world examples of the *art of the* possible and prioritize solutions that are scalable to the whole world. The multi-dimensional nature of the problem requires inter-disciplinary as well as cross-disciplinary collaboration for crafting a set of solutions to *Bend the Curve* of carbon emissions and climate change.

Figure 1. Simulated temperature change under various mitigation scenarios and SLCP Climate benefits.

Towards this ambitious goal, fifty researchers and scholars (UC-Fifty)— from a wide range of disciplines across the University of California system — formed a climate solutions group and came together in 2015 to identify these solutions, many of which emerge from UC research as well as the research of colleagues around the world. Taken together, these ten solutions can bend the curve of climate change. The 10 scalable solutions, described here, present pragmatic paths for achieving carbon neutrality and climate stability in California, the United States and the world. The 10 solutions were derived from detailed analyses of the climate change problem as well as its multi-dimensionality by the UC-Fifty. These analyses and resulting recommendations are described in 8 companion papers in this special volume. The companion papers fall under five categories: I. Science Solutions Cluster; II. Societal Transformation Solutions Cluster; III. Governance Solutions Cluster; IV: Market- and Regulations-Based Solutions Cluster; and V. Technology-Based Solutions Cluster

The effort by the UC-Fifty is inspired by California's recent pledge to reduce carbon emissions by 40 percent below 1990 levels by 2030 [5], and by the University of California's pledge to become carbon neutral by 2025 [6]. What is taking place in California today is exactly the sort of large-scale demonstration project the planet needs. And this statewide demonstration project is composed of many of the kinds of solutions that can be scaled up around the world.

California has provided a remarkable example for the world by achieving dramatic reductions in air pollution, while continuing to grow economically [7]. Furthermore, the air pollution control industry in California generated $6.2 billion in revenues and employed 32,000 people in 2001 [8]. In this study, we propose a set of strategies for combating climate change and growing the economy in California, the nation and the world, while building present-day and intergenerational wealth, and improving the well-being of people and the planet. The University of California has played a key role in California's pioneering leadership in energy and environmental policy through research, teaching and public service, and currently is partnering with local, state, federal and international leaders in the public, private and philanthropic sectors to address our pressing climate change challenges (e.g, [9]) .We still have much more to do here in California. We are eager to share these lessons with the world and together build a better, safer, healthier and more equitable world, while bending the curve of climate change. As we make the changes necessary to achieve carbon neutrality at the University of California, employing solutions that can be scaled up to developing energy and climate solutions for the world, hundreds of thousands of faculty, students and staff across our 10 campuses and three affiliated national laboratories will be learning and sharing with the world how we can bend the curve of greenhouse gas emissions and stop global warming through taking bold yet pragmatic steps and lowering the barriers so others can follow.

1.2 WE ARE AT A CROSSROADS AND WE MUST MAKE A CHOICE

This is evident in the increased frequency and intensity of storms, hurricanes, floods, heat waves, droughts and forest fires [10, 11]. These extreme events, as well as the spread of certain infectious diseases, worsened air pollution, drinking water contamination and food shortages, are creating the beginning of what soon will be a global public health crisis. A whole new navigable ocean is opening in the Arctic. Sea levels are rising, causing major damage in the world's most populous cities. All this has resulted from warming the planet by only about 0.9 ºC, primarily from human activities [10]. Since 1750, we have emitted 2 trillion metric tons of carbon dioxide (CO_2) and other greenhouse gases. The emission in 2011 was around 50 billion tons and is growing at a rate of 2.2 percent per year [11]. If this rate of increase continues unabated, the world is on target to warm by about 2 ºC in less than 40 years [3, 4]. By the end of the century, warming could range from 2.5 ºC to a catastrophic 7.8 ºC [10]. We are transitioning from climate change to climate disruption. With such alarming possibilities the planet is highly likely to cross several tipping points within decades, triggering changes that could last thousands of years [12]. All of this is occurring against a backdrop of growing needs and pressures by humans, as our population is set to increase by at least 2 billion people by 2050.

1.3 BENDING THE CURVE

Bending the curve refers to flattening the upward trajectory of human-caused warming trends. Reducing CO_2 emissions by 80 percent by 2050 and moving to carbon neutrality post-2050 would begin to bend the temperature curve downward and reduce overall warming by as much as 1.5 ºC by 2100 [11, 13]. Temperature estimates for future warming trends as well as for the mitigated warming given throughout this study have a 95 percent probability range of ±50 percent. For example, a value of 2 ^{0}C given here is the central value with a 95 percent range of 1 to 4 ºC. That is, there is a 95 percent probability the true value will be within that range.

More rapid reductions can be achieved by reducing four short-lived climate pollutants. These short-lived climate pollutants, known as SLCPs, are methane (CH4), black carbon, hydrofluorocarbons (HFCs, which are used in refrigerants) and tropospheric ozone. If currently available technologies for reducing SLCPs were fully implemented by 2030, projected warming could be reduced by as much as 0.6 ºC [3, 13, 14] within two to four decades, keeping the mid-century warming well below 2 ^{0}C relative to the pre-industrial average. This could give the world additional time to achieve net-zero emissions or even negative carbon emissions through scaling up existing and emerging carbon- neutral and carbon sequestration technologies and methods.

Achieving both maximum possible mitigation of SLCPs and carbon neutrality beyond 2050 could hold global warming to about 2 ^{0}C through 2100, which would avert most disastrous climate disruptions. This is our goal in this study.

In what follows, we describe 10 practical solutions to mitigate climate change that are scalable to the state, the nation and the world. There are many such reports offering recommendations and solutions to keep climate change under manageable levels. We take full account of such action-oriented reports and offer some unique solutions to complement them. Many of the solutions proposed here are being field tested on University of California campuses and elsewhere in California. The background, the criteria, the quantitative narrative and justification for these solutions can be found in the companion papers in this special volume.

1.4 THE CALIFORNIA EXPERIENCE: 1960 TO 2015

In the economic boom following World War II — fueled by large increases in population, vehicles, diesel trucks and coal-burning industries — California recorded some of the highest air pollution levels, competing with the city of London for the dubious title of the worst polluted region in the world. Since then, California has made a remarkable turnaround. From 1960 to the present, California has reduced levels of particles and gases related to air pollution by as much as 90 percent [15].

The concentration of black carbon was reduced by 90 percent across California. In the meantime, fuel consumption for the transportation sector increased by a factor of five and population grew from 15.5 million (1959) to 39 million (2014). California also has made impressive gains in energy efficiency and in lowering its carbon footprint. Its per capita energy consumption is among the lowest in the United States (48th) and its per capita electricity consumption is the lowest — roughly half of the U.S. per capita consumption [16, 17].

California is one of the most energy- efficient and greenest economies in the world. It is the second-to-least carbon-intense economy in the world next to France, which relies heavily on nuclear power. It also is a leader in renewable power generation with 23 percent of its electricity generated from renewables (not including hydropower), second only to Germany (which generates 27 percent of its electricity from renewables). These impressive environmental gains did not hurt California's economy, which grew at an impressive pace with the highest gross domestic product of all states in the nation, constituting the world's eighth largest economy. California has shown how to reduce fossil fuel related pollution emissions while sustaining strong economic growth.

