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CO_2 emissions are rising at a rate that could raise global temperature 2°C above preindustrial values within about 20 years and 3°C by midcentury.

Two or Three Degrees

CO_2 Emissions and Global Temperature Impacts

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The world's energy mix is changing rapidly. Renewables such as wind and solar photovoltaics (PV) increasingly provide low-carbon, low-water, and low-air-pollution energy around the world (BP 2014). Denmark now generates 40 percent of its electricity yearly from wind power, and in Germany 20 percent of the country's electricity can be solar generated on sunny summer days.

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The rapid ascent of renewables is being driven by both policies and pricing. The European Union is on track to reduce greenhouse gas (GHG) emissions by one fifth in 2020 compared to 1990 levels, in part because of increased penetration of renewables and energy efficiency. California is similarly on course to cut its emissions to 1990 levels in the same time frame, a reduction of around 15 percent compared to business-as-usual scenarios. The levelized cost of electricity for wind and solar PV is already on par with fossil fuels and nuclear power in many markets around the world, in part because the prices of solar PV modules plunged three quarters from 2009 to 2014 and because the installed costs of utility-scale PV fell by one to two thirds (IRENA 2015).

Accompanying—and to an extent offsetting—the revolution in renewables is a parallel revolution in unconventionally mined fossil fuels. There is considerably more economically accessible oil and natural gas today than there was decades ago. The combined technologies of horizontal drilling and hydraulic fracturing increased US shale gas production from about 5 billion ft^3 (Bcf) per day in 2007 to more than 25 Bcf per day in 2014, now accounting for about 40 percent of total US natural gas production (EIA 2014). Similarly, production of shale and other unconventional oil drove US production to 9 million barrels per day in 2014, on par with the world's largest oil producer, Saudi Arabia (Jackson et al. 2014).

The balance of fossil and nonfossil fuels and the extent to which global energy use continues to grow will determine the Earth's future temperature. In this paper we place the current trajectory of carbon dioxide (CO_2) emissions in the context of both cumulative emissions since 1870 and *emission quotas*, the remaining emissions "allowable" to hold temperatures below a given threshold, in our case 2–3°C (3.6–5.4°F). In simple terms, the atmosphere can be viewed as a bucket that can hold a given amount of CO_2 before a particular temperature increase is reached. The amount in the bucket, plus the amount of CO_2 taken up by the oceans and lands, is considered the emission quota. We also compare emission quotas with the size of various fossil fuel pools available (through current technologies) and examine different pathways to keep temperatures from rising too far or fast.

Growing Global Energy Use and Fossil Fuel Emissions

Primary energy supply is increasing rapidly around the world, with a changing mix of fuels. From 2004 to 2013 global energy consumption rose 24 percent, from 9.7 to 12.7 billion tonnes of oil equivalents, driven primarily by increased demand in China and India (BP 2014). Coal use grew 50 percent during the decade (in large part because of growing consumption in Asia), compared with about 15 percent total growth for oil and 30 percent for natural gas. And the global share of energy supply from coal rose from 26 percent at the beginning of 2004 to 30 percent at the end of 2013, largely at the expense of oil, which declined from 37 percent to 33 percent of global energy supply (BP 2014). The shift to more coal and relatively less oil came despite declining coal consumption in the United States, Canada, and the European Union, among other nations and regions.

The European Union is on track to reduce GHG emissions by one fifth in 2020 compared to 1990 levels.

Rising Emissions

Notwithstanding the growing awareness of climate change in recent decades, GHG emissions have continued to rise. CO_2 emissions from fossil fuel burning and cement production in 2013 were 36.1 ± 1.8 billion metric tonnes (Gt), up 2.3 percent from 2012 emissions (35.4 Gt CO_2) and more than 60 percent from 1990 emissions (22.5 Gt CO_2) (Friedlingstein et al. 2014). Combined fossil fuel and cement emissions grew 1.0 percent per year during the 1990s but almost 3.0 percent annually since then, though with slightly smaller (2.5 percent) increases in the past few years.

One bit of good news is the near halving of CO_2 emissions from deforestation and other land use change (3.3 ± 1.8 Gt CO_2/yr on average) relative to the 1990s. Nonetheless, the world is moving toward GHG thresholds faster than anyone predicted in 1990, the reference year that the United Nations Framework Convention on Climate Change chose for climate change targets (UNFCCC 2006).

