Written Testimony of

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The Science Behind Impacts of the Climate Crisis

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Introduction

Good morning Chairwoman Johnson, Ranking Member Lucas, and members of the Committee. I am grateful for the opportunity to join you today and the opportunity to share my perspective on the science behind the impacts of climate change.

My name is Zeke Hausfather. I am the director of climate and energy at the Breakthrough Institute, an environmental think tank located in Oakland, California. I also serve as a research scientist with Berkeley Earth, and a contributor to Carbon Brief. I am a climate scientist whose research focuses on observational temperature records, climate models, and mitigation technologies. I am also a contributing author to the IPCC 6th Assessment Report. My testimony today will draw upon my work and that of my colleagues to present a view of our changing climate and its impacts, the future warming pathways the world may take, the accelerating global energy transition away from carbon-intensive fuels, and the technologies needed to decarbonize the US economy.

In many ways 2020 was the year in which both climate change and the accelerating energy transition became impossible to ignore. On the climate front we saw 2020 tie with 2016 as the warmest year since records began, with global temperatures around 1.3ºC (2.3ºF) above the temperatures of the late 1800s. Land areas – where we all live – were nearly 2ºC (3.6ºF) warmer. We saw devastating wildfires in California and Australia, extreme heat in Siberia, and the second lowest level of Arctic sea ice ever observed, among other climate extremes.

At the same time, the world has made substantial progress in moving away from the worst-case outcomes of climate change over the past decade. Rather than a 21st century dominated by coal that energy modelers foresaw, global coal use peaked in 2013 and is now in structural decline. We have succeeded in making clean energy cheap, with solar power and battery storage costs falling 10-fold since 2009. The world produced more electricity from clean energy – solar, wind, hydro, and nuclear – than from coal over the past two years. And according to major oil companies peak oil is upon us – not because we have run out of cheap oil to produce, but because demand is falling as consumers shift to electric vehicles.

Current policies adopted by countries put us on track for around 3ºC (or 5.4ºF) of warming by the end of the century, compared to the late 1800s. Including pledges and targets – such as those included in the Paris Agreement – brings this down to 2.5ºC (4.5ºF). We have seen a proliferation of longer-term decarbonization commitments in recent years, with countries representing around half of global emissions – including China – pledging to reach net-zero by 2050 or 2060. If these longer term commitments are achieved, it would bring end-of-century warming down close to 2ºC (3.6ºF).

Some caution is warranted here; long-term pledges should be discounted until reflected in short-term policy commitments. And warming could well be notably higher – or lower – than these best estimates, given scientific uncertainties surrounding both the sensitivity of climate to our greenhouse gas emissions and likely changes in the ability of the land and oceans to absorb a portion of what we emit. CO_2 accumulates in the atmosphere over time, and until emissions reach net-zero the world will continue to warm. This is the brutal math of climate change, and it means that the full decarbonization of our economy is not a matter of if but when.

Cost declines in clean energy go a long way toward making deep decarbonization more achievable at a lower cost than appeared possible a decade ago. Low-cost renewables can provide a sizable share of our energy needs in modern grid-integration models. In the near term, however, America's cheap and abundant supplies of natural gas will play a key role in filling in the gaps as we build out more wind and solar and keep existing clean energy sources like nuclear online.

In the longer term, there is a growing recognition of the need for both complementary technologies – such as grid-scale storage and long-distance transmission – as well as clean firm generation like advanced nuclear, enhanced geothermal, and gas with carbon capture and storage to wean the system off natural gas. Studies have consistently shown that low-carbon power grids with a sizable portion of clean firm generation are a lower cost option than wind, solar, and hydro alone.

Debates around climate mitigation are often framed as a choice between the technologies we have today and future innovations. In reality we need to do both; to deploy what is cost-effective today, and to invest in the range of solutions needed to tackle the hard-to-decarbonize parts of the economy. The recent omnibus bill takes an important step in this direction, authorizing billions of dollars for investments in clean energy, vital energy R&D, and grid modernization. It shows that there is real potential for bipartisan energy solutions that both reduce emissions and create jobs.