Emboldened by this favorable experience in regulating air pollution, California in 2002 passed the first law in the country that targeted greenhouse gas emissions from vehicles. In 2006, it enacted the precedent-setting Global Warming Solutions act and gave authority to California's air pollution agency, the California Air Resources Board (CARB), to enact policies to reduce its greenhouse gas emissions to 1990 levels by 2020. The state responded with a suite of measures that include a cap and trade program, a low carbon fuel standard for vehicles, automobile emission standards expected to reduce emissions by 30 percent by 2016, renewable portfolio standards for utilities, energy efficiency programs for buildings and appliances, and transit and land use programs to reduce vehicle miles traveled. This has been followed by another milestone in 2015 when Gov. Brown issued an executive order setting a goal of reducing CO_2 emissions to 40 percent below 1990 levels by 2030, which is the pathway required for stabilizing climate below 2 ^{0}C relative to the pre-industrial average. The legacy of California's air quality and energy efficiency programs since the 1960s and the depth of expertise at CARB on the multi-dimensional aspects of climate change mitigation have placed California in a unique position to embark on such ambitious low carbon pathways.

While its geography, equable climate and commerce have favored green growth, this progress came as a result of five decades of consistent and innovative policies that relied on sound research, innovative development and aggressive implementation of policies. While California relied only on command and control regulation until the 1990s, the state began rolling out market incentives for controlling nitrous oxide emissions and demonstrated the efficacy of market instruments to mitigate certain types of emissions. Relying on this experience, CARB launched a cap and trade system in 2013 to reduce carbon emissions from utilities, industrial facilities and fuel distributors, covering 85 percent of California's emissions, making it the most comprehensive cap and trade market in the world [18].

1.5 THE CARBON NEUTRALITY INITIATIVE OF THE UNIVERSITY OF CALIFORNIA

California cannot address climate change on its own, but the state can serve as a living laboratory for "the art of the possible," sharing its good practices and cooperating with other states and nations to mitigate their emissions [19]. To achieve this goal, California has created an "Under 2 MOU," [20] an agreement Gov. Brown co-founded with the state of Baden-Württemberg in Germany. The "Under 2 MOU" is an agreement among subnational jurisdictions around the world to limit the increase in global average temperature to below 2 ºC. Since the global agreement was first signed in May 2015, a total of 45 jurisdictions in 20 countries and five continents, with a total GDP of US $14 trillion, have signed or endorsed the agreement.

This study is an outgrowth of the University of California President's Carbon Neutrality Initiative. The authors of this study and our colleagues at the University of California's 10 campuses and three affiliated national laboratories are strongly motivated by the special demands of this ambitious goal, and we are also motivated by corresponding goals for the state of California, the nation and the world. The UC Carbon Neutrality Initiative is dedicated to achieving net-zero greenhouse gas emissions by 2025 across all 10 UC campuses. It should be emphasized that a net- zero emission target is enormously demanding and requires careful strategic planning to arrive at a mix of technologies, behavioral measures and policies, as well as highly effective communication — all of which, taken together, are far more challenging than simply reducing emissions by some 40 percent or even 80 percent. Each campus has a unique set of requirements based on its current energy consumption and emissions. Factors such as a local climate, reliance on cogeneration facilities, access to wholesale electricity markets and whether the campus has a hospital and medical school, shape the specific challenges of the campuses, each of which is a "living laboratory" for learning and adapting.

Examples of current projects related to the Carbon Neutrality Initiative are described in the companion papers. These include an 80 megawatt solar array in the Central Valley (the largest at any U.S. university), an experimental anaerobic digester that is using food waste to produce bio-methane, a large fuel cell that generates 2.8 megawatts of electricity from a municipal waste water treatment facility, smart lighting and smart building systems that dramatically reduce energy consumption and a solar greenhouse that selectively harvests light for solar electricity. These and other works at the University of California illustrate the commitment that we have made to mitigate climate change.

2. THE SOLUTIONS

2.1 10 Scalable Solutions

These 10 pragmatic, scalable solutions — all of which can be implemented immediately and expanded rapidly — will clean our air and keep global warming under 2 ºC and, at the same time, provide breathing room for the world to fully transition to carbon neutrality in the coming decades. More details on each solution can be found in Section 3.

1. Bend the warming curve immediately by reducing short-lived climate pollutants (SLCPs) and sustainably by replacing current fossil-fueled energy systems with carbon neutral technologies. Achieve the SLCP reduction targets prescribed in solution #9 by 2030 to cut projected warming by approximately 50 percent by 2050. To limit long-term global warming to under 2 ºC, cumulative emissions from now to 2050 must be less than 1 trillion tons and approach zero emissions post-2050. Solutions #7 to #9 cover technological solutions to accomplish these targets.

2. Foster a global culture of climate action through coordinated public communication and education at local to global scales. Combine technology and policy solutions with innovative approaches to changing social attitudes and behavior.

3. Deepen the global culture of climate collaboration by designing venues where stakeholders, community and religious leaders converge around concrete problems with researchers and scholars from all academic disciplines, with the overall goal of initiating collaborative actions to mitigate climate disruption.

4. Scale up subnational models of governance and collaboration around the world to embolden and energize national and international action. Use the California examples to help other state- and city-level jurisdictions become living laboratories for renewable technologies and for regulatory as well as market-based solutions, and build cross-sector collaborations among urban stakeholders because creating sustainable cities is a key to global change.

5. Adopt market-based instruments to create efficient incentives for businesses and individuals to reduce CO_2 emissions. These can include cap and trade or carbon pricing and should employ mechanisms to contain costs. Adopt the high quality emissions inventories, monitoring and enforcement mechanisms necessary to make these approaches work. In settings where these institutions do not credibly exist, alternative approaches such as direct regulation may be the better approach — although often at higher cost than market-based systems.

6. Narrowly target direct regulatory measures — such as rebates and efficiency and renewable energy portfolio standards — at high emissions sectors not covered by market-based policies. Create powerful incentives that continually reward improvements to bring down emissions while building political coalitions in favor of climate policy. Terminate subsidies that encourage emission-intensive activities. Expand subsidies that encourage innovation in low emission technologies.

7. Promote immediate widespread use of mature technologies such as photovoltaics, wind turbines, battery and hydrogen fuel cell electric light- duty vehicles, and more efficient end-use

devices, especially in lighting, air conditioning, appliances and industrial processes. These technologies will have even greater impact if they are the target of market-based or direct regulatory solutions such as those described in solutions #5 and #6, and have the potential to achieve 30 percent to 40 percent reduction in fossil fuel CO_2 emissions by 2030.

8. Aggressively support and promote innovations to accelerate the complete electrification of energy and transportation systems and improve building efficiency. Support development of lower-cost energy storage for applications in transportation, resilient large- scale and distributed micro-scale grids, and residential uses. Support development of new energy storage technologies, including batteries, super-capacitors, compressed air, hydrogen and thermal storage, as well as advances in heat pumps, efficient lighting, fuel cells, smart buildings and systems integration. These innovative technologies are essential for meeting the target of 80 percent reduction in CO_2 emissions by 2050.

9. Immediately make maximum use of available technologies combined with regulations to reduce methane emissions by 50 percent and black carbon emissions by 90 percent. Phase out hydrofluorocarbons (HFCs) by 2030 by amending the Montreal Protocol. In addition to the climate and health benefits described under solution #1, 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.

10. Regenerate damaged natural ecosystems and restore soil organic carbon to improve natural sinks for carbon (through afforestation, reducing deforestation and restoration of soil organic

carbon). Implement food waste reduction programs and energy recovery systems to maximize utilization of food produced and recover energy from food that is not consumed. Global deployment of these measures has the potential to reduce 20 percent 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.

Of the 10 solutions proposed here, seven (solutions #1 and #4 through #9) have been or are currently being implemented in California (see section 1.4).

California's experience provides valuable lessons, and in some cases direct models, for scaling these solutions to other states and nations. Decades of research on University of California campuses and in national laboratories managed by the university contributed significantly to the development of these solutions. Several of the renewable energy technology solutions in solutions #6 and #7 have been field tested on University of California campuses (see section 1.5). Scaling these solutions to other states and nations and eventually globally will require attitudinal and behavioral changes covered in solutions #2 and #3.

UC researchers currently are working on many of these solutions, along with colleagues around the world. UC faculty also are involved in research on solution #10 to identify and improve carbon sinks in natural and managed ecosystems by expanding existing, proven practices worldwide. The cost of fully implementing these solutions will be significant, but California shows that it can be done while maintaining a thriving economy. And the cost is well justified in light of the social costs of carbon emissions, including 7 million deaths every year due to air pollution linked to fossil fuel and biomass burning which also releases climate warming pollutants to the atmosphere.

If we can scale these 10 solutions beginning now, we can dramatically bend the curve of deadly air pollution and global warming worldwide (Table 1). California can't bend the curve on its own. Neither can the University of California. But we can be part of powerful networks and collaborations to scale these solutions.

Table 1. California's Living Laboratory Solutions: "Art of the Possible" for Bending the Climate Change Curve

Solutions by Topical Cluster	**CA's Climate Strategy & Estimated Benefits**	**Potential Climate Strategy & Benefits for the World**
Science Solutions		
Solution 1: SLCPs and carbon neutrality: Reduce short-lived climate pollutants (SLCPs) and replace current fossil-fueled energy systems with carbon neutral technologies	CA's key targets to reduce greenhouse gas (GHG) emissions: * Increase electricity derived from renewable sources to 50%. * Double building energy efficiency savings rate; make heating fuels cleaner. * Reduce SLCP release (methane and black carbon). * Increase carbon sequestration on farms and rangelands, and in forests and wetlands. CA 2016-17 Governor's Budget includes: * $3.1 billion for the Cap and Trade Expenditure Plan to reduce GHG emissions for programs to support clean transportation, reduce SLCPs, protect natural ecosystems, and benefit disadvantaged communities *$100 million to support local climate actions in the state's top 5% of disadvantaged communities (projects that integrate multiple, cross-cutting approaches to reduce GHG emissions). The State is currently **on track to** achieve its reduction of 40% GHG by 2030 under state Assembly Bill 32; however, more will need to be done to achieve 80% reductions by 2050 .	▪ The SLCPs solution can keep global warming below $2^{\circ}C$ until 2050; ▪ Carbon neutrality is necessary to keep global warming below $2^{\circ}C$ beyond 2050. [[Globally these efforts would save as many as 100 million lives lost to air pollution by 2050]]
Societal Transformations Solutions *Solution 2: Attitudinal and behavior change*: Foster a global culture of climate action through coordinated public communication and education. *Solution 3:Climate collaboration*: design venues where stakeholders converge around concrete problems *Governance Solutions* *Solution 4: Subnational models of governance and collaboration:* *Market & Regulation-Based Solutions* *Solution 5: Adopt market-based instruments* to create efficient incentives for businesses and individuals to reduce CO2 emissions.	*Solutions 2 - 6 are essential to obtain public support for the decisive actions required for carbon neutrality. These can variably work in tandem with solutions #1, 7, 8, 9, and 10 to achieve emissions reductions.* ▪ Solid majorities of Californians favor government regulation of greenhouse gas emissions and policies to curb global warming. ▪ California's air quality and energy efficiency programs since the 1960s and the depth of expertise at the California Air Resources Board (CARB) and the multi-dimensional aspects of its climate change mitigation have placed California in a unique position to embark on today's ambitious low carbon pathways. ▪ California in 2002 passed the first law in the country that targeted greenhouse gas emissions from vehicles. ▪ In 2006, it enacted the precedent-setting Global Warming Solutions act and gave authority to CARB, to enact policies to reduce its greenhouse gas emissions to 1990 levels by 2020. ▪ A suite of measures were developed: a cap and trade program; a low carbon fuel standard for vehicles, automobile emission standards expected to reduce emissions by 30 percent by 2016, renewable portfolio standards for utilities, energy efficiency programs for buildings and appliances, and transit and land use programs to reduce vehicle miles traveled. ▪ This has been followed by another milestone in 2015 with the state's goal of reducing CO2 emissions to 40 percent below 1990	California leads the way in providing Solutions for other Subnational and National Jurisdictions and their Governments: ▪ CA has created an "Under 2 MOU," an agreement to limit the increase in global average temperature to below 2 degrees Celsius. Since the global agreement was first signed in May 2015, a total of 45 jurisdictions in 20 countries and five continents, with a total GDP of US $14 trillion, have signed or endorsed the agreement. ▪ CA provides transferable lessons drawn from its pioneering regulatory bodies such as the California Air Resources Board (CARB) and its tough climate statutes; ▪ CA provides transferable lessons drawn from its pioneering work in emissions trading, the world's most comprehensive.

Solution 6: Narrowly target direct regulatory measures at high emissions sectors not covered by market-based policies	levels by 2030, the pathway required for stabilizing climate below 2 degrees Celsius.	
Technology-Based Solutions		
Solution 7: Promote immediate widespread use of mature technologies such as photovoltaics, wind turbines, battery and hydrogen fuel cell electric light duty vehicles, and more efficient end-use devices, especially in lighting, air conditioning, appliances and industrial processes	Demonstration of technology in California has made policies and implementation feasible: *Zero emission vehicles program:* first developed in the 1990s, successful demonstrations today are making it possible to ramp up zero emission vehicle policies not possible earlier. As a technologies improve for renewables, *Renewable Portfolio Standards (RPS)* ramp-up becomes feasible. First piloted in the 1990s, successful demonstrations are making scalability possible. *UC demonstrations* include an 80 megawatt solar array, an experimental anaerobic digester that is using food waste to produce bio-methane, a large fuel cell that generates 2.8 megawatts of electricity from a municipal waste water treatment facility, smart lighting and smart building systems that dramatically reduce energy consumption and a solar greenhouse that selectively harvests light for solar electricity. The program will combine climate investments within a local area for catalytic impact, including investments in energy, transportation, active transportation, housing, urban greening,land use, water use efficiency, waste reduction, and other areas, while also increasing job training, economic, health and environmental benefits.	Together solutions #7 and 8 are necessary for achieving worldwide carbon neutrality post-2050.
Solution 8: Aggressively support and promote innovations essential for meeting the target of 80 percent reduction in CO2 emissions by 2050.(energy and transit electrification; building efficiency, energy storage, etc.)		
Solution 9: Methane and black carbon reduction & HFCs phase-out	Pursuant to Chapter 523, Statutes of 2014 (SB 605), the Air Resources Board has developed a plan that calls for a 50% reduction in black carbon and fluorinated gas emissions and a 40% reduction in methane emissions by 2030. Reducing methane emissions from landfills will be a key component of the short‑lived climate pollutant strategy. A key to achieving these goals is the successful collection and recycling of organic and other materials.	A global reduction of methane emissions 50% and black carbon emissions 90%, would provide immediate reductions in global greenhouse effects and avoid crossing over tipping points within next three decades
Natural and Managed Ecosystem Solutions		
Solution 10: Control deforestation, support forest recovery and agroforestry production systems, reduce food waste and energy recovery	Reducing methane emissions from landfills will be a key component of the short‑lived climate pollutant strategy. A key to achieving these goals is the successful collection andrecycling of organic and other materials. • $100 million for the Department of Resources, Recycling and Recovery to provide financial incentives for capital investments that expand waste management infrastructure, with a priority in disadvantaged communities. Investment in new or expanded clean composting, anaerobic digestion, fiber, plastic, and glass facilities is necessary to divert more materials from landfills. These programs reduce GHG emissions and support the state's 75‑percent solid waste recycling goal. Carbon Sequestration As a result of four consecutive years of drought conditions and an infestation of bark beetles, the U.S. Forest Service recently estimated that over 22 million trees in California are dead and tens of millions more are likely to die. In addition to increasing the frequency and severity of the state's wildfire risk, the number of dead and dying trees compromises the carbon sequestration capabilities of the state's forested lands. • $150 million for CAL FIRE to support forest health programs that reduce GHG emissions through fuel reduction, reforestation projects, pest and diseased tree removal, and long‑term protection of forested lands vulnerable to conversion. Funds will also support biomass energy generation projects.	*Forests* can offset 20% of U.S. fossil fuel emissions (*15*); Controlling Amazon de-forestation by 70% avoids emitting 3.2 GTs CO_2 (16); tropical forest regrowth absorbs 1.64 GTs of carbon per year (*17*); regrowth rates ~12-20 times that of old growth *(18)*

2.2 Unique Aspects of the 10 Solutions

This collaborative study is one of the first such effort that treats mitigation of air pollution and climate disruption under one framework. The solutions proposed here recognize the fact that fossil fuel combustion — which produces greenhouse gases — also produces particles and gases such as ozone and black carbon, which also contribute to global warming. Others, such as sulfates, cause sunlight to dim and dry the planet. We can accelerate solutions and gain some time for long-term change to a carbon-neutral world by bending the curve of all of these pollutants immediately and simultaneously as part of one unified strategy.

These 10 solutions leverage the power of concern for human health worldwide. People care about human health. Burning fossil fuels causes both air pollution and climate changes that result in human illnesses and death. As the Lancet Commission concluded in June 2015: “The effects of climate change are being felt today and future projections represent an unacceptably high and potentially catastrophic risk to human health” [21].

This study recognizes that intra- regional, intra-generational and inter-generational equity and ethical issues are inherent in climate change and any solutions to climate change. These issues arise in part because consumption by about 15 percent of the world’s population contributes about 60 percent of climate pollution; while 40 percent of the population, who contribute very little to this pollution, as well as generations unborn, are likely to suffer the worst consequences of climate disruption. These solutions represent an integrated approach that includes familiar goals for achieving carbon neutrality through renewable energy, with new goals for reducing SLCPs immediately; building on California’s success to encourage sub-national governance, regulations and market-based instruments; and innovative approaches in education, communication and incentives to encourage attitudinal and behavioral changes. To be effective, this integrated strategy requires engagement by diverse stakeholders and the creation of a culture of climate action through localized interventions that lower barriers for citizens to take concrete steps to participate in solving our climate crisis.

These solutions recognize the fact that fundamental changes in human attitudes and behaviors toward nature and each other are critical for bending the curve of air pollution and global warming. As a result, two of the solutions deal with bringing researchers and scholars together with community and religious leaders and stakeholders to lower barriers to addressing climate change from the local level on up.

The study also recognizes the fundamental importance of effective communication to reach and engage diverse constituencies throughout the world to bend the curve of emissions and warming, achieve carbon neutrality and stabilize Earth's climate.

2.3 Pathways for Implementing the 10 Solutions

Our 10 scalable solutions are grouped in five clusters listed below.

- *Science Solutions Cluster*
- *Societal Transformation Solutions Cluster*
- *Governance Solutions Cluster*
- *Market- and Regulations-Based Solutions Cluster*
- *Technology-Based Solutions Cluster*

Science Solutions Cluster

1. Bend the warming curve immediately by reducing short- lived climate pollutants (SLCPs) and sustainably by replacing current fossil-fueled energy systems with carbon neutral technologies. Achieve the SLCP reduction targets prescribed in solution #9 by 2030 to cut projected warming by approximately 50 percent by 2050. To limit long-term global warming to under 2 ºC, cumulative emissions from now to 2050 must be less than 1 trillion tons and approach zero emissions post-2050. Solutions #7 to #9 cover technological solutions to accomplish these targets.

- Maximize use of existing technologies to cut emissions of methane and black carbon immediately. Since both are air pollutants, air pollution control agencies can require this now. This also will reduce another short-lived climate pollutant, ozone. Phase out HFCs immediately — replacement refrigerant compounds are available now. Mitigation of SLCPs also has significant local benefits, saving 2.4 million lives lost to outdoor pollution and 3 million lives lost to indoor pollution each year, and saving as much as 140 million tons of maize, rice, soybean and wheat lost annually to air pollution.

- Phase out the current fossil- fueled energy system and replace it with a diverse mix of carbon-neutral and carbon sequestration technologies. California's targets of 50 percent renewables in power generation, a 50 percent increase in energy efficiency, and a 40 percent reduction in greenhouse gas emissions by 2030 provide an excellent medium-term roadmap for the nation and the world. If carbon emissions are reduced by 80 percent by 2050, transitioning to zero emissions soon after, this action along with the SLCP mitigation action can keep global warming below 2 ºC for the rest of the century.

- Set up calibrated monitoring to quantify trends in emission sources and verify and make public the bending of ambient concentration curves of all air and climate pollutants.

Societal Transformation Solutions Cluster

The intra-regional, intra-generational and inter-generational equity issues of climate change raise major questions of ethics and justice. These questions compel us to reflect deeply on our responsibility to each other, to nature, and to future inhabitants of this planet — Homo sapiens and all other living beings alike. It is for these reasons that societal transformation merits such high ranking in this study, even above regulatory and technological solutions. Top-down action will be difficult to implement without substantial support from the general public, which can be accelerated by societal transformations from the bottom up.

2. Foster a global culture of climate action through coordinated public communication and education at local to global scales. Combine technology and policy solutions with innovative approaches to changing social attitudes and behavior.

- Promote coordinated information campaigns to inform choices available to strategic constituents:
    - The world's top carbon emitters, numbering 1 billion people, both individuals and institutions, who contribute about 60 percent of the world's greenhouse gas emissions. This targeted audience is easy to reach as they have readily available access to information technologies.

- Investors in and supporters of sustainable development throughout the world, by providing information on best practices in clean energy access for the world's poorest 3 billion citizens with very low carbon footprints. Among the energy poor are forest managers who offset the consumption and energy patterns of other consumers.
- The 3 billion low carbon emitters can serve as partners in worldwide de-carbonization by actively committing themselves, their families and their communities to learn about and to strategize for future access to carbon-neutral energy.

- Make the distribution of accountability and responsibility for sustainable energy consumption clear to all constituencies through accurate, transparent, widely available energy calculators that reveal how much energy different constituencies are consuming.

- Provide evidence-based indicators of the cumulative impacts of climate injustices. Past studies have demonstrated that the poorest 3 billion, whose emissions account for only 5 percent of total emissions, will nevertheless be disproportionately harmed by climate change, and that energy access choices based on more sustainable, low-carbon sources for these populations will result in prevention of climate disruption and collective harm to the planet and biodiversity.

- Create and integrate curricula at all levels of education, from kindergarten through college, to educate a new generation about climate change impacts and solutions.

3. Deepen the global culture of climate collaboration. Design venues where stakeholders, community and religious leaders converge around concrete problems with researchers and scholars from all academic disciplines, with the overall goal of initiating collaborative actions to mitigate climate disruption.

- Climate solutions require integrated behavioral, ethical, political, social, humanistic and scientific knowledge. Public and private institutions at every scale can create venues where decision makers, business leaders, community and religious leaders, and academics spanning the natural sciences, social sciences, humanities and arts converge around concrete problems, with the goal of creating dialogues, developing common understanding, and fostering collaborative action to mitigate climate disruption. Public universities must use their public missions and mobilize their knowledge and resources to partner with community-based agencies, local school districts and industry partners to educate locally for climate action.

- Initiate a culture of climate action by localizing interventions. Research shows that behavioral change and positive public opinion are more likely when the impacts of climate are recognized at a local scale and when barriers are lowered for people to participate in concrete actions to solve our climate crisis.

- Religious leaders can integrate protection of the environment with their traditional efforts to protect the poor and the weak. A model exhortation in this vein is Pope Francis' encyclical Laudato Si', which stated: "We are faced not with two separate crises, one environmental and the other social, but rather with one complex crisis which is both social and environmental. Strategies for a solution demand an integrated approach to combating poverty, restoring dignity to the excluded, and at the same time protecting nature."

Governance Solutions Cluster

4. Scale up subnational models of governance and collaboration around the world to embolden and energize national and international action[22]. Use the California examples to help other state- and city-level jurisdictions become living laboratories for renewable technologies and for regulatory as well as market-based solutions, and build cross-sector collaborations among urban stakeholders because creating sustainable cities is a key to global change[19].

- 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. Such efforts also speed up translation of science to policy actions, especially if those who have been marginalized in systems of governance are included in authentic ways that advance justice and equity. Over the past several decades, California has shown that subnational leadership in technological development, regulatory action, market-based solutions and provision of equitable benefits has demonstrated a viable path forward for other states and nations.

- National and subnational leaders must promote international action and cooperation in order for unilateral climate policies — such as California's climate mitigation mandate AB 32 or the American Clean Energy and Security Act — to succeed and to minimize potential detrimental effects, such as the risk of emissions leakages which arise when only one jurisdiction (California, for example) imposes climate policy but other jurisdictions do not.

- State-level climate policy should 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.

- Accelerate the impact of cities on climate mitigation through: (1) municipal and regional Climate Action Plans (CAPs); (2) green infrastructure projects, such as: (a) urban forestry to improve carbon sequestration and reduce the urban heat island effect; (b) locally decentralized micro-grids using renewable energy sources; (3) smart mobility planning and design for active living and healthy place-making (such as mixed- use in-fill and transit oriented development), which reduces greenhouse gas emissions by making cities less auto-centric and more walkable and bikeable; (4) incentivizing photovoltaic retrofits and new net-zero energy technology; and (5) corresponding civic engagement and public education strategies, accompanied by concrete local opportunities for participatory climate action, to change attitudes and behaviors.

- The 25th session of the UN-Habitat's Governing Council (April 2015) approved new International Guidelines on Urban and Territorial Planning which highlight the vital role cities can play in addressing climate change and other pressing social and ecological problems of the 21st century.
- Cities cover less than 2 percent of Earth's surface, but they consume 78 percent of the world's energy and produce more than 60 percent of all carbon dioxide and significant amounts of other greenhouse gas emissions[23].

Market- and Regulations-Based Solutions Cluster

5. Adopt market-based instruments to create efficient incentives for businesses and individuals to reduce CO_2 emissions. These can include cap and trade or carbon pricing and should employ mechanisms to contain costs. Adopt the high quality emissions inventories, monitoring and enforcement mechanisms necessary to make these approaches work. In settings where these institutions do not credibly exist, alternative approaches such as direct regulation may be the better approach — although often at higher cost than market-based systems.

6. Narrowly target direct regulatory measures — such as rebates and efficiency and renewable energy portfolio standards — at high emissions sectors not covered by market-based policies. Create powerful incentives that continually reward improvements to bring down emissions while building political coalitions in favor of climate policy. Terminate subsidies that encourage emission-intensive activities. Expand subsidies that encourage innovation in low-emission technologies.

The problem of emissions won't solve itself. Policy makers must send decisive signals to firms and individuals. So far, very few places in the world have adopted strong greenhouse gas mitigation policies. California is an exception, but California is less than 1 percent of the global problem. If we are to lead, we need to adopt policies that others can emulate; this is tricky because the best policies will vary with local circumstances. In general, there are two flavors of emissions policies: direct regulation and market- based (cap and trade and carbon pricing) regulation.

Economic theory and empirical evidence tell us that market approaches are more cost-effective. In a few cases where market based control systems have been used at scale — such as trading of lead pollution, trading of sulfur dioxide pollution, and European and Californian carbon markets — that theory is borne out by evidence. Yet it is already clear that market approaches are politically very difficult to implement in part for the very reasons that many analysts find them attractive: They make the real costs of action highly transparent[19].

As a matter of policy design, we have chosen not to come down in favor of either market based or regulatory approaches, but to include both. Specifically, we recommend the following:

- It is imperative to anticipate and design climate policies in a way that can contain compliance costs. Pure regulation leaves policies susceptible to large increases in compliance costs, particularly in the presence of capacity or production constraints that are inherent in energy markets.

- Another artificial market distortion that must be corrected is subsidization of fossil fuels worldwide, which provides carbon-intensive fuels with an advantage over low-carbon fuels. Where necessary, charge royalties for fossil fuels extracted on public lands and territorial waters.

- Regulation requires extremely sophisticated institutions and enforcement (such as the California Air Resources Board) to prevent leakage and to look ahead and assess how regulatory decisions interact with business strategy and the evolution of technology.

- Revenues from cap and trade or carbon taxes should be used to fund aggressive pursuit of innovative new technologies that can bend the curve and protect disadvantaged communities and those adversely affected by cap and trade or other regulatory strategies (for example, through payments for environmental services to rural communities engaged in low carbon development paths, such as forest dependent communities).

Technology-Based Solutions Cluster

The technological measures under solutions #7 and #8, if fully implemented by 2050, will reduce global warming by as much as 1.5 ºC by 2100, and combined with measures to reduce SLCPs in solution #9 will keep warming below 2 ºC during the 21st century and beyond.

Global emissions of CO_2 and other greenhouse gases in 2010 totaled 49 gigatons of equivalent CO_2 per year, with 75 percent due to increases in CO_2 and 25 percent from other greenhouse gases. This estimate from the IPCC 2013 [10] does not include two of the SLCPs, ozone and black carbon. About 32 gigatons per year are due to CO_2 from fossil fuels and industrial processes. The challenge for technology solutions is to bring down emissions of CO_2 to less than 6 gigatons per year by 2050, and reduce the emissions of methane and black carbon by 50 percent and 90 percent respectively by 2030. This in turn will reduce ozone levels by at least 30 percent. In addition, HFCs must be phased out completely by 2030. To indicate the importance of these non- CO_2 mitigation measures: HFCs are the fastest growing greenhouse gases; if emissions continue to grow at current rates, HFCs alone will warm the climate by 0.1 ºC by 2050 and 0.5–1.0 ºC by 2100.

7. Promote immediate widespread use of mature technologies such as photovoltaics, wind turbines, battery and hydrogen fuel cell electric light-duty vehicles and more efficient end-use devices, especially in lighting, air conditioning, appliances and industrial processes. These technologies will have even greater impact if they are the target of market-based or direct regulatory solutions such as those described in solutions #5 and #6 and have the potential to achieve 30 percent to 40 percent reduction in fossil fuel CO_2 emissions by 2030.

- Use of renewables and other low carbon energy sources are increasing rapidly. Catalyzed by falling prices, in 2014, renewables accounted for about 50 percent of all new power generation in the world (primarily in China, Japan, Germany and the United States), representing an investment of about $270 billion[24].

- Technologies exist today that can provide significant carbon reductions if used widely. Achieve a more reliable and resilient electric grid with at least 90 percent of all new generation capacity by 2030 from distributed and renewable technologies, such as photovoltaics, wind turbines, fuel cells, biogas and geothermal.
- Expand electrification of highly-efficient end-use devices, especially lighting, electric vehicles, machinery and plug load appliances.
- Examples from UC campuses demonstrate that deep energy efficiency investments are immediately amenable to widespread implementation.
- Accelerate the 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.
- Overall, these measures, if implemented with market and regulatory measures, can mitigate about 10 gigatons per year of CO_2 emissions by 2030.

8. Aggressively support and promote innovations to accelerate the complete electrification of energy and transportation systems and improve building efficiency. Support development of lower cost energy storage for applications in transportation, resilient large-scale and distributed micro-scale grids, and residential uses. Support research and development of a portfolio of new energy storage technologies, including batteries, super- capacitors, compressed air, hydrogen and thermal storage, as well as advances in heat pumps, efficient lighting, fuel cells, smart buildings and systems integration. These innovative technologies are essential for meeting the target of 80 percent reduction in CO_2 emissions by 2050.

- This solution will require significant investments in both basic and applied research and development, demonstration of prototypes, and commercial deployment.
- Energy storage is a vital enabling technology that holds the key to transitioning 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. While these innovations are promising, more research and development is needed to reduce the cost and ensure widespread deployment of battery and hydrogen storage. To achieve carbon- free electrification, complementary energy storage technologies over a variety of scales must be developed and deployed, requiring a new generation of sophisticated dynamic system control methods.
- Smart grid and micro-grid technology 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, thereby meeting the challenging environmental goals associated with climate change, air quality and water consumption. The evolution of this technology represents a paradigm shift. Our power grids will be designed, configured and operated in the future across a range of scales, from smart home devices to central plant power generation. Smart micro-grid systems also enable the ability to go off the main grid, which is especially important in regions that historically have been deprived of energy access, such as developing countries in

Africa and Asia.

- Advanced lighting based on efficient light-emitting diode (LED) technology is now commercially available and has a pay-back time of only one to two years. The replacement of all incandescent, metal halide and fluorescent lighting fixtures with LED lighting can reduce energy consumption from lighting by 40 percent. Investments are needed to capture further efficiencies, which are possible with the development of next-generation intelligent and more efficient 200 lm/Watt LED lighting products. These will be optimized for color and brightness to improve work and school productivity and building efficiency.

- Residential natural gas consumption can be reduced by 50 percent or more with widespread deployment of heat pumps and systems coupled to solar thermal and solar power generation. To accelerate this goal, we recommend deployment of an incentive program of rebates comparable to those for energy efficiency appliances. We also recommend the elimination of disincentives such as outdated and inappropriate regulations for ground source heat pump installations. Although more challenging, widespread deployment of heat pumps in larger commercial buildings also is possible, but will require further investments in applied research and development to accomplish comparable reductions in natural gas consumption. A promising approach that now is being tested is the capture of waste heat (and water) from cooling towers and recirculating it with heat pumps into the heating loop of buildings.

- The development of zero-carbon fuels such as hydrogen and highly-efficient engines with zero criteria pollutant emissions is required to substantially reduce the carbon footprint from light-duty vehicles and goods movement (medium-duty and heavy-duty vehicles, locomotives and ships) and, at the same time, achieve urban air quality goals [25].

- While full electrification is an achievable goal for light- duty and medium-duty transportation, some form of environmentally friendly renewable fuel solutions will be needed for heavy-duty transport, such as algal-based biofuels. Using algae, we can capture and beneficially reuse carbon dioxide produced from existing fossil energy sources such as natural gas electricity generation to produce diesel and jet fuels. Using wastewater and saline waters for algae growth, we will not place additional burdens on our limited fresh water resources, and can remediate pollutants such as nitrogen and phosphate from wastewaters before they reenter the environment to contaminate aquifers or oceans. Because these currently are not scalable in an economically competitive manner, further research is needed in this area.

9. Immediately make maximum use of available technologies combined with regulations to reduce methane emissions by 50 percent and black carbon emissions by 90 percent. Phase out hydrofluorocarbons (HFCs) by 2030 by amending the Montreal Protocol. In addition to the climate and health benefits described under solution #1, 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.

- The specific technological measures for reducing methane and black carbon are described in Table 2. These measures were developed by an international panel and reported in *UNEP WMO Report, 2011* [11].

Natural and Managed Ecosystem Solutions Cluster

10. Regenerate damaged natural ecosystems and restore soil organic carbon to improve natural sinks for carbon (through afforestation, reducing deforestation and restoration of soil organic carbon)[26]. Implement food waste reduction programs and energy recovery systems to maximize utilization of food produced and recover energy from food that is not consumed[27]. Global deployment of these measures has the potential to reduce 20 percent 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 potential for carbon mitigation from afforestation, reduced deforestation and restoration of soil organic carbon is about 8 to 12 gigatons per year.
- Integrate payment for environmental services into global, national and local economic systems to support forest-dependent communities in sustaining forest ecosystems as an effective and rapid means of sequestering carbon and achieving carbon neutrality. This also will achieve co-benefits for biodiversity, hydrological cycles and soil development.

- Support policies that reward complex agro-ecological systems rather than simplified tree crop systems. Half the world is still rural, and rural communities need to be part of the solution. This can be facilitated by reforming agrarian policy with a focus on managing carbon, which in many areas will involve natural forest management or agroforestry.

- Globally, one-third of food produced is not eaten; in the United States 40 percent is not eaten. The CO_2 and other greenhouse gases emitted in producing this wasted food contribute 3.3 gigatons annually to emissions. And when food is thrown away, methane — which is about 80 times more potent than CO_2 as a greenhouse gas — is released in landfills.

Table 2. Technological measures for curbing SLCP emissions (reproduced from [4])

CH_4 measures

Extended pre-mine degasification and recovery and oxidation of CH_4 from ventilation air coal mines Extended recovery and utilization, rather than venting, of associated gas and improved control of unintended fugitive emissions from production of oil and natural gas Reduced gas leakage from long-distance transmission pipelines	Extraction and transport of fossil fuels
Separation and treatment of biodegradable municipal waste through recycling, composting and anaerobic digestion as well as landfill gas collection with combustion/utilization Upgrading primary wastewater treatment to secondary/tertiary treatment with gas recovery and overflow control	Waste management
Control of CH_4 emissions from livestock, mainly through farm-scale anaerobic digestion of manure from cattle and pigs Intermittent aeration of continuously flooded rice paddies	Agriculture

BC measures (affecting BC and other co-emitted compounds)

Diesel particle filters for road and off-road vehicles Elimination of high-emitting vehicles in road and off-road transport	Transport
Replacing coal by coal briquettes in cooking and heating stoves Pellet stoves and boilers, using fuel made from recycled wood waste or sawdust, to replace current wood-burning technologies in the residential sector in industrialized countries Introduction of clean-burning biomass stoves for cooking and heating in developing countries[2,3] Substitution of clean-burning cookstoves using modern fuels for traditional biomass cookstoves in developing countries[2,3]	Residential
Replacing traditional brick kilns with vertical shaft kilns and hoffman kilns Replacing traditional coke ovens with modern recovery ovens, including the improvement of end-of-pipe abatement measures in developing countries	Industry
Ban on open field burning of agricultural waste[2]	Agriculture

1 There are measures other than those identified in the table that could be implemented. For example, electric cars would have a similar impact to diesel particulate filters but these have not yet been widely introduced; forest fire controls could also be important but are not included due to the difficulty in establishing the proportion of fires that are anthropogenic.

2 Motivated in part by its effect on health and regional climate, including areas of ice and snow.

3 For cookstoves, given their importance for BC emissions, two alternative measures are included.

3. THE URGENCY, THE HUMAN DIMENSIONS, AND THE NEED FOR SCALABLE SOLUTIONS

3.1 How Did We Get Here?

The invention of the steam engine and the subsequent acquisition of breathtaking technological prowess culminating in the current information age two centuries later have led to enormous improvements in human well- being. But the impressive improvement has come at a huge cost to the natural environment. The combination of air and water pollution, species extinction, deforestation and climate change has become an existential threat to life on this planet. The gargantuan transformation of the environment has stimulated ecologists and geologists to consider whether the Holocene epoch — the past 12,000 years of relatively constant climate and environmental conditions that stimulated the development of human civilization — has ended, and a new epoch, the Anthropocene, has begun, an epoch that recognizes that human exploitation of Earth has become akin to a geologic force [28].

Most of the changes listed in Table 3, and many others, have occurred in a span of time equivalent to a human lifetime beginning in the 1950s, which is considered the beginning of the so-called "great acceleration" of human impacts. This also is the period that has seen the steepest increase in global mean temperatures, global pollution and deforestation.

Table 3. Anthropocene: Growth in human activities from 1880s to 1990s [28]

Human activity	Increase in size
World population	Increased six-fold
Urban population	Increased thirteen-fold
World economy	Increased fourteen-fold
Industrial output	Increased forty-fold
Energy use	Increased sixteen-fold
Coal production	Increased seven-fold
Carbon dioxide emission	Increased seventeen-fold
Sulfur dioxide emission	Increased thirteen-fold
Lead emission	Increased eight-fold
Water use	Increased nine-fold
Fish catch	Increased thirty-five fold
Blue whale population	99 percent decrease

Reproduced from [29]

3.2 Carbon Dioxide Is Not the Only Problem

The greenhouse gas CO_2 contributes about 50 percent to the manmade heat added to the planet. The other 50 percent is due to several other greenhouse gases and particles in soot. Those greenhouse gases include nitrous oxide, methane, halocarbons (CFCs, HCFCs and HFCs), and tropospheric ozone. The warming particles in soot are black carbon and brown carbon [30]. The sources of these pollutants include fossil fuels (ozone, methane, black carbon), agriculture (methane and nitrous oxide), organic wastes (methane), biomass cooking and open burning (black and brown carbon) and refrigeration (halocarbons). Among these pollutants, the SLCPs (methane, black carbon, tropospheric ozone and HFCs) have lifetimes of days (black carbon) to 15 years (HFCs), which are much shorter than the century or longer lifetimes of CO_2 and nitrous oxide.

When we add up the warming effects of CO_2 with the other greenhouse gases, the planet should have warmed by about 2.3 ºC, instead of the 0.9 ºC observed warming. About 0.6 ºC of the expected warming is still stored in the deep oceans (to about 1,500 meters). That heat is expected to be released and contribute to atmospheric warming in two to four decades. The balance of 0.8 ºC involves a complication due to air pollution particles. In addition to black and brown particles (which warm the climate), fossil fuel combustion emits sulfate and nitrate particles, which reflect sunlight like mirrors and cool the planet. The mechanisms of warming and cooling are extremely complex. But when we add up all of the effects, sulfate and nitrate particles have a net cooling effect of about 0.8 ºC (0.3–1.2 ºC range). Summing 0.9 ºC of observed warming, 0.6 ºC stored in the oceans, and the 0.8 ºC masked by particles, adds up to the 2.3 ºC warming we should have seen from the build up of greenhouse gases to-date.

The particle cooling effect of 0.6 ºC should not be thought of as offsetting greenhouse gas warming. This is because the lifetimes of these particles last just days, and when stricter air pollution controls worldwide eliminate the emission of these particles, the 0.6 ºC cooling effect will disappear. This however does not imply that we should keep on polluting, since air pollution leads to 7 million deaths worldwide each year, as well as reductions in precipitation and decreases in crop yields.

3.3 Planetary-Scale Warming: How Large and How Soon?

Of the CO_2 released to the air, 44 percent remains for a century or longer; 25 percent remains for at least a millennium. Due to fast atmospheric transport, CO_2 envelopes the planet like a blanket. That blanket is growing thicker and warmer at an accelerating pace. It took us 220 years — from 1750 to 1970 — to emit about 1 trillion tons of CO_2. We emitted the next trillion in less than 40 years. Of the total 2 trillion tons humans have put into the atmosphere, about 44 percent is still there. At the current rate of emission — 38 billion tons per year and growing at a rate of about 2 percent per year — the third trillion will be added in less than 20 years and the fourth trillion by 2050.

How does the CO_2 blanket warm the planet? It works just as a cloth blanket on a cold winter night keeps us warm. The blanket warms us by trapping our body heat. Likewise, the CO_2 blanket traps the heat given off by the Earth's surface and the atmosphere. The surface and atmosphere absorb sunlight and release this solar energy in the form of infrared energy, some of which escapes to space. The human-made CO_2 blanket is very efficient at blocking some of this infrared energy, and thus warms the atmosphere and the surface.

How large? Each trillion tons of emitted CO_2 can warm the planet by as much as 0.75 ºC. The 2 trillion tons emitted as of 2010 has committed the planet to warming by 1.5 ºC. The third trillion we would add under business-as-usual scenarios would commit us to warming by 2.25 ºC by 2030.

How soon? A number of factors enter the equation. To simplify, we likely will witness about 1.5 ºC (or two-thirds of the committed warming) by 2050, mostly due to emissions already released into the atmosphere (although that amount of warming could come as early as 2040 or as late as 2070). By 2050, under a business-as-usual scenario, we will have added another trillion tons and the 2050 warming could be as high as 2 ºC — and the committed warming would be 3 ºC by 2050.

What is our predicament? We get deeper and deeper into the hole as time passes if we keep emitting at present rates under business-as-usual scenarios. The problem is that CO_2 stays in the atmosphere so long; the more that is there, the hotter Earth gets. If we wait until 2050 to stop emitting CO_2, there would be no way to avoid warming of at least 3 ºC because the thickness of the blanket covering Earth would have increased from 900 billion tons (as of 2010) to about 2 trillion tons (in 2050). Our predicament is analogous to stopping a fast-moving train: You have to put on the brakes well in advance of the point you need to stop; otherwise you will overshoot the mark.

3.4 Facing the Worst Scenario: the Fat Tail

A projection such as 2 ºC warming by 2050 is subject to a three-fold uncertainty range. It is important to note, however, that the uncertainty goes both ways: Things could be a little better than the average expectation, or a lot worse. The most disturbing part of the uncertainty is that it has a so-called “fat tail,” that is, a probability of a warming two to three times as much, or even more, than the 2 ºC that would result from best- case greenhouse gas mitigations. For example, the IPCC (2013 report) gives a 95 percent confidence range of 2.5–7.8 ºC warming for the baseline case without any mitigation actions [10]. A warming in the range of 4 to 7.8 ºC can cause collapse of critical natural systems such as the Arctic sea ice, the Asian monsoon system and the Amazon rain forest. Economists argue that our decisions should be guided by such extreme possibilities and that we should take actions to prevent them, much as we already do in requiring buildings to withstand earthquakes and automobile manufacturers to equip our cars with seat belts and air bags in the unlikely event of an accident.

3.5 From Climate Change to Climate Disruption: Amplifying Feedbacks

Observations with satellites, aircraft, ships and weather balloons gathered over the past three decades are providing disturbing evidence of nonlinear amplification of global warming through feedbacks. This has raised concerns that continued warming beyond 2 ºC can lead to crossing over tipping points in the climate system itself or in other natural and social systems that climate influences. Examples of climate-mediated tipping points include depletion of snowpack, drought, fires and insect infestations threatening whole forests, and the opening of new oceans in the Arctic. The following are among the many major feedbacks for which we have empirical evidence.

Feedbacks between warming, Arctic sea ice and absorption of the sun's heat

Observations from 1979 to 2012 reveal that warming in the Arctic has been amplified by 100 percent due to a feedback (a vicious cycle) between surface warming, melting sea ice and increased absorption of solar heat [31]. Melting ice exposes the underlying darker ocean, which then absorbs rather than reflecting sunlight as the bright ice does. The added absorption of solar energy has been equivalent to the addition of 100 billion tons of CO_2 to the air. The large warming has exposed a whole new oceanic region in the Arctic.

Feedbacks between warming, snowpack, drought and fires

The California example: California has kept up with the average warming of the planet by about 0.9 ºC, with regions such as the Central Valley warming in excess of 2 ºC. This warming melts the snowpack, and the dark surface underneath absorbs more heat and therefore increases moisture loss by 7–15 percent per degree of warming. This amplified drying becomes chronic, since the warming gets worse each year due to increase in emissions of warming pollutants. The chronic drying is drastically magnified into a mega- drought when rainfall decreases sporadically due to variability in the weather, similar to what has happened over the past four years. The resulting extreme drying of the soil and vegetation contributes to fires. The forest fires, in turn, emit more CO_2 as well as black carbon and methane, the two largest contributors to warming next to CO_2. This phenomenon is not confined to California. Similar problems are occurring throughout western North America. The melting of northern latitude permafrost and resultant increases in methane emissions are another potential feedback element in warming driven by similar patterns.

Feedbacks between warming and atmospheric moisture

With every degree of warming, air holds about 7 percent more moisture. This means that warming is amplified by a factor of two, since water vapor itself is a dominant greenhouse gas [10, 32]. This is one of the most vicious cycles that amplifies greenhouse warming. Increases in water vapor also contribute to extreme storms and increased rainfall, which have become more common, leading to devastating floods around the world.

3.6 The Human Dimension: Public Health and Food and Water Security

Climate change directly affects human health through heat waves and increasing frequency and severity of weather extremes such as storms, floods and droughts. Secondary effects include wildfires, worsened air quality, drinking water scarcity and contamination, crop and fishery failures, and expansion of transmissible diseases. Floods, droughts and resource shortages trigger population displacement, mental health effects and potentially violent conflict, both within countries and across borders. Such events will affect poorer nations much more severely, at east initially, but wealthy countries will not be spared significant harm, such as we have already seen from several major hurricanes, floods, droughts and fires in the United States. Within wealthy nations, poor communities will tend to suffer disproportionately from the health effects of climate change.

While the focus of climate change discussions is on CO_2 from fossil fuel combustion particulate pollution — nitrogen oxides, toxic pollutants and ozone created from power plants, vehicles and other fossil fuel combustion — also have devastating impacts on human lives and well-being [33], including:

- 3 million premature deaths every year from air pollution originating from fossil fuel combustion.
- Stroke, cardiovascular disease, acute and chronic respiratory disease and adverse birth outcomes.
- More than 200 million tons of crops are destroyed every year by ozone pollution[14].

- Mega-droughts in sub-Saharan Africa and the Indo-Gangetic plains of South Asia. The blocking of sunlight by particles from combustion of coal and petroleum, and the resulting surface dimming has slowed down rain-bearing weather systems [34, 35].

Direct and Indirect Health Effects of Coal, Petroleum and Gas are also immense and include: Mortality and morbidity; Cardiovascular disease; Acute respiratory infection; Stroke; Mental health; Vector-borne diseases; Water- and food-borne diseases; Heat stroke and other extreme weather related effects; Lung cancer, drowning, under-nutrition; Harmful algal blooms; Mass migration; Decreases in labor productivity[21]. The estimated cost of the health effects is in the range of $70 to $840 per ton of CO_2.

3.7 Environmental Equity, Ethics, and Justice: What Is Our Responsibility?

One billion of us consume about 50 percent of the fossil fuel energy consumed on Earth and emit about 60 percent of the greenhouse gases; In contrast, the poorest 3 billion, who still rely on pre-industrial era technologies for cooking and heating, contribute only 5 percent to CO_2 pollution [36]. Thus, the climate problem is due to unsustainable consumption by just 15 percent of the world's population. Fixing the problem thus has to simultaneously lower the carbon footprint of the wealthiest 1 billion, while allowing for growth of energy consumption and expansion of carbon sinks, such as forests, needed to empower the poorest 3 billion. It is in this context that it is critical to bend the curve through transforming to carbon neutrality in developed nations while sharing technology that enables developing nations to leapfrog over use of fossil fuels to produce the energy they need [37]. Indeed, for the poorest 3 billion, doing so is literally a matter of life and death.

For example: The poorest 3 billion live mainly in rural areas relying on mixed market and subsistence farming on few acres. A four- year mega-drought of the type that California is experiencing now would change their forms of livelihood and expand the likelihood of both temporary and permanent migration. Small island nations in the tropical Pacific already are facing mass migration caused by increased sea level. If sea level rise reaches 1 meter or more, as is plausible with business as usual, low- lying coastal nations with populations of more than 100 million people — such as Bangladesh — will move to India and other neighboring nations. While likely slower than sudden catastrophic events, the size and scope of such climate migration could make today's Syrian migration crisis look mild by comparison.

- With melting of Himalayan and other glacier systems, such as those of the Andes, more than 1.5 billion people would be left without most of their permanent water supply.
- These are critical practical issues, but there are even more substantial inter-generational ethical issues. A large fraction of CO_2 gases stay in the air longer than a century, and when combined with the added heat stored in the depths of the ocean, will affect climate for thousands of years. Moreover, increased CO_2 makes the oceans more acidic, which threatens at least a quarter of the ocean's species with extinction.

If the carbon footprint of the entire 7 billion became comparable to that of the top 1 billion, global CO_2 emissions would increase from the current 38 billion to 150 billion tons every year and we would add a trillion tons every seven years, in turn adding 0.75 ºC warming every seven years. Such impacts mean that children alive today, their children, and their grandchildren, along with all generations to come, will suffer from our unsustainable burning of fossil fuels. What is our responsibility to them?

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Supporting Information Captions

Figure 1. Simulated temperature change under various mitigation scenarios and SLCP Climate benefits

Table 1. California's Living Laboratory Solutions: "Art of the Possible" for Bending the Climate Change Curve

Table 2. Technological measures for curbing SLCP

Table 3. Anthropocene: Growth in human activities