Calculus of Emissions and Global Temperatures

Emission targets are important because long-term global temperatures respond more or less linearly to cumulative CO_2 emissions, such as those from fossil fuel burning, cement production, and land use changes (Allen et al. 2009; IPCC 2013; Matthews et al. 2009; Peters et al. 2013). Cumulative CO_2 emissions were approximately 1,000 Gt between 1870 and 1980 and another 1,000 Gt between 1980 and 2013 (net global CO_2 emissions in 2013 were 40 Gt).

To have at least a 90 percent chance of keeping average global temperature increases below 2°C (3.6°F), global Earth system models (i.e., the most sophisticated climate models) suggest that cumulative emissions since 1870 need to be capped at no more than about 2,440 Gt CO_2 (figure 1) (IPCC 2013). If policymakers choose a riskier probability—say, at least a 66 percent chance of staying below 2°C for a cumulative threshold (table 1)—the allowable CO_2 emissions are some 500 Gt higher, about 2,900 Gt CO_2 cumulatively (figure 1) (IPCC 2013). (The 66 percent probability case comes with a one-in-three chance of the Earth's warming more than 2°C despite a capping of cumulative emissions at 2,900 Gt CO_2.) These emission thresholds are already close at hand because, as seen in figure 1, cumulative emissions from human activities totaled about 2,000 Gt CO_2 at the end of 2013 (roughly 75 percent from fossil fuels + cement and 25 percent from land use change; Friedlingstein et al. 2014; Le Quéré et al. 2014).

Figure 1 shows just how quickly the world is approaching thresholds for average global temperature increases of 2°C and possibly 3°C. For the 2°C scenario, the average growth in global CO_2 emissions since 2000 (2 percent/yr for fossil fuel, cement, and land use emissions combined) will carry the global temperature over that threshold just one decade from now in the 90 percent probability case and in two decades for the 66 percent probability case (figure 1, dashed red line). Zero percent growth (constant emissions at 2013 levels; black line) or a moderate emission decline of 2 percent/yr (dark blue dashed line) buys a few more years in the 90 percent probability case and a decade or two in the 66 percent probability case.

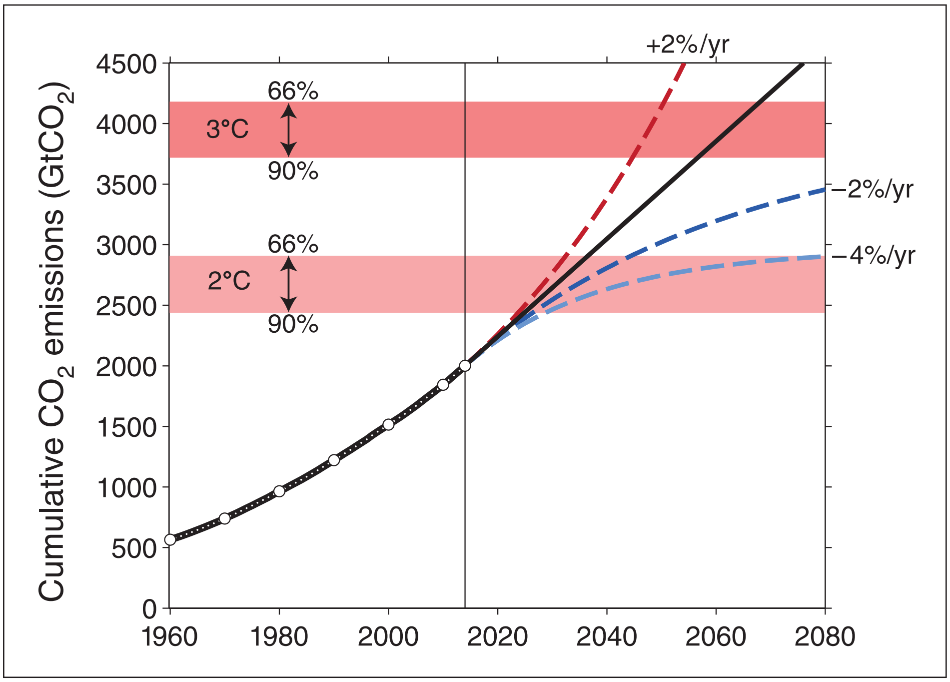

FIGURE 1 Cumulative global carbon dioxide (CO_2) emissions from fossil fuel combustion, cement manufacturing, and land use change from 1960 through 2013 (Le Quéré et al. 2014), plus four simplified future pathways: continued growth at the actual rate of +2%/yr observed over the past 15 years (dashed red line), constant 2013 emission rate (zero growth; solid black line), and mitigation at rates of −2%/yr (dark blue dashed line) and −4%/yr (light blue dashed line). Temperature threshold ranges for global average increases of 2° and 3°C (3.6° and 5.4°F) are from the IPCC (2013). The 90% and 66% probability cases refer to the likelihood of keeping global average temperatures below a given temperature if the cumulative emission threshold is not crossed (e.g., a 90% probability scenario for 2°C has a one in ten chance of having temperatures increase more than 2°C if cumulative emissions are capped at ~2,450 Gt CO_2 (bottom of the lower red band), whereas the 66% case has a one in three chance of having temperatures increase more than 2°C if cumulative emissions are capped at ~2,900 Gt CO_2.

In short, without immediate and substantial mitigation (e.g., 4 percent/yr; light blue dashed line in figure 1), time has nearly run out for 2°C mitigation (e.g., Stocker 2013). Such mitigation is possible but challenging, given the many-decade lifetime of existing power plants and other industrial infrastructure.

What is less well recognized is how fast global increases of 3°C (upper red band in figure 1) are approaching at current growth rates. For this higher temperature threshold, models suggest a total of about 3,700 and 4,200 Gt cumulative CO_2 emissions to have at least a 90 percent and 66 percent chance, respectively, of staying below a 3°C increase in

TABLE 1 Cumulative carbon dioxide (CO_2) emissions, measured in billion metric tonnes (Gt), remaining to have at least a 90% and 66% chance of staying below a 2°C and 3°C increase in global average temperature

	Cumulative CO_2 emissions (Gt) remaining by year			
	2°C		3°C	
	90%	66%	90%	66%
1980	1,450	1,900	2,700	3,200
2013	450	900	1,700	2,200

global temperature. The 2,000 Gt CO_2 already emitted at the end of 2013 thus indicates about 1,700 and 2,200 Gt CO_2 remaining for the 3°C scenarios.

How quickly either threshold is reached will depend, of course, on the trajectory of global CO_2 emissions. If they continue increasing at the average rate of 2 percent per year (red dashed line in figure 1), the 3°C threshold will be crossed in only 30 years (around 2045) for the 90 percent probability case and about 35 years (around 2050) for the 66 percent probability case. Carbon mitigation could lengthen them considerably (figure 1).

If emissions stay constant at the 2013 rate (figure 1, black line), the number of years to cross each threshold would be 11, 23, 43, and 55 for the 2°C (90 percent and 66 percent) and 3°C (90 percent and 66 percent), respectively. If emissions stopped growing today and remained constant at the 2013 rate of about 40 Gt CO_2/yr, the 90 percent and 66 percent thresholds would be crossed around 2055 and 2070, respectively. In contrast, if mitigation activities lead to an immediate global decline in CO_2 emissions of 2 percent or 4 percent per year (blue lines in figure 1), the 3°C threshold won't be reached at all in the timeline of our analysis (through 2080) and likely beyond.

Role of Fossil Fuel Reserves

Could the amount of carbon stored in fossil fuel reserves surpass the climate targets presented in figure 1? Based on global reserve data, the answer is clearly "yes" for temperature increases of 3°C and beyond.

Estimates of Reserves in 1980 and 2013

Proven reserves for oil and natural gas are greater today than they were decades ago, in spite of rapid growth in fossil fuel consumption and emissions. Table 2 shows that, in 1980, the global proven oil reserve was 683 billion barrels (BP 2014). From 1980 through the end of 2013, global oil consumption was a cumulative 884 billion barrels, about 30 percent more than the 1980 reserve estimate. Yet at the close of 2013 the proven oil reserve had grown to 1,688 billion barrels, almost 2.5 times larger than in 1980 and with a current reserve-to-production ratio of 53 years (BP 2014). Summing the 1980–2013 consumption and the most recent oil reserve estimate shows that actual proven oil reserves were 3.75 times higher than estimated back in 1980. Based on the continuing growth of unconventional oil production from shales, tight sandstones, and heavy sands, these reserves are almost certain to rise further in the future.

The history of proven reserves for natural gas shows a similar increase over time. The global proven reserve of natural gas rose from 72 trillion (10^{12}) m^3 in 1980 to 186 trillion m^3 at the end of 2013, an increase of

TABLE 2 Proven fossil fuel reserves in 1980 and 2013 for oil, natural gas, and coal, and their potential carbon dioxide (CO_2) emissions if fully used

	Proven fossil fuel reserves			
	Oil (billion barrels)	Natural gas (trillion m^3)	Coal (billion metric tonnes, Gt)	
1980	683	72	~1,100	
2013	1,688	186	892	
	Potential CO_2 emissions (Gt)			Total
1980	293	137	2,300	2,730
2013	725	355	1,865	2,945

Note: The fossil fuel reserves shown here do not include the larger set of probable and possible reserves. The potential CO_2 emissions from the total fossil fuel pool were larger in 2013 than in 1980 despite 1,000 billion metric tonnes (Gt) of total CO_2 emissions during the interval. For coal, 1 tonne = 10^3 kg.