If we want to ensure that the rest of the world follows the US lead in reducing CO_2 emissions, there is no better step that we can take than making clean energy technologies cheaper than fossil fuel alternatives. Making clean energy cheap can set the US up to be a leader in developing and selling these technologies to the rest of the world while building new industries and creating jobs at home.

This testimony is divided into three parts. The first focuses on our changing climate, looking at the exceptional conditions of 2020, the uncertainties in future climate change and recent advances in our understanding of climate sensitivity, what we do and do not know about climate impacts, and the reason why emissions need to be reduced to net zero emissions to avoid continued warming.

The second part focuses on the accelerating energy transition, examining the declining fortunes of coal and the rise of cheap clean energy, the implications for future emissions pathways, the reasons why worst-case emissions outcomes are increasingly unlikely, and why the 1.5ºC global climate target is likely out of reach at the same time that pathways to well-below 2ºC are becoming more plausible.

The third part explores how have some – but not all – of the technologies we need to cost-effectively decarbonize different parts of the economy, examines the results from three newly-published US decarbonization models, and looks toward the challenge of stranded fossil fuel assets in a post peak-oil future.

Our changing climate

The state of the climate in 2020

2020 was a remarkable year for the Earth's climate. It saw surface temperatures tying for the warmest year since records began in the mid-1850s, a fact all the more remarkable because the latter half of 2020 saw some natural cooling effect from a modest La Niña event in the tropical Pacific. It was the warmest year on record for ocean heat content – which in many ways serves as a our best indicator of the Earth's changing temperature as upwards of 90 percent of net heat trapped by greenhouse gases in the atmosphere accumulates in the oceans. It was the warmest or second warmest in the Earth's troposphere – the lower part of the atmosphere – depending on the dataset examined. Arctic sea ice experienced its second lowest summer minimum, with record lows in sea ice extent and volume in the Arctic for much of the period between July and November. Sea level and atmospheric greenhouse gas concentrations continued to rise, while the world's glaciers continued to shrink and decline.[1]

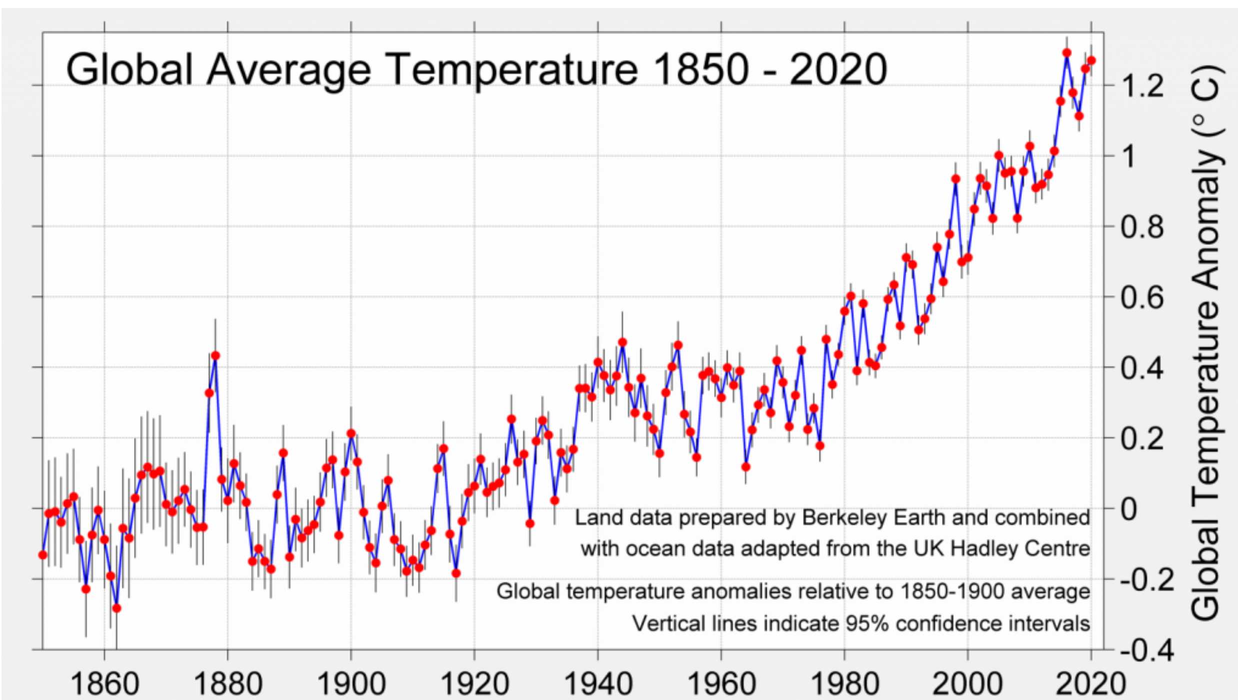

Figure 1: Annual global mean surface temperature anomalies between 1850 and 2020 from Berkeley Earth, along with 95% confidence intervals.[2]

[1] For more details on 2020 climate see: Hausfather, Z. 2021. State of the climate: 2020 ties as warmest year on record. *Carbon Brief*. Available: https://www.carbonbrief.org/state-of-the-climate-2020-ties-as-warmest-year-on-record

[2] Rohde, R., and Hausfather, Z. 2020. The Berkeley Earth Land/Ocean Temperature Record. *Earth System Science Data*. Available: https://essd.copernicus.org/articles/12/3469/2020/

Global surface temperatures in 2020 were between 1.2ºC and 1.4ºC (2.2ºF and 2.5ºF) above the 1880-1900 average depending on the dataset used.[3] The earth has been warming at a rate of nearly 0.2ºC (0.4ºF) per decade since the 1970s.

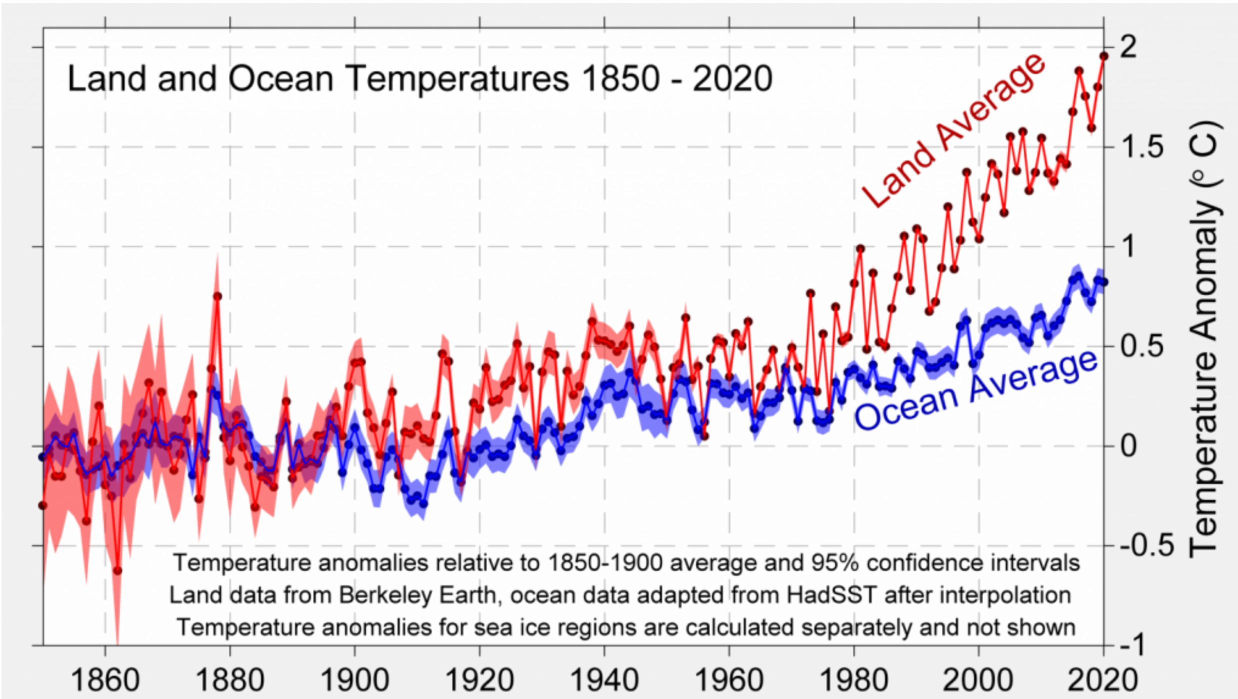

Figure 2: Annual mean surface temperature anomalies for land (red) and ocean (blue) regions between 1850 and 2020 from Berkeley Earth, along with 95% measurement confidence intervals.

Two thirds of the Earth's surface is covered by oceans, where temperatures are increasing at a slower rate than land regions. While the globe as a whole was around 1.3ºC warmer than late 19th Century levels in the Berkeley Earth dataset in 2020, we find that land temperatures are already nearly 2ºC (3.6ºF) above preindustrial levels, compared to only 0.8ºC (1.4ºF) over the oceans. Some regions of the land are warming faster still; high latitude areas above 60N – which includes nearly all of Alaska and Northern Canada – have warmed by 3ºC (5.4ºF).

[3] The 1880-1900 period is used for this calculation to maximize the number of global surface temperature datasets that can be compared. Note that the "preindustrial" baseline period is itself inconsistently defined. Some global surface temperature datasets begin in 1850, and tend to use an 1850-1900 baseline, while others start in 1880 and use an 1880-1900 or 1880-1899 baseline.

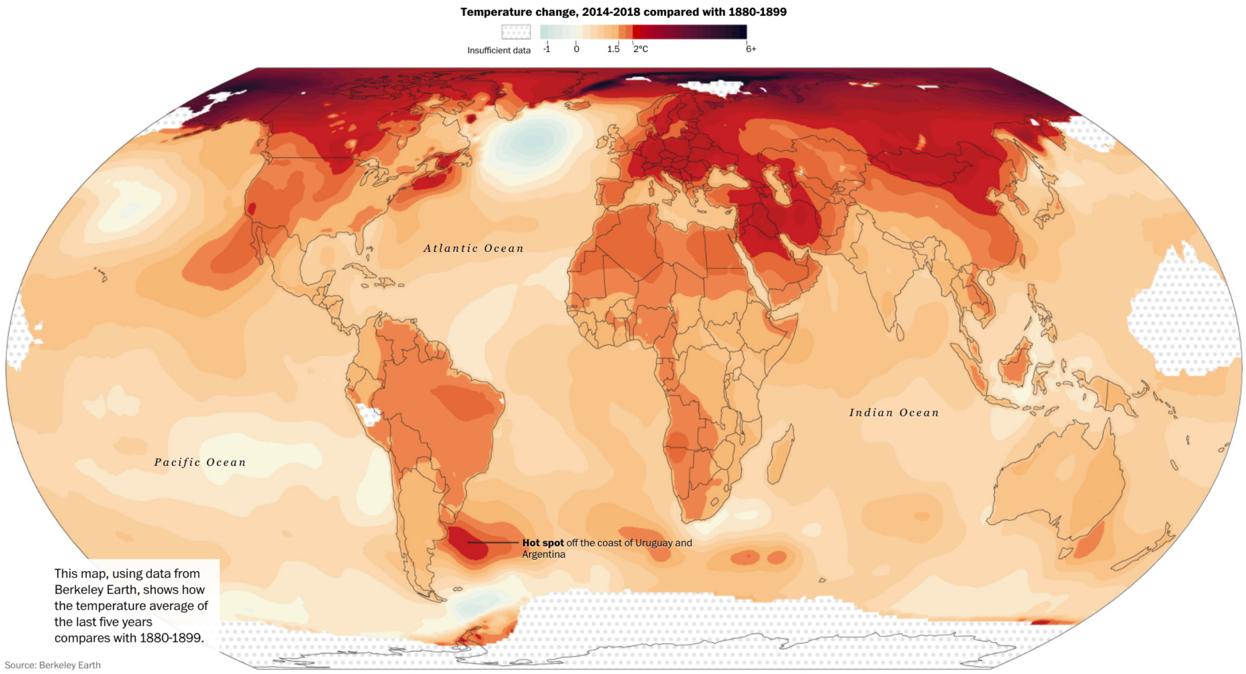

Figure 3: Global surface temperature changes between the 1880-1899 period and the 2014-2018 period in the Berkeley Earth dataset. Figure from the Washington Post; white areas represent regions where 1880-1899 temperature estimates are unavailable.[4]

A simple continuation of the warming trend over the past few decades suggests that the world will pass 1.5ºC above preindustrial levels in the mid 2030s and 2ºC in the early 2060s. This is also consistent with the results that the latest generation of global climate models find in scenarios where our emissions of CO_2 and other greenhouse gases remain close to current levels through 2050.[5,6]

[4] Washington Post. 2019. 2°C: Beyond the Limit: Dangerous new hot zones are spreading around the world. Available: https://www.washingtonpost.com/graphics/2019/national/climate-environment/climate-change-world/

[5] E.g. in the RCP4.5 scenario for the prior generation of climate models (CMIP5) and the SSP2-4.5 scenario in the latest generation (CMIP6). For details see: Hausfather, Z. 2020. Analysis: When might the world exceed 1.5ºC and 2ºC of global warming? *Carbon Brief*.

[6] For more details on climate/earth system models see: McSweeney, R. and Hausfather, Z. 2018. Q&A: How do climate models work? Carbon Brief. Available: https://www.carbonbrief.org/qa-how-do-climate-models-work

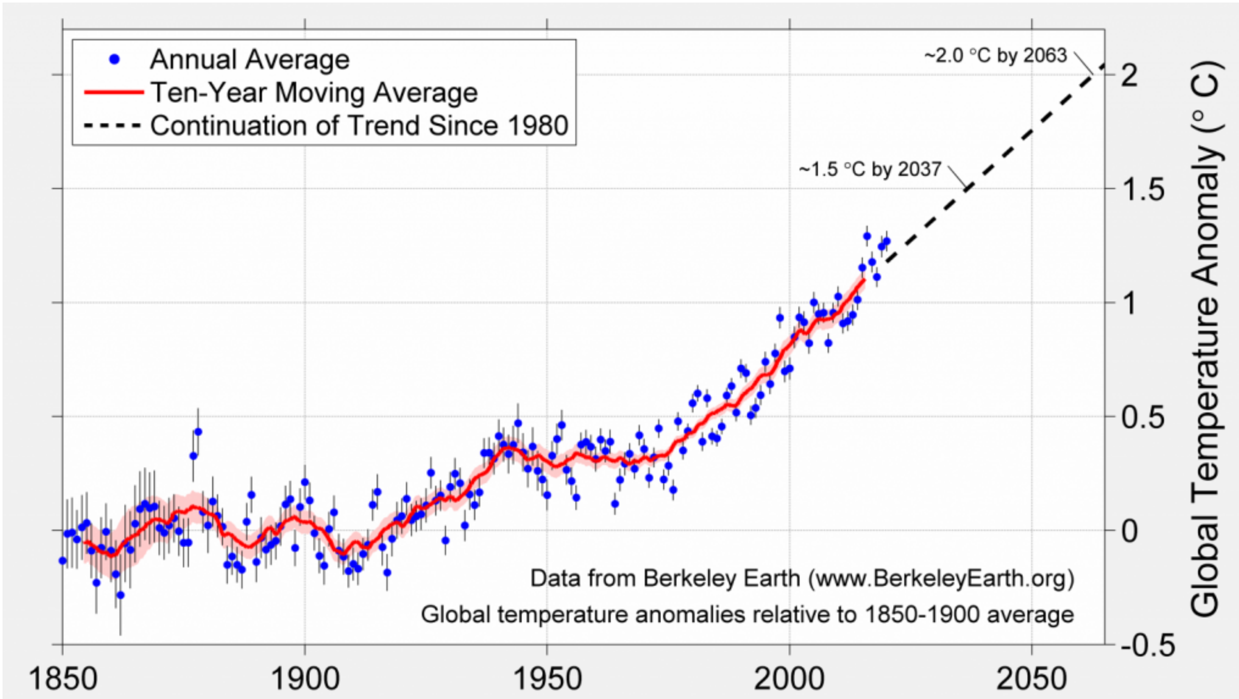

Figure 4: Annual global mean surface temperature anomalies between 1850 and 2020 from Berkeley Earth and a linear projection of future warming through 2065 if the warming trend since 1980 continues.

Uncertainties in future climate change

When projecting future climate change we have to deal with three different – and important – sources of uncertainty.

The first of these is the one that is in our control – our emissions of CO_2 and other greenhouse gases.[7] The IPCC 5th Assessment Report examined four different future concentration scenarios – called Representative Concentration Pathways (RCPs) – that are driven by different emission trajectories:

- RCP2.6 – would require sharp near-term reductions in CO_2 emissions and ultimately result in around 1.7ºC (3.1F) global mean surface temperature warming by 2100 relative to preindustrial.[8]
- RCP4.5 – has global CO_2 emissions remaining roughly flat though 2050 before declining to around half of current levels by 2100, and would result in around 2.5ºC (4.5F) warming by 2100.

[7] While human emissions of CO2 is the major factor driving recent warming, our emissions of black carbon, halocarbons, sulphur dioxide, nitrous oxide, methane, nitrogen oxide, and albedo changes from land use also contribute to our changing climate (and to total “radiative forcing”).
[8] Note that the number associated with each RCP – 2.6, 4.5, 6.0, and 8.5 – refers to the change in well-mixed greenhouse gas radiative forcing in watts per square meter of the Earth’s surface by 2100.

- RCP6.0 – has emissions staying relatively flat, ending only around 25 percent above current levels by 2100 with warming of around 3ºC (5.4F).
- RCP8.5 – has rapid growth of future emissions, with global emissions around 2.5 times greater than current levels by 2100 and warming of around 4.6ºC (8.3F).

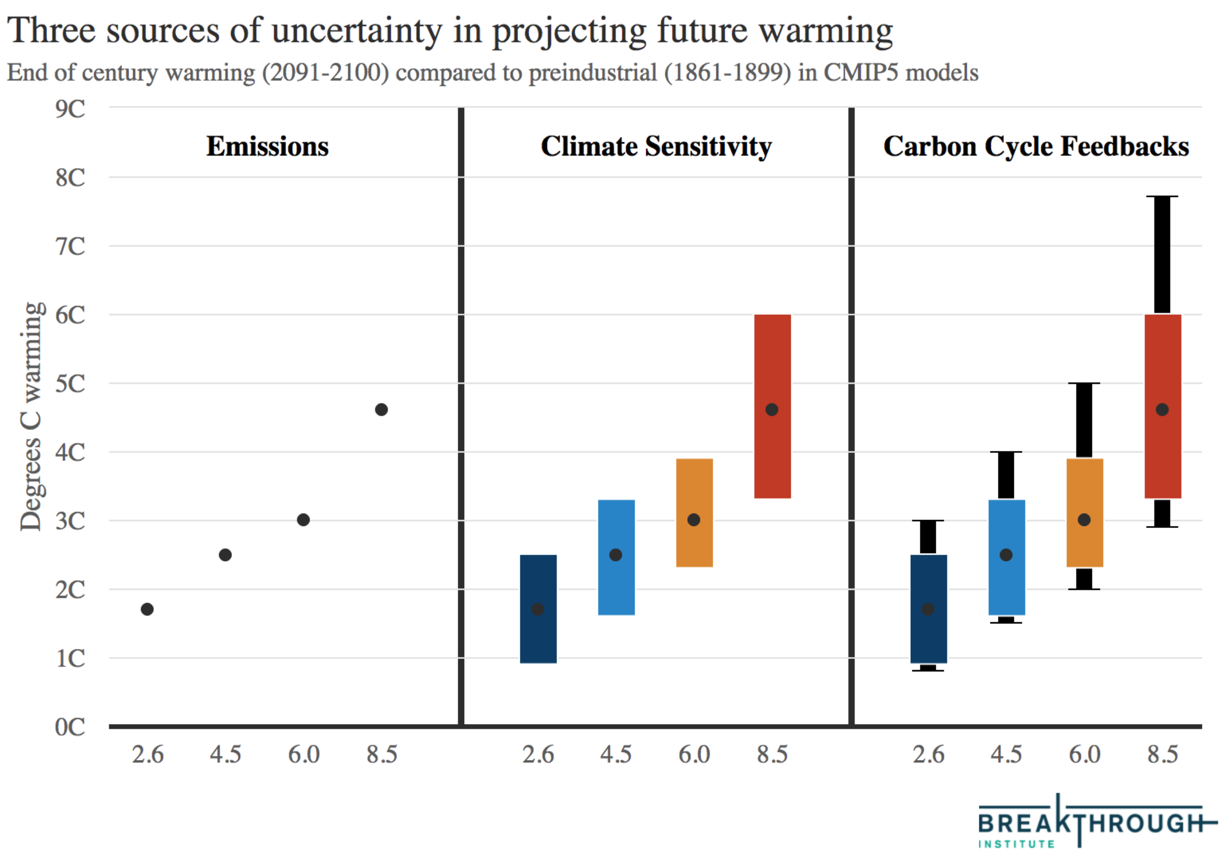

Figure 5: Projected end-of-century (2091-2100) warming relative to 1861-1899 across the four RCP scenarios (2.6, 4.5, 6.0, and 8.5) based on the climate models (CMIP5) featured in the IPCC Fifth Assessment Report. The first panel shows the multimodal mean warming for each RCP scenario; the second panel shows the range of warming across all the individual models in each RCP driven by differences in model sensitivity; the third panel shows the estimated range of warming for each RCP when carbon cycle feedback uncertainties are also included.

Unfortunately future emissions alone provide a fairly limited picture of the amount of warming the world may actually experience. This is due to the other two sources of uncertainty: climate sensitivity and carbon cycle feedbacks. Climate sensitivity refers to the amount of warming the world will experience as CO_2 in the atmosphere increases; it is typically expressed using a simple metric of how much the world will warm over the long-term if atmospheric concentrations of CO_2 are doubled.

Climate sensitivity has long been a “holy grail” of sorts for the climate science community, but has been difficult to narrow down. Back in 1979 Dr. Jules Charney led a National Academy of Sciences report that suggested if atmospheric concentrations of CO_2 were to double (e.g. from their preindustrial value of 280 parts per million to 560 parts per million), the world would likely warm by somewhere between 1.5ºC and 4.5ºC (2.7F to 8.1F). The most recent IPCC assessment report (AR5), published 34 years after Charney's report, gave the same "likely" range of 1.5ºC to 4.5ºC warming per doubling of CO_2.[9]

Thankfully some meaningful progress has been made on the question of climate sensitivity in the past few years. A recent assessment of climate sensitivity undertaken under the auspices of the World Climate Research Programme – where I was a coauthor – provided the first comprehensive case for narrowing the range of climate sensitivity based on multiple lines of evidence.[10] We suggest that climate sensitivity is likely to be between 2.6ºC and 4.1ºC per doubling CO_2; we also find that it now appears extremely unlikely that the climate sensitivity could be below 2C. While we were unable to fully rule out that the sensitivity could be above 4.5C, we find that it is not likely.

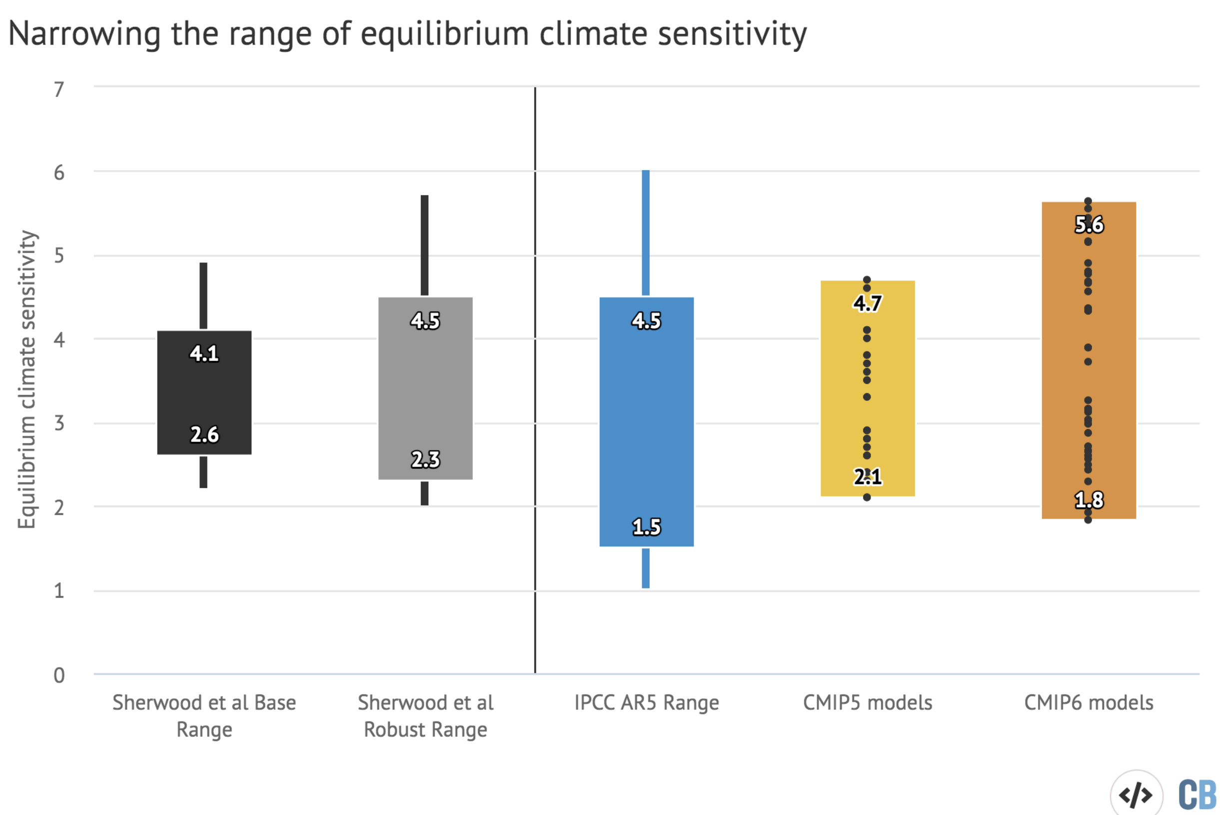

Figure 6: Equilibrium climate sensitivity estimates (degrees C warming per doubling of atmospheric CO_2 concentrations in Sherwood et al 2020 compared to the IPCC AR5 range and the climate sensitivity of all the old CMIP5 models and new CMIP6 models. Thick bars represent the "likely" (66%) range, while narrow bars represent the "very likely" (90%) range. Sherwood et

[9] Note that "likely" here refers to a 66th percentile range; e.g. there is a roughly 33% chance that sensitivity could either be above or below this range.
[10] Sherwood, S.C., et al. 2020. An Assessment of Earth's Climate Sensitivity Using Multiple Lines of Evidence. *Reviews of Geophysics*. Available: https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2019RG000678

al ranges are shown for both the base case when all lines of evidence are included, and the robust case where any one line of evidence is excluded. Figure via Carbon Brief.[11]

This suggests that some of the latest generation of climate models – CMIP6[12] – that have very high climate sensitivity may not provide realistic long-term global surface temperature projections, a conclusion supported by numerous other recent studies showing that most of these very high (5C+) sensitivity models have relatively poor hindcast performance when compared with observed global mean surface temperature change over the past decade or the Earth's more distant past.[13,14,15,16,17,18,19]

Carbon cycle feedbacks represent the third major source of uncertainty when projecting future warming. Today, around half of the CO_2 emitted by humans remains in the atmosphere, with the remainder absorbed by the oceans and land. However, as the Earth warms this is expected to change. For example, warming reduces the amount of CO_2 absorbed by surface ocean waters and the amount of carbon sequestered in soils. It can also accelerate tree death and the risk of wildfires. Thawing permafrost may release additional carbon into the atmosphere. Overall, the carbon cycle is expected to weaken as a result of climate change, leading to more emissions remaining in the atmosphere and less being absorbed by the land and oceans. All of these processes introduce uncertainty when translating future CO_2 emissions into changes in atmospheric CO_2 concentrations.

Future warming scenarios developed by the climate modelling community do consider carbon-cycle feedbacks, but often use single estimates of the feedback strength from previous studies and do not include any of the uncertainties in carbon-cycle feