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ORIGINAL RESEARCH REPORT

Chapter 3. Science and Pathways for Bending the Curve

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Greenhouse gas emissions from fossil fuel combustion and land use are changing the radiative budget of the Earth and changing its climate. The negative impacts of this climate change on natural and human systems are already emergent. The solution is to eliminate greenhouse gas emissions altogether as soon as possible, but the rate at which these emissions can decrease is limited by human reliance on fossil fuels for energy and the infrastructural, socio-economic, and behavioral inertia of current systems around the world. In this chapter, we discuss the physical impacts as well as the many challenges and obstacles to 'bending the curve', and provide a framework of possible solutions.

Introduction

Causality of Global Environmental Change

Scientific consensus on global warming. It is now abundantly clear that the Earth's climate is warmer than it has been in centuries, and that the climate is continuing to warm at an accelerating rate [1]. The warming is evident in California, as 2014 was the warmest year and January-March the warmest winter on record for the state [2]. This warming is manifested not only in higher temperatures but also in longer growing seasons, rising sea levels, rapid melting of glaciers and sea ice, and the disappearance of snow from colder and more mountainous regions throughout the northern continents [1].

All available evidence suggests that anthropogenic emissions of long-lived greenhouse gases and short-lived climate forcings are the primary cause of the warming [1]. Natural causes of warming, for example higher solar irradiance, long-term variations in the Earth's seasonal cycles, or reduced volcanic activity, are all clearly inconsistent with the observed patterns of temperature increase [1]. Long-lived greenhouse gases increase the Earth's natural and beneficial greenhouse effect by trapping heat in the climate system before it can be released to outer space. In contrast to conventional pollutants such as smog, once these gases are produced, they can reside in the atmosphere for centuries to millennia. Short-lived climate forcers include aerosols such as black carbon as well as greenhouse gases such as tropospheric ozone and methane. Black carbon and other carbon-containing aerosols absorb sunlight and convert it to heat, thereby warming the surrounding air. Fortunately the characteristic atmospheric lifetimes of these species range from just days to weeks for soot and ozone to roughly a decade for methane.

Main sources of greenhouse gases and short-lived climate forcings. The main long-lived anthropogenic greenhouse gases are carbon dioxide, nitrous oxide, and the flourinated or so-called F gases in order of their impact on the environment. Due to the very different strengths and lifetimes of these gases, it is easiest to understand their sources in common units of equivalent CO_2, or the amount of carbon dioxide that would lead to the same amount of radiative forcing over a century as each individual greenhouse gas. Using these common units [3], CO_2 produced by fossil fuel combustion and industrial processes represents 65% of all anthropogenic greenhouse emissions during 2000–2010, and it is therefore the most important agent of climate forcing. Combined with the 11% of CO_2 emissions from forestry and other land use, carbon dioxide comprises over 75% of all greenhouse emissions. On a global scale, half of these greenhouse emissions are contributed by just three economic sectors encompassing electricity and heat production, transport, and industry [3]. Global emissions of greenhouse gases are equivalent to 49 Gt of CO_2, and grew at an average rate of 2.6%/year between 2010 and 2015, though it is estimated that CO_2 emissions from burning fossil fuels increased by an average of just 0.3%/year 2014–2016 (GCP budget [1]). However, roughly half of the cumulative anthropogenic emissions of CO_2 since the start of the industrial age some 265 years ago have occurred in just the last 40 years [3].

The main short-lived climate forcing agents are tropospheric ozone, methane, and black carbon [4]. Because

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anthropogenic tropospheric ozone is a by-product of emissions of methane and other non-greenhouse gases, controls on ozone require controls on these other gases. The impacts of short-lived climate forcers decay relative to those of long-lived greenhouse gases as the time horizon for the impacts grows from decades to centuries. The impacts on various time horizons can be quantified using the concept of global warming potential [4], a measure of the greenhouse effects of these species relative to that of CO_2. Since the maximum benefits from emission controls on methane and black carbon are realized in just decades, these benefits are reflected in the global warming potentials of these species on comparable time horizons. On timescales of 10 years, the emissions-weighted global warming potentials of methane and black carbon are roughly 100% and 60% that of CO_2 [3]. Over 20 years, the potentials for methane and black carbon drop to approximately 80% and 35% of the CO_2 potential. These large potentials show that emissions controls on short-lived climate forcers could have an effect comparable to that of large reductions in CO_2, the dominant long-lived greenhouse gas, on decadal time horizons.

California emissions in 2013 were nearly 460 Mt of CO_2 equivalent and represented roughly 1% of global emissions [5]. Carbon dioxide represented 84% of these emissions followed by methane at 9% and the other long-lived greenhouse gases at 7%. The dominant sources by economic sector are emissions from transportation (37%), industrial activity (23%), and electrical generation (20%). Current black carbon emissions are highly uncertain due to the uncertainties in source inventories and range between 18 to 25 Gg (i.e. kt) per year [6].

Physical effects

Continued emissions of greenhouse gases and short-lived species will lead to alterations in the physical climate and environment that are unprecedented in human history. Many of the patterns of these alterations have been observed in the present-day Earth system, and predictions strongly suggest that these patterns will amplify over the next several centuries. These global patterns include higher surface temperatures, greater ocean temperatures, elevated evaporation and rising atmospheric moisture, large-scale shifts in precipitation, more frequent extreme phenomena such as droughts and heat waves, and faster melting of sea ice, land glaciers, permafrost, and the Greenland and Antarctic ice sheets [1]. Climate models consistently show that these impacts increase with increasing emissions. It is useful to consider the impacts under a future scenario with minimal coordinated international mitigation of greenhouse emissions that approximates a plausible business-as-usual pathway for humanity [7]. Under this scenario, by 2100 global temperatures increase by 3.7 °C, land temperatures increase by 4.8 °C, and the Arctic warms by 8.3 °C [1]. Since the ocean has greater heat capacity and hence thermal inertia than land, it warms more slowly but still heats up by 3.7 °C over the 21st century. The lower Earth's atmosphere, or troposphere, warms in conjunction with the surface.

For each additional degree Celsius increase in atmospheric temperature, its holding capacity for water vapor increases by 7%. As a result, rates of evaporation increase over most of the globe with notable exceptions in regions where precipitation is projected to decline sharply. Global rainfall does not rise nearly as rapidly with temperatures as does atmospheric moisture, increasing just 1 to 3% per °C of surface warming [1]. Instead, the two main alterations to precipitation are a shift of the storm tracks poleward and a strengthening of the gradients between regions with high and low rainfall, especially over oceans, following a pattern known as the "wet get wetter and the dry get drier". Both types of alterations are already underway and have been extensively documented in the current climate [1]. In addition, the strength of extreme downpours that recur every 20 years strengthens by 4–5% for each °C of additional warming.

These patterns have significant implications for the climate of California and the western U.S., including their temperature, precipitation, and water resources. The last decade was already the warmest in the 110 instrumental record [8]. Assuming business-as-usual, average projected temperatures in the western U.S. could increase by roughly 5 °C in winter and by over 6 °C during summer [1] by 2100. Since annual mean temperatures for California have typically fluctuated by less than 1 °C since records started in 1895 [9], these warmings are historically unprecedented and would alter California's climate and ecosystems for centuries to millennia. The storm tracks are likely to shift northward by 1 or 2 degrees latitude under business-as-usual [1], potentially exacerbating drier conditions in southern California. The drying in southern arid regions of the state is increasingly likely by 2100. Rainfall will probably not change during summer but will increase by up to 10% in winter, although the fraction of this precipitation that falls as rain rather than snow will increase with greater warming [1]. As a result of this shift towards rain and higher temperatures in the Sierras, critical snowpack and streamflow are projected to decline by 1/3 by mid century [8]. At the same time, the risks of extremes is increased in a warmer climate, with southern California facing downpours from wintertime atmospheric rivers that are three times as intense as downpours today.

Negative impacts

Challenges from climate change arise from longer-term, gradual changes, such as sea-level rise, as well as from projected changes in weather extremes that have more sudden impacts. The independent implications of climate change for water security, agriculture, human health, energy systems and ecosystems are important, with the intersection of these impacts producing highly non-linear impacts on society overall. Knowledge about climate impacts continues to evolve and be refined, through both direct observations over time and improvements in impact modeling to synthesize those observations and project future impacts. The intersection of climate warming and climate variability may produce the most devastating societal impacts, such as health, water, ecosystem and agriculture impacts from heat waves, cold waves, extreme precipitation, floods and droughts. There have been changes in some types of extreme weather events over the last several decades. Heat waves have become more frequent and intense, apparent in the Western United States and elsewhere. Cold waves have become less frequent and intense across the nation. There have been regional trends in floods and droughts. Droughts in the Southwest and heat waves everywhere are projected to become more intense. These impacts are the societal interaction with climate change. What climate change means to our individual and collective wellbeing, to our economic opportunities, to our quality of life, to imminent humanitarian emergencies and to the future for succeeding generations are among the reasons we care about climate. Systematic identification, characterization and prioritization of the greatest and most urgent risks we face from global change, along with the appropriate responses, are scientific and societal grand challenges [10].

Sea-level rise. Increased coastal flood damage and corresponding adaptation may be the most costly aspect of climate change, both in California and globally. Average global flood losses in 2005 are estimated to be approximately $6 billion per year; and in the absence of adaptation the projected increase in average losses by 2050 is huge, with aggregate losses increasing to more than $1 trillion per year [11]. Damages of this magnitude are unlikely to be tolerated by society; and widespread adaptation, though costing tens of billions per year, is much less than the cost of avoided damages [12]. It is estimated that in California property worth $50 billion and at least 260,000 people are currently located in areas vulnerable to a 100-year coastal flood. Even with no further development, a 100-year flood in 2100, after a 55-inch sea-level rise, would put at risk 480,000 people and $100 billion of property [13]. Note that even if concentrations of greenhouse gases had been stabilized in 2000, we are already committed to warming of about another 0.5 °C and additional global sea level rise of over three times what has already occurred, by the end of the 21st century [14]. Sea level is expected to occur at an increasing rate. Along the California coastline in 2050 sea level could be 10–18 inches higher than in 2000, and 31–55 inches higher by the end of this century [13]. A wide range of critical infrastructure — including schools, roads, hospitals, emergency facilities, wastewater treatment plants, airports, ports, and energy facilities — will be at increased risk of flooding.

Water shortages. The level of a region's water security — defined as the reliable availability of an acceptable quantity & quality of water for health, livelihoods & production, coupled with an acceptable level of water-related risks — depends heavily on storage to balance supply and demand in a variable climate. Recent multi-year dry periods in California, the Western United States and other regions have highlighted vulnerabilities as groundwater storage declined and evaporative demand increased [15, 16]. The western United States and other areas are also experiencing a decline in mountain snowpack storage, which will further decline in a warmer climate. Challenges to California's long-term water security are indicative of those in many regions. For example, both grey (e.g. levees, canals, dams) and green (e.g. watersheds) are either decayed or vulnerable [17]. Land subsidence together with rising sea levels in the Sacramento-San Joaquin Delta may cause water levels to reach dangerous levels as early as 2050, challenging both the adequacy of levees and the ability of the state to respond to improve preparedness [13]. Sierra Nevada forests, which provide over 60% of the state's water supply, have unsustainably high tree densities, affecting both water yield and wildfire intensity. These watershed challenges will increase as growing seasons lengthen in response to warming, more precipitation is used by forest vegetation and less is available for runoff and thus for water supplies [18]. A precipitation shift from snow towards rain may lead to a decrease in streamflow over broad areas of the earth [19]. Difficult legal and political barriers and institutional challenges impede implementing the most effective adaptation strategies; and lack of accurate, timely, transparent water-resources data and information limit decision making [13, 20]. This crisis is amplified by the increase demand due to current and future population growth. California is estimated to have 44 million people by 2030, and 50 million by 2050, up from the current 38 million.

Agricultural losses. Climate-change effects on agriculture will have consequences for food security, both in the U.S. and globally, through changes in crop yields and food prices and effects on food processing, storage, transportation, and retailing. Adaptation measures can help delay and reduce some of these impacts [21]. Agriculture is the dominant water user, consuming more than 70% of total global water demand. Up to now agriculture has adapted to climate change in many diverse regions by adaptive actions, including expansion of irrigated acreage in response to drought, regional shifts in crops and cropped acreage, continued technological advancements, and other adjustments. Changes in temperature and water availability — annual and seasonal shifts as well as extremes — affect both crop yield and quality, making California's agriculture sector highly sensitive to climate change. Indirect impacts will also take a toll, including possible further decreases of pollinators and increases of pests and disease [13]. These same negative impacts will be found globally. The rising incidence of weather extremes will have increasingly negative impacts on crop and livestock productivity because critical thresholds are already being exceeded. The length of the frost-free season (and the corresponding growing season) is increasing nationally, with the largest increases occurring in the western U.S., affecting ecosystems and agriculture [21]. Projected yield losses from changes in minimum and maximum temperature, as well as changes in water availability, are crop and region dependent, making actual impacts challenging to predict accurately. Nevertheless, simple measures of growing season temperatures and precipitation suggest that recent climate trends have had a discernible negative impact on global production of several major crops [22].

Direct health impacts. Climate change threatens human health and well-being in many ways, including impacts from increased extreme weather events, wildfire, decreased air quality, threats to mental health, and illnesses transmitted by food, water, and disease-carriers such as mosquitoes and ticks. Some of these health impacts are already underway in the United States [23]. Many of the gravest threats to public health in California stem from the increase of extreme conditions, principally more frequent, more intense, and longer heat waves. Particular concern centers on the increasing tendency for multiple hot days in succession, and heat waves occurring simultaneously in several regions throughout the state [13]. Public health could also be affected by climate change impacts on air quality, food production, the amount and quality of water supplies, energy pricing and availability, and the spread of infectious diseases. These impacts could have potentially long-term repercussions, and the severity of their impacts depends largely on how communities and families can adapt. The public-health implications of short-lived greenhouse gases, including ozone, black carbon and sulfate, that are known account for most of the direct damage to human health from energy use worldwide [24, 25].

Decreased efficiency and reliability of the energy systems. Increasing temperatures, decreasing water availability, more-intense storm events, and sea level rise will each independently, and in some cases in combination, affect the ability of the United States to produce and transmit electricity from fossil, nuclear, and existing and emerging renewable energy sources. In California and many other regions of the world, increases in average temperature and higher frequency of extreme heat events combined with new residential development will drive up the demand for summer cooling; and this growing demand will only partially be offset by decreased winter heating and improved energy efficiency [13]. Thermoelectric power plants, which provide much of the electricity for the United States and Europe, directly depend on the availability and temperature of air and water resources for cooling. It is projected that lower summer river flows and higher water temperatures will reduce cooling capabilities and thus power-plant capacity on the order of 5–20% in mid-century [26]. High-elevation hydropower is especially vulnerable to climate, as evidenced in part by the over 60% drop in production in California from water-abundant 2011 to 2014, the third year of drought [27]. Lower-elevation hydropower is also vulnerable, and all hydropower will continue to suffer from sparse hydrologic information and inaccurate forecasts [13]. Electricity transmission and distribution systems carry less current and operate less efficiently when ambient air temperatures are higher, and they may face increasing risks of physical damage from more intense and frequent storm events or wildfires [28].

Ecological impacts. Terrestrial ecosystems have encountered substantial warming over the past century, and the projected rapid pace of 21st-century global warming implies required range shifts of up to several kilometers per year, raising the prospect of daunting challenges for ecosystems [29]. The length of the frost-free season (and the corresponding growing season) has been increasing for decades, with large increases occurring in the western United States that affect both ecosystems and agriculture [30]. In addition to being one of the most ecologically diverse regions globally, California's ecosystems provide a wide spectrum of goods and services supporting the economy of California and human well-being, including fresh water, fertile soil, biological and genetic diversity, crop pollination, carbon storage, climate stabilization, and recreational opportunities [13]. The combination of high climate-change velocity and multidimensional human fragmentation will present terrestrial ecosystems with an environment that is unprecedented in recent evolutionary history [29]. Besides affecting ecosystem health and fragmentation, climate warming determines the extent and intensity of wildfires, challenging the ability of resource managers to assist in ecosystem adaptation. Climate change, combined with other stressors, is reducing the ability of ecosystems to improve water quality and regulate water flows, and overwhelming their capacity to buffer the impacts from extreme events like fires, floods, and storms [31].

Urgency of the Problem

Problematic inertia

Earth's climate system more accurately encompasses two coupled systems: the physical – consisting of natural forcing and internal dynamics – and the anthropogenic, with its own technological, social, political, and cultural dynamics. In addition to lags in the physical system, these human elements add additional key inertias to the climate system as a whole, and thus limit the maximum potential rate of mitigation. Study of human system dynamics has often been overlooked in past climate research (e.g., [32]), but recent interdisciplinary Earth systems science work and climate-focused studies across the social sciences have resulted in tremendous progress in our understanding of the sources and structures of these inertial elements.

Broadly, such research underscores that mitigating actions will not occur unless the appropriate incentives – whether economic, policy-based, or social norms-driven – exist for individuals, firms, communities, states, and nations to undertake them. Changing economic incentives elicit relatively quick responses, but may be economically or politically costly to engineer (e.g., by new R&D, taxes, subsidies, or other policies). Behavioral changes may result in effectively "free" mitigation through demand shifts, but can be very slow.

Physical inertia. Several factors essentially guarantee that global warming will continue and likely accelerate during the 21st century. First, many of the long-lived greenhouse gases emitted in the past still reside in the atmosphere and therefore still enhance the Earth's greenhouse effect. Half the carbon dioxide emitted since the start of industrialization in 1780 were emitted in the last 40 years [33]—concentrations of CO_2 are now 142% higher now than they were in 1780. Due to the extremely long residence times of CO_2 in the atmosphere, ranging from centuries to millennia [34], these emissions will continue to force climate change for the foreseeable future. The flourinated greenhouse gases were chosen for industrial activities precisely because they are chemically inert in the lower atmosphere, and these F gases have residence times measured in tens of thousands of years [1]. Cumulatively, these historical emissions of 1900 Gt of CO_2 plus other gases represent a long-term commitment of the Earth and its inhabitants to a warming climate for centuries [1]. Climate models consistently show that even if we were to stop increasing the concentrations of long-lived greenhouse gases, the climate continues to warm by between 0.5 and 1 °C [1]. If we continue business as usual and burn an additional 1000 Gt of CO_2, it is reasonably likely the climate will warm by 2 °C by 2100.

The annual average increase in anthropogenic emissions of CO_2 since 2000 is nearly 3% [33]. These anthropogenic emissions have helped push the atmospheric concentration to 400 ppm, a concentration the Earth has not experienced for millions of years [35]. These continued and growing emissions elevate greenhouse gas concentrations, enhance the greenhouse effect, and accelerate global warming.

Third, the climate system takes millennia to readjust to a balanced state once it is disturbed by significant emissions of long-lived greenhouse gases. The reason is that the ocean has nearly 1000 times the heat capacity of the atmosphere [36]. Numerical experiments have recently confirmed the estimates of this long equilibration timescale based on basic principles of thermodynamics [37]. Even though other parts of the climate system respond much more quickly both to the emission and mitigation of greenhouse gases, the long response time and huge heat capacity of the ocean guarantee that climate change will be a continued burden on society and the environment for the next several thousand years.

Technological inertia. A growing body of literature recognizes that the enormous infrastructural investments that have been made both publicly and privately over the past century have created a path dependence that cannot be instantaneously undone. Since such investments are made with expectations of certain returns over the lifetime of the technology – and since cutting those revenue streams short would require both tremendous political and economic resources – one of the most plausible strategies for disruptive technology changes is to replace carbon-intensive technologies, like fossil fuel-burning power plants, with cleaner alternatives at the ends of their lifetimes. However, the corollary of such a strategy is that emissions from existing capital stock remain effectively "locked in" until such technologies can be reasonably replaced [38]. The existence of this infrastructural inertia suggests that we should use "commitment accounting" – which takes into account all future anticipated emissions from a lumpy technological investment – rather than annual accounting, to better quantify and compare the full impacts of different types of infrastructure investments [39].

Political/institutional inertia. Additional inertia results from both time lags inherent to the policymaking process (e.g., the time needed to craft, adopt, and implement new legislation, even when there is broad agreement) and from politics itself. This latter category includes ideological disagreement about what should be done, the need (at all scales) to balance multiple other non-climate objectives, and the length and timing of political cycles, which may render serious action on climate impossible during (re)election campaigns or for the entire duration of certain leaders' tenure. Recent research has found that earlier efforts to promote international cooperation have not been effective, but the new Paris framework is much more auspicious. Namely, climate mitigation is a difficult political problem for structural reasons: deep carbon cuts are expensive and politically costly to leaders in the domestic arena, while the benefits of mitigation are (mostly) global public goods, and the time scale for accrual of those benefits is slower than any democratic political tenure [40]. Finally, even if these hurdles are overcome, credibility (both in terms of setting goals within coalitions and in terms of regulatory enforcement) remains a looming issue; theoretical models suggest that lack of credibility creates one of the most costly inertias in terms of locked-in emissions because it creates a ripple effect of uncertainty throughout an economy that incentivizes business-as-usual [41].

Behavioral inertia. Deep carbon cuts will require widespread individual buy-in, both to facilitate demand-side changes and to create a social and political climate in which serious climate mitigation (and adaptation) measures may be undertaken with domestic support. Such buy-in is notoriously slow to attain, however, and thus constitutes another source of inertia. The psychology literature has identified major categories of psychological barriers that explain the discrepancy between individuals' understanding of the climate mitigation challenge and their own behaviors, even when taking into account technology lock-in and political environments [42], but it is unclear just what it might mean to address such barriers.

An additional source of behavioral inertia stems from a relative lack of understanding about the dynamics governing individuals' attitudes about and behaviors surrounding climate mitigation, compared to other social issues. We do not yet have a consistent picture and key knowledge gaps remain [3]. However, recent large-scale experiments with customized energy consumption reports suggest that social messaging can change consumption patterns, but counterintuitively find that such messaging needs to be repeated over time, and that individuals continue to respond [43]. Even more surprising are recent findings that individuals seem to respond to and act on a notion of collective responsibility for climate change more than a personal one [44]. Such findings resonate with theories of social norms change, in which communities collectively, and in a short amount of time, radically articulate and then behave in accordance with new values. Such theories of social change offer intriguing hope for alleviating human inertias in the climate system, but more research is needed to understand how such theories can be successfully applied to climate [45].

Rising energy demand

In 2010, total anthropogenic emissions reached 49 Gt CO_2-eq per year, with 65% of these emissions in the form of CO_2 from fossil fuel combustion and industrial processes; 11% as CO_2 from forestry and land use change; 22% as N_2O and CH_4, mostly from agriculture; and the remaining

2% from high-GWP F-gases [3]. Perhaps most notable is that between 2000–2010, anthropogenic emissions rose more than 20%. From these global trends, the dominance of the energy and industrial processes, and the primary role of fossil fuels as drivers of emissions, stand out. Nevertheless, these global sectoral trends hide tremendous heterogeneity at the national level.

The drivers of anthropogenic emissions can be categorized or accounted for in numerous ways, but broadly, several key societal trends explain both changes in global total emissions and changes in the sectoral and species composition of those emissions. These trends also help to explain the heterogeneity in these patterns across countries. As outlined in the IPCC 5th Assessment Report, key drivers include population growth, economic growth, trade, structural changes towards service economies, and energy consumption. They key takeaway message from the IPCC and other emissions assessments is that, while economies have become more efficient, from an emissions perspective – that is, CO_2-eq emissions per \$GDP increase have steadily declined – that efficiency is being far outweighed by overall demand.

The first driver of increased emissions is population. While total global per capita emissions (across all sectors) appear to be leveling off, this is a function of rapid population growth and an inability to construct energy infrastructure fast enough to meet growing demand. Most of this growth is in Asia and the Middle East and Africa, but with enormous variation in overall population and growth rates between countries. For example, China has a population growth rate of 0.5%, while most countries in sub-Saharan Africa have growth rates in the high 2% or low 3% range.

The second driver of increased emissions is economic development, mediated by energy demand. The relationship between energy, emissions, and development remains the subject of study, but all agree that the two are strongly correlated, though to different degrees at different levels of development. While more advanced economies with lower population growth rates do show increased efficiency (both in terms of growth in energy demand and in CO_2-eq emissions per \$GDP) that may be attributed in part to technical change and real efficiency gains (as opposed to simply off-shoring of emissions-intensive activities), there is no empirical consensus on the existence of a Kuznets Curve for overall energy demand or emissions (e.g., [46]). This may be because increased demand for emissions intensive goods and services as individuals become wealthier outpaces emissions efficiency gains within economies. For global development objectives, continued and strong economic growth is desired; as such we should expect continued increased emissions, particularly from less developed economies where the correlation between growth and emissions is strongest.

As economies evolve (at sub-national and national scales), they tend to move away from industrial activities towards service activities. These structural changes have ramifications for developed regions' emissions profiles, if emissions are accounted for on a production basis (i.e., by totaling emissions produced with in a given administrative region). However, as economies move out of industrial activities and manufacturing and into service provision (which is less emissions-intensive), they tend to and import more finished products, whose production created emissions elsewhere. As such, these economies look very different when emissions are accounted for on a consumption basis (i.e., by totaling emissions 'embodied' in final goods and services consumed within a given administrative region) [47]. Trade has thus become an ever more important driver of emissions, both because the volume of global trade itself has increased with economic specialization and because the energy systems and technologies in emerging markets like China frequently emit more CO_2 to produce a certain good than if the good were produced in a developed country [48, 49].

High cost of delay

The total cost of mitigation can be estimated as the total cost of replacement of all current capital stock and agricultural practices with zero-emission alternatives, plus the net-zeroing of any remaining emissions, through implementation of net carbon sequestering technologies (e.g., bioenergy + carbon capture and sequestration, or BECCS). Likewise, the total cost of adaptation can be thought of as the integrated cost of dealing with (in potentially many different ways) the impacts of committed emissions due to current infrastructure and agricultural practices. Since both are a function of present infrastructure and present committed emissions, and since demand is rising (as described above), both mitigation and adaptation costs will rise with time.

This rise in cost comes both from committed emissions of infrastructure expansions as mitigation is delayed, as well as the increasing constraints such emissions place on the emissions intensity of future capital stock. This lock-in points to the critical importance of sequencing of mitigation actions. A commitment accounting framework favors more stringent near-term mitigation, given the long temporal footprint of fossil fuel-based energy and transportation infrastructure [50]. In conjunction with strict climate targets, commitment accounting also provides a constraint on the carbon intensity of future capital stock: for example, to meet the 2 °C target, the carbon intensity of new economic production needs to be between 33–73 g CO_2/\$, compared to present intensity of 360 g CO_2/\$ [51]. Further, with each year of business-as-usual, this carbon intensity cap decreases by 1.0–1.5 g CO_2/\$ [51].

Of particular concern is the likely presence of non-linearities in impacts that would create discontinuous jumps in the cost of both mitigation and adaptation, potentially driving the emissions goal beyond zero to drastic net sequestration. (It is unclear whether, if surpassed, some of these so-called tipping points might even be recovered from at all.) Most of these non-linearities involve large-scale changes to the cryosphere–thawing of permafrost (see Sidebar 1 in this chapter), decline in Arctic sea ice extent, melting of Himalayan glaciers, etc. – and significant uncertainties remain about when (and at what level of mean temperature rise) such critical thresholds would be reached. But systems beyond the cryosphere also demonstrate non-linear responses to rising temperature. Crop yields show steep negative responses to exposure above their ideal growing temperature (e.g., [52]). And new macroeconomic research shows a parabolic response of entire economies to average temperature [53]. The existence of these stark negative impacts – with very real and immediate human consequences – points to the urgency of immediate and dramatic action.

Again, because significant non-linearities in impacts and costs become more highly probable with greater accumulated and committed emissions, appropriate sequencing of policies and actions becomes critical. Research has shown, for example, that mitigation of short-lived climate warming pollutants like black carbon and tropospheric ozone and its precursors can dramatically impact the rate of sea level rise, but that such mitigation has to come in the immediate term, as the benefits are smaller as the cryosphere shrinks [54]. However, immediate actions (whether addressing short-lived climate pollutants or long-lived greenhouse gases) must be strong and sensible, or they will limit the capacity for longer-run change. For example, modeling estimates suggest that buy-in by countries to the modest pledges made at Copenhagen would, counter-intuitively, create substantial technological lock-in with significant committed emissions in the short term, thus limiting the possibilities for reaching stabilization targets in the long run [55].

Solutions Framework

Warming proportional to cumulative CO_2 emissions

Due to the millennial atmospheric lifetime of CO_2 [56], the increase in global mean temperatures this century will be proportional to cumulative CO_2 emissions to the atmosphere [57]. This means that limiting global warming to any level entails a finite budget of carbon that can be emitted [58, 59], with modest adjustments to that long-term budget depending on emissions of short-lived climate pollutants [60].

Short-lived climate pollutants (SLCPs) include methane (CH_4), tropospheric ozone (O_3), black carbon (a component of fine particulate matter), and hydrofluorocarbons (HFCs). They are harmful air pollutants and powerful climate forcers that remain in the atmosphere for a much shorter period of time than longer-lived climate pollutants, including CO_2. On a molecule-to-molecule basis, their climate impact is tens to thousands of times greater than that of CO_2. They contribute about 40 percent to current, net anthropogenic global radiative forcing [61, 62].

Thus, while levels of CO_2 emissions are the most important driver of total global warming over the long-term, cutting emissions of SLCPs can provide immediate climate and health benefits. In fact, aside from fanciful schemes to geo-engineer our planet or significantly scale potential carbon-negative strategies, the only way to immediately slow the rate of global warming is to take strong actions to cut emissions of SLCPs. Taking immediate action to significantly cut emissions of both SLCPs and CO_2 is one of the few viable pathways to keep average global warming below 2 °C this century (see **Figure 1**) [63]. Near-term action on SLCPs can reduce warming in 2050 by four times more than strong action on CO_2 alone would [64], and can reduce sea level rise in 2100 by twice as much as action on CO_2 would [65].

Fortunately, cost-effective and available technologies and strategies exist to significantly cut anthropogenic sources of SLCP globally over the next 10–15 years. An analysis by the UN Environment Programme and World Meteorological Society found that a small number of measures to reduce black carbon and ozone precursors, including methane, could significantly cut emissions from these sources by 2030 [64]. Many of these measures could be implemented under existing policy frameworks to address air quality and development. Full implementation of these measures would bring significant global climate, health, and food security benefits. They would reduce future global warming by 0.5 °C in 2050, and by 2030, could avoid 2.4 million premature deaths and the loss of 52 million tons in agricultural production, each year. The economic value of these benefits would be about $6 trillion annually by 2030 [66] and about half of the climate benefits associated with these measures could be achieved at negative cost [67]. Strong action on black carbon and methane may also help to reduce disruption in historic precipitation patterns [68, 69] can reduce the rate of warming in the Arctic by two-thirds by 2040 [64] and can help avoid expensive and compounding climate feedback mechanisms that could accelerate the rate of global warming, make the challenge much more costly and difficult to solve, and lead to potential "tipping points" (see discussion of non-linearities on pg. 6) [62].

In addition to strong action on black carbon and methane, phasing down the production and use of HFCs under the Montreal Protocol could and avoid an additional 0.1 °C warming by 2050 and up to 0.5 °C of warming by 2100 [70]. At the October 2016 Meeting of the Parties to the Montreal Protocol in Kigali, Rwanda, nearly 200 countries agreed to such a global phase down. Parallel efforts to improve the energy efficiency of room air conditioners could avoid peak energy use equivalent to 2,500 medium-sized (500 MW) power plants globally by 2050 [71].

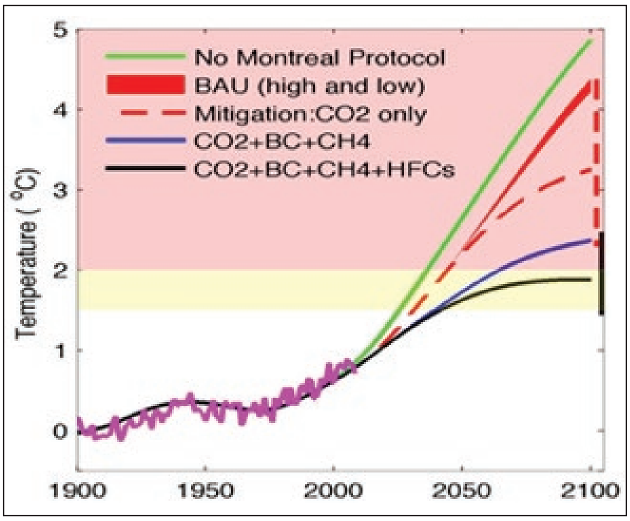

Figure 1: Strong action on both CO_2 and SCLPs is only way to limit warming below 2 °C this century [70] (Xu et al, 2013).

California is already a leader in addressing air pollution, climate change, and emissions of SLCPs. The State's policies to address air pollution have cut black carbon emissions by more than 90 percent since the 1960s, and existing policies will cut black carbon from mobile sources by 75 percent from 2000–2020, alone [72]. If the rest of the world replicated California's success on black carbon alone, it could achieve many of the human health benefits cited above, and slow the rate of global warming by an estimated 15 percent [6], essentially offsetting one-to-two decades' worth of CO_2 emissions globally [73]. The State also has leading policies in place or under development to reduce HFC emissions and cut methane from landfills, oil and gas systems, dairies, and other sources. Governor Jerry Brown has highlighted the importance of action on short-lived climate pollutants as one of "five pillars" of action needed to reduce greenhouse gas emission in California through 2030, and State law (Senate Bill 1383, Lara, Chapter 395, Statutes of 2016) requires the State to cut emissions of methane and HFCs by 40 percent below 2013 levels, and black carbon by 50 percent below 2013 levels, by 2030 [72].

California is not alone in its efforts on SLCPs, however. The Obama Administration has set a target to reduce methane from the oil and gas sector by 40–45 percent below 2012 levels by 2025; proposed regulations on methane from oil and gas and landfills; helped achieve a strong agreement on the phase down of HFCs in Kigali, Rwanda; and is pushing action on black carbon through its current position as chair of the Arctic Council. Norway has developed a short-lived climate pollutant plan of its own, and the Climate and Clean Air Coalition to Reduce Short-Lived Climate Pollutants is helping member countries plan for reducing emissions of short-lived climate pollutants. Europe is implementing a phase down in the use of HFCs already, and many countries have banned the disposal of organic waste in landfills. Finally, as part of its Intended Nationally Determined Contribution as a party to the United Nations Framework Convention on Climate Change, Mexico has set a target to reduce black carbon emission by 51 percent by 2030.

Aiming for zero

In the past year, nations have been submitting Intended Nationally Determined Contributions (INDCs) to the United Nations Framework Convention on Climate Change (UNFCCC) that describe future reductions in their CO_2 emissions. Typically, these proposed reductions are relative to some year in the past (e.g., 40% below 1990 levels) or relative to what is expected to happen in the future without climate policy (e.g., 20% below no-policy levels in 2030). Such targets and timetables are critically important both as expressions of existing national policies and commitments to develop new ones.

However, relative targets are not sufficient. Global mean temperature will continue to rise until net carbon emissions to the atmosphere are zero. As discussed above, the relationship between 21st-century warming and cumulative carbon emissions is linear, meaning that every ton of CO_2 added to the atmosphere ratchets up the global thermostat. Further, unless humans actively intervene in the Earth system (e.g., by removing tremendous quantities of carbon from the atmosphere or by reflecting some sunlight back to space), the temperature increase and its related impacts on human and natural systems will persist for centuries.

The ultimate goal of climate-energy policies must be therefore zero net carbon emissions—carbon neutrality. Although implicit in any scenario that stops anthropogenic global warming, widespread agreement on a goal of zero global emissions could be powerful: the complete phase-out of net CO_2 emissions is an exceptionally clear goal. Aiming for full decarbonization of the global economy means no percentages, no base years, and no hypothetical baselines. "Global carbon neutrality" is unambiguous, easy to communicate and aspirational. Major businesses have already called for such a straightforward goal [74], as have scientists [75], NGOs, the World Bank [76], and multi-stakeholder initiatives of governments, business, investors and communities [77]. The UC-system goal of carbon neutrality is thus a powerful and symbolic signal that will help to set the long-term context of mitigation efforts and foster the socio-economic dynamics necessary to meet the challenge of global warming.

A framework of drivers and solutions

In assessing solutions to the global carbon-climate-energy problem, a context of global drivers and trends is invaluable. A particularly useful and widely applied analytical framing is the Kaya identity [78, 79], which decomposes the rate of carbon emissions from energy production as the product of four factors including population, per-capita GDP, energy consumption (or intensity) per unit GDP, and the carbon emissions (or intensity) per unit energy consumption.

By considering these four factors in turn, one can more easily recognize the global challenge and available levers for change. Global population is projected to increase to more than 11 billion at the end of this century. While smaller population size would certainly make the solving climate change easier, the best way to slow population growth is to improve health care and education in developing countries, which implies increasing per-capita GDP per capita. For this reason, and because robust economic growth is a nearly universal goal of individuals, businesses, and countries, globally-averaged per-capita GDP is also projected to increase in the future. Thus, decreasing carbon emissions requires that the expected increases in population and per-capita GDP are countered by proportionally larger decreases in energy or carbon intensity.

The energy intensity of the global economy reflects the economic productivity of energy use. It can be decreased by improving the energy efficiency of end-use technologies, or by structural shifts away from energy-intensive activities like manufacturing and building capital infrastructure and toward valuable economic activities with lower energy requirements, such as many services.

The economic structure of developed countries has also shifted over the past several decades, as manufacturing and extractive sectors have given way to the high technology industries and higher value-added financial and legal services. However, this structural shift is in part reflecting the globalization of the world economy and the offshoring of energy-intensive industries from developed countries to emerging economies like China. Indeed, goods consumed in developed countries may still be very energy-intensive, but such goods are increasingly imported.

Between 1985 and 2010, the energy intensity of the global economy decreased by about 0.8% per year. Yet between 2000 and 2010, progress has stagnated, with energy intensity instead increasing by < 0.1% per year, primarily due to rapid and energy-intensive economic growth in China. Although most scenarios anticipate resumed decreases in global energy intensity, it remains a question how low the energy requirements of the global economy can ultimately be and how quickly such requirements might decline, particularly given the energy demand entailed by human development goals. For instance, decreasing the energy intensity of GDP by 2% per year would mean that the expected increases in global population and economic output would not increase total global energy use. What is certain is that the energy demand of modern civilization will never be zero. For this reason, the goal of carbon neutrality cannot met by decreases in energy intensity alone, but such decreases are likely to be critical to ensure that the necessary transformation of the global energy system is possible.

Mathematically, a goal of zero global emissions from energy production requires that at least one of the 4 factors in the Kaya identity must be zero or negative. Having explored the first three factors, one can see that the only possibility is thus for the carbon intensity of the global energy system to eventually reach zero. Given that 84% of global energy in recent years is supplied by fossil fuels, a radical transformation is required to fully decarbonize the global energy system. Current climate goals, such as avoiding 2 °C of warming relative to the preindustrial era, further require that this transformation happen extremely quickly—sooner than the end of the century.

Decarbonization can conceivably result from either capturing and sequestering the carbon emissions produced during combustion of fossil fuels or by using low-carbon or renewable energy resources such as nuclear, solar, wind and sustainably harvested biomass. In principle, such non-fossil energy sources could be "carbon-free," or "carbon-neutral," but for the foreseeable future their life cycle will likely include some amount of carbon emissions. As will be discussed in detail in subsequent chapters, there are advantages and challenges specific to each of these energy technologies.

Under any plausible scenario of total energy demand, the wholesale decarbonization of the energy system is possible only by deploying massive capacities of low-carbon energy technologies. Although solar photovoltaic and wind capacity have increased dramatically in the past decade and signs point to continuing expansion of these energy sources, between 1999 and 2010 the globally-averaged carbon intensity of energy increased from 0.51 kg C per year per watt to 0.54 kg C per year per watt. The increase has been linked to countries like China and India, where rapid industrialization is being primarily fueled by the most carbon-intensive fossil fuel: coal.

The build-out of coal-burning power plants in China implicates a challenge to all of the low-carbon energy options, which is overcoming the tremendous socioeconomic inertia of the current fossil fuel-based energy system (discussed above). Existing infrastructures that burn fossil fuels (e.g., power plants and vehicles) represent enormous investment in future CO_2 emissions, supported by an equally prodigious base of supporting infrastructure (e.g., refueling stations, pipelines, wells, mines, etc.) as well as deeply-entrenched institutions and behavior norms. The carbon lock-in represented by this techno-institutional complex has been established by tens of trillions of dollars of investment over two centuries, and the barriers to its disruption should not be trivialized [80, 81]. Indeed, recent research has shown that roughly half of the carbon budget allowable under the 2 °C target will be used up by now-existing energy infrastructure unless it is retired early or retrofitted with carbon capture and storage (CCS) technology [39, 82]. Meanwhile, multinational firms have been financing the establishment and expansion of fossil fuel-burning infrastructure in developing countries, working at cross-purposes to the goal of technological "leapfrogging" [83]. In light of the magnitude and trends in committed emissions, analysts and policymakers have begun discussing and quantifying the "stranded assets" implicit in ambitious climate-energy policies [55, 84]. For instance, investments in new fossil fuel-burning infrastructure without CCS and with expected lifetimes longer than 5 years seem inconsistent with the UC goal of carbon neutrality by 2025.

Policy and socioeconomic considerations

Fundamentally, the problem of global climate change arises because the firms and individuals do not fully internalize the consequences of their actions. Some of these failures are known as negative externalities—that is, harm caused to the rest of the planet from the pollution that is a byproduct of how firms in energy, agriculture and other sectors do business. According to standard economic theory, one role of policy is to force firms and individuals to internalize those harms—for example, by charging an extra tax on emissions or imposing regulations. When firms are forced to internalize those consequences then they will make better decisions—such as decisions to switch technologies and practices to cut pollution.

Some of the failures to internalize the full consequences of decision follow the opposite logic—they are positive externalities. If firms invent radically new methods for producing energy then many of the benefits spread to other firms and eventually globally throughout the economy. The inventor, itself, can't get all the benefit. By this logic, firms will tend to under-invest in innovation—leading, collectively, to society as a whole putting insufficient resources into new ideas. According the standard economic theory, solutions to these problem lie with government to fix the market failure—for example, by providing R&D tax credits to incent firms to invest more in innovation and through public funding of innovation programs, universities and research labs.

What makes it particularly difficult to bend the curve on climate pollution—which will require that firms internalize their pollution externalities and that societies invest adequately in innovation—is that these externalities exist at the global level [3, 85]. The pollutants that cause climate change mix across national borders in the atmosphere and the economic effects of controlling those emissions are felt throughout the global economy. Thus the climate problem inherently involves what are known as global public goods. All societies benefit, to different degrees, from a safe climate and nobody can be excluded from those benefits regardless of their own actions. Knowledge, as well, is a global public good [86].

Managing global public goods requires cooperation, and whole fields of social science and law have emerged to understand where and how cooperation actually works [87]. There has been no shortage of efforts to cooperate on the problem of climate change—notably through the United Nations system and the UN Framework Convention on Climate Change. While there is a range of views on how effective the UNFCCC process has been, it is hardly surprising to experts on international cooperation that the process has been beset by gridlock and other troubles [40]. Too many countries with diverse interests are involved. The UN Process requires consensus for decisions but some of the countries that are formal members actively want climate cooperation to fail. For more than two decades a highly centralized UN diplomatic process has been under way—aimed at getting countries to agree on centralized "top down" emission commitments.

The difficulties with a top down diplomatic process led countries, NGOs and others to seek alternative, better strategies. The Paris Agreement of 2015 reflects the first step in a different "bottom up" process — a process that gives countries flexibility to set their own commitments and then encourages diplomats to stitch together those national efforts into stricter cooperative agreements. In addition, small groups of countries—for example, the US-China bilateral diplomatic process—are also working in parallel with the hope that their efforts focused within a small club will spill over into deeper and broader cooperation over time [88].

The success of this bottom up process will hinge on many factors. One will be whether the national pledges for action—the earlier mentioned INDCs—offer genuine additional efforts to control emissions. To date 161 INDCs from 188 countries, accounting for over 90 percent of global emissions have been submitted, according to the Climate Action Tracker. It is already clear that if this process is to become effective much stronger standards for INDCs will be needed as will be an effective review mechanism.

Another critical factor in the success of this bottom up process will be leadership. Global cooperation is hard to achieve with many countries that have diverse interests, but if a few lead and build confidence then others will follow. California's policies can be seen in this light—while the state is only ~1% of global CO_2 emissions [5], if its efforts can show what is feasible while also boosting innovation in technologies that cut the cost of mitigation then broader cooperation to control emissions may follow.

The INDCs that have been submitted so far reveal that countries are adopting highly diverse strategies for controlling emissions. A few have adopted emission taxes—a solution that is usually favored by economists but difficult to implement politically. More have adopted cap and trade systems, such as the one under AB32 in California, although prices have generally been low—suggesting that politicians are not willing to let market mechanisms reveal the true marginal cost of controlling emissions. Most countries have relied heavily on existing regulatory structures to control emissions. And in many countries the effort to control emissions that cause climate warming is linked closely to other national priorities—such as clearing the air from soot and improving energy efficiency as a strategy for increased energy security. Numerically, China is doing more to cut emissions from its baseline trajectory than any other country—and the vast majority of China's effort is rooted in efforts by Chinese political leaders to address these other problems. This realization is important to understanding the politics of global climate change. In a few jurisdictions, such as California, the central concern is about climate change itself. But for most of the world—including the emerging economies that will account for essentially all growth in future emissions—it is much harder to keep political leaders focused on the dangers of climate change without linking the topic to other matters of more pressing local concern.

Innovation. Innovation has a special role to play in allowing deep cuts in emissions needed, over the coming few decades, to stop climate warming. While there are some studies that suggest all the technologies needed are available "off the shelf," it is more likely the case that big innovations will be essential [20]. Innovations will, as well, make the politics of climate change easier to manage—so long as the problems of climate policy is framed as one of high up-front cost for uncertain future benefits few societies will do much to protect the planet. Innovation helps lower those costs and makes the path to even less expensive, benign energy and agricultural systems easier for political leaders to fathom.

What would a big push on innovation policy look like? The answer to this question lies with policies that combine efforts to "push" new ideas and technologies into being as well as incentives that "pull" those innovations into use.

Policy can "push" new technologies into service by funding research—often basic research into fundamental new technologies. That was the insight from early government investment in information technology, software and health—that sponsorship for fundamental research from the National Science Foundation (NSF), the Office of Naval Research (ONR), DARPA, DOE's Office of Science, NIH and other basic science enterprises pushed new ideas into viability.

One of the central challenges in fostering a revolution is creating a big enough push. **Figure 2** shows total federal spending on energy-related research development and demonstration (RD&D)—a broad category that includes basic science as well as applied ventures such as demonstration projects. RD&D data are, in many ways, flawed measures of how much a country actually spends pushing basic ideas, but they are a good place to start. In real dollars, spending has been flat since the early 1980s. (Other data show that the focus of spending has shifted quite a lot—away from nuclear power and toward renewables, for example. Globally, nuclear power accounted for more than half of all energy-related RD&D spending in 1980; today it is about one-quarter. Renewables and energy efficiency account for about half of today's energy-related RD&D spending globally, up from about one-fifth in 1980. There is a broad consensus that at the federal level the government under-invests in RD&D by a factor of 3 to perhaps 10 [89]. One of the major roles for state policies, such as in California, is to help fill that gap.

In some fields, proving the existence of a new scientific concept can be enough to bring the new idea into service. In pharmaceuticals, for example, many ideas for new drugs spring directly from basic science. But in most of the energy system, a viable idea must be demonstrated—a process that requires still more funding. Failure to offer that funding leads to what is often called the valley of death—a chasm between the large supply of intriguing new ideas and those that are sufficiently well developed to be taken up by commercial firms on their own.

In tandem with pushing new ideas into being, a "pull" from the market is needed to convince firms to invest. Pulls can come in many forms—such as direct regulation or the use of market incentives. Whether regulation or market-based, the effectiveness of forces that pull new technologies into service is based on credibility. If firms believe that new standards or market signals will come into force then they will make anticipatory changes in behavior. When the US sulfur trading program was created in 1990, for example, firms immediately saw this legislation as credible and had assumed (erroneously) that permit prices would rise over time. They invested, in anticipation, in new scrubber technologies. One of the reasons that emission credit systems for CO_2 and other warming gases have not yet had much impact on innovation is that firms do not know whether these schemes will yield credibly higher prices. Europe's Emission Trading Scheme (ETS), for example, generated high prices for several years and inspired firms to look at new technologies such as carbon capture and storage (CCS). But when policy makers allowed ETS prices to fall sharply and offered no credible solution that would raise prices in the future firms lost faith that market signals, by themselves, merited much investment.

Communication

Why is it so difficult to talk about climate change? Within the American public there is a sizable political divide between liberals and conservatives on the issue of global warming; and flows of political messages and news

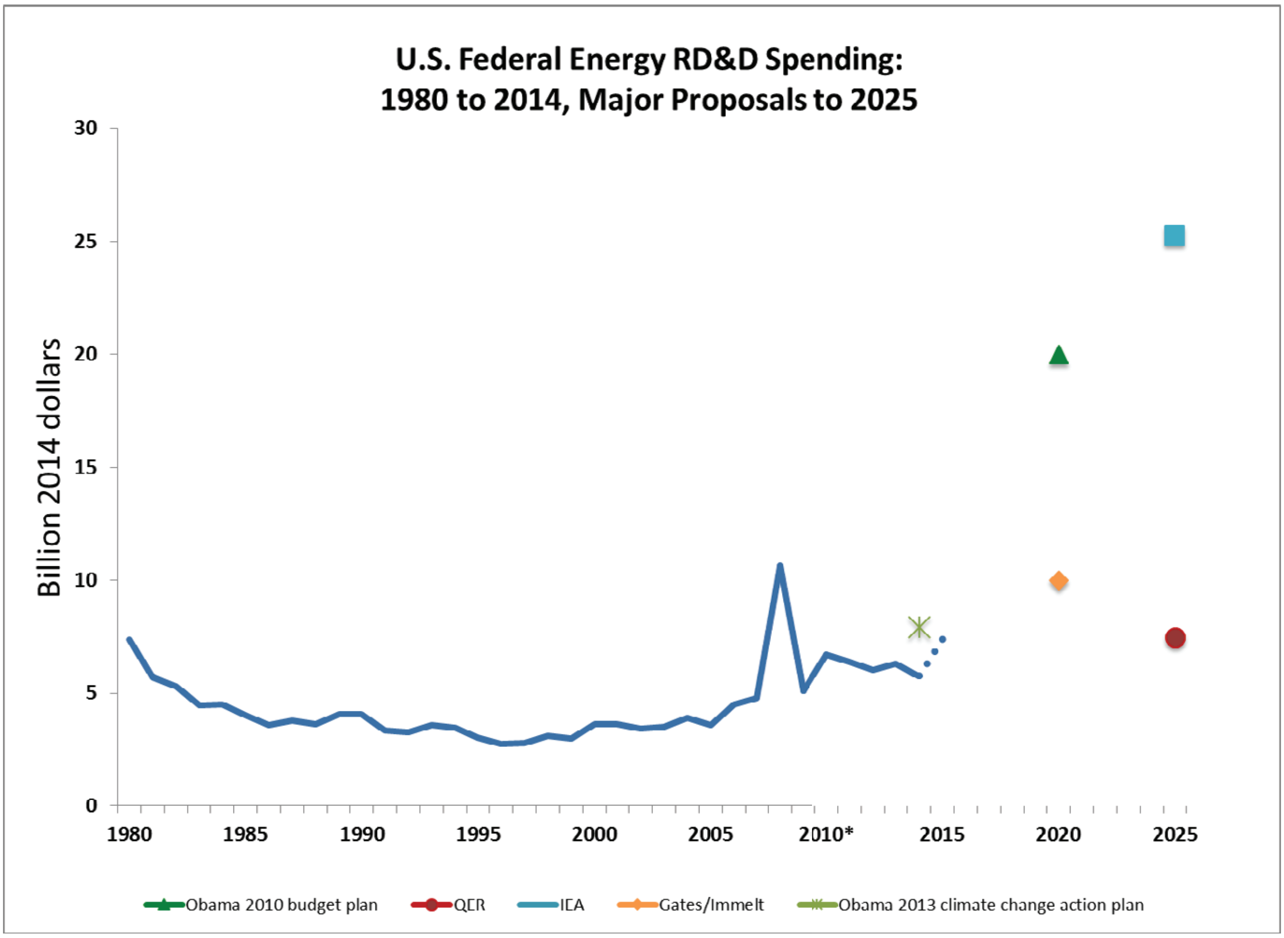

Figure 2: Source: ILAR analysis using data from International Energy Agency Energy Technology RD&D; The President's Budget FY2015 & FY2016; American Energy Innovation Council "Restoring American Energy Innovation Leadership: Report Card, Challenges, and Opportunities" (2015); The President's Climate Action Plan (2013).

	Gain	Loss
High probability Certainty effect	Fear of disappointment *Risk averse* Accept less than expected value (good but not optimal option)	Hope to avoid loss *Risk seeking* Reject expected value (go for broke)
Low probability Possibility effect	Hope of large gain *Risk seeking* Reject expected value (buy lottery ticket)	Fear of large loss *Risk averse* Accept less than expected value (buy insurance)

Table 1: Fourfold problem, adapted from Kahneman, 2011. Note that risk-averse behavior leads to accepting a good but not optimal outcome when a gain is considered, and to buying insurance for more than the expected value of a loss in order to achieve peace of mind. Risk-seeking behavior such as buying lottery tickets is a low-probability gain. Going for broke and risking a greater loss in order to avoid a high-probability loss is the upper right. Climate messages should consider framing as gain or loss relative to current or future reference point, especially when risk-averse behavior is considered. Contrasts with risk-loving behavior may be helpful in some contexts.

concerning global warming have contributed to substantial growth of this divide over the past decade [90]. There is evidence that public divisions over climate change stem not from a deficit of knowledge, but from a distinctive conflict of interest: between the personal interest individuals have in forming beliefs in line with those held by others with whom they share close ties (cultural politicization) [91, 92]. Climate-communication strategies must then shield policy-relevant facts from the influences that turn them into divisive symbols of political identity [93]. There is also evidence that climate-change acceptance is increased by mechanism-explaining interventions (wisdom deficit) [94]. Framing and use of a trusted message source are essential. A survey of customers in 10 large water utilities clearly found that: (1) 92% of Americans want their water utility to be a leader in preparing for the local impacts of climate change, and (2) developing a well-designed message can significantly increase support for the actions utilities will need to take to address the impacts of climate change [95].

Engaging the public in a discussion of complex scientific issues, especially "wicked problems", is difficult because of the basic neurological wiring of the human brain. A wicked problem has no solution that is positive across all values. Research is moving beyond documenting how values correspond with attitudinal variables such as levels of concern about climate change, and to adopt more explicitly normative goals, such as investigating how messages about climate change might be framed and how more-substantive behavioral engagement can be promoted [96]. Framing climate messages in terms of health, water security, disaster prevention and other immediate concerns, while avoiding some of the more-traditional biospheric or self-transcendent aspects of the challenge of climate change, may be effective in reaching different segments of society. Because people often cope with moral threats in defensive ways, non-moral framing of persuasive messages, promoting coping mechanisms that do not reflect defensiveness and developing change-oriented moral convictions can help guide framing [97]. Note that a key insight of social marketing is to tailor the content of a campaign to the values of the target audience—no matter what they are [96]. Some players in the climate debate use this approach, and climate-communications research have started to identify possible approaches (e.g., [98]). Effective climate communications efforts will require more knowledge of how people form their views about climate change, climate policy, and household actions, including an understanding of the role of media and of social networks [99].

Prospect theory is an attractive alternative to expected value as a theory of decision making under conditions of risk, and is potentially relevant to analyzing climate communications opportunities [100]. Tversky and Kahneman have demonstrated in numerous highly controlled experiments that most people systematically violate all of the basic axioms of subjective expected utility theory in their actual decision-making behavior at least some of the time [101]. Prospect theory predicts that individuals tend to be risk averse in a domain of gains, or when things are going well, and relatively risk seeking in a domain of losses, such as in the midst of a crisis. Tversky and Kahneman observed that people attach values to gains and losses rather than to absolute values of outcomes, leading to a fourfold pattern of risk attitudes (**Table 1**). Thus the reference point for a decision, and whether it is perceived in the domain of losses or in the domain of gains, is important. As a consequence, the topic of framing emerges. Pain hurts more than pleasure feels good. Framing potentially affects the perception of climate scenarios, e.g., is the reference scenario today or is the gross damage path resulting from inaction the reference? The former notion implies a higher value of climate response measures to the decision maker than the latter. Framing can also influence the perception whether an outcome is certain or not [100]. Scientists and climate communicators need to consider how messages are framed, (e.g., in the domain of loss versus gain, reference of today or the future, and high or low probability).

Acronyms

AB32	Assembly Bill 32
AR5	(IPCC) Assessment Report 5
ARPA	Advanced Research Project Agency
BECCS	Bioenergy + Carbon Capture and Sequestration
CADWR	California Department of Water Resources
CARB	California Air Resources Board

CCAC	Climate and Clean Air Consortium
CCS	Carbon Capture and Storage
CCST	California Council on Science and Technology
CH4	Methane
CO_2	Carbon Dioxide
DARPA	Defense Advanced Projects Research Agency
DC	District of Columbia
DOE	Department of Energy
EIA	(U.S.) Energy Information Administration
ETS	(Europe's) Emission Trading Scheme
FY	Fiscal Year
GDP	Gross Domestic Product
GNP	Gross National Product
GWP	Global Warming Potential
$GtCO_2$	Gigatons of CO_2
HFC	Hydrofluorocarbon
IGSD	Institute for Governance and Sustainable Development
ILAR	(UCSD's laboratory for) International Law and Regulation
INDCs	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
MW	Megawatt
NGOs	Non-Governmental Organizations
NIH	National Institutes of Health
NOAA	National Oceanographic and Atmospheric Administration
NSF	National Science Foundation
ONR	Office of Naval Research
RCP	Representative Concentration Pathway
RD&D	Research Development and Demonstration
RTMD	Reinforced Theistic Manifest Destiny
SLCP	Short-Lived Climate Pollutants
UNEP	United Nations Environmental Programme
UNFCCC	United Nations Framework Convention on Climate Change
WG3	(IPCC) Working Group 3
WIREs	Wiley's Interdisciplinary Reviews
WMO	World Meteorological Organization
ZEW	Centre for European Economic Research

Competing Interests

The authors have no competing interests to declare.

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