160 percent (BP 2014). During the same period, natural gas production more than doubled, from 1.4 trillion m^3 per year in 1980 to 3.4 trillion m^3, a cumulative production of 78 trillion m^3. The sum of proven reserves in 2013 plus cumulative production from 1980 through 2013 therefore yields an actual proven reserve of at least 264 trillion m^3, 3.7 times the 1980 estimate (BP 2014).

Proven reserves of coal have not increased in recent decades but are nonetheless more extensive than for either oil or natural gas. The proven coal reserve in 1980 was approximately 1,100 billion metric tonnes (1 tonne = 10^3 kg); in 1993 it was 1,039 billion metric tonnes, and by the end of 2013 it declined 14 percent to 892 billion metric tonnes (table 2), roughly attributable to cumulative global extraction during 1993–2013 (121 billion metric tonnes) (BP 2014). Proven reserves in 2013 were sufficient for an additional 113 years at the 2013 global production rate (7.9 billion tonnes/yr).

Potential CO_2 Emissions from Reserves

Summing the carbon in proven reserves for natural gas, coal, and oil, there are some 3,000 Gt of potential CO_2 emissions if reserves are fully used. Based on conversion factors from the US Energy Information Administration,[1] the amount of potential CO_2 in the current natural gas reserve is 355 Gt CO_2, and for coal and oil the values are 1,865 Gt CO_2 and 725 Gt CO_2, respectively. These amounts total almost 3,000 additional Gt CO_2—more than enough to push cumulative emissions well past the 1,700 and 2,200 Gt remaining for the 3°C thresholds at 90 percent and 66 percent.

Importantly, the additional nearly 3,000 Gt of potential CO_2 emissions do not take into account several factors that will likely raise the total reserves available in the future. Because proven oil and natural gas reserves have been growing (table 2), it seems plausible that they will continue to do so. Moreover, the estimates used here are conservative as they do not take into account probable or possible fossil fuel reserves that have already been identified. McGlade and Ekins (2015) estimate that remaining fossil fuel resources are almost four times larger than the tally of proven reserves used here and may contribute 11,000 Gt of CO_2 emissions.

[1] The conversion factors are available at www.eia.gov/environment/emissions/co2_vol_mass.cfm.

Possible Mitigating Factors

Several factors beyond increased renewable energy could work to limit net CO_2 emissions even if fossil fuels are used. Considerable research is under way on the broad application of carbon capture and storage (CCS) technologies, which have the potential to store hundreds of Gt CO_2 if substantial technological and economic barriers can be overcome (e.g., Eccles et al. 2012; Haszeldine 2009).

Furthermore, negative emission technologies, defined as the deliberate removal of CO_2 from the atmosphere by technologies such as direct air capture of CO_2 or biomass energy coupled to CCS (Fuss et al. 2014), could permit larger emission quotas or the overshoot of emissions beyond a threshold if the future availability of those technologies were assured. But how effective such technologies might be, and how widely available they could become, is uncertain and depends both on technological developments not yet realized and on a high market price of CO_2 emissions.

Conclusions

Carbon dioxide emissions from human activities have grown substantially over the past decade, reaching about 40 Gt CO_2 per year in 2013 and some 2,000 Gt of cumulative CO_2 since 1870. Very high mitigation rates and sustained reductions in greenhouse gases are now required to have any chance of keeping global temperatures from rising less than 2°C compared to preindustrial levels. To date, however, such aggressive mitigation is not consistent with observed mitigation over the past 25 years or with current national emission reduction targets. Keeping global warming below 2°C also implies that the majority of proven fossil fuel reserves will stay in the ground, unless CCS techniques—unproven at the necessary scale—are rapidly implemented (McGlade and Ekins 2015).

Despite all the important global policy discussions to keep global temperature increases below 2°C, few people realize how quickly the world is approaching the cumulative emission threshold for an increase of 3°C. If global CO_2 emissions continue to grow at the annual rate of 2 percent observed for the past 15 years, increases of 3°C could be the reality only 30 years from now.

Stronger mitigation efforts are needed to reduce the rate of climate change, and adaptation policies are, and will be, needed to cope with the unavoidable climate impacts.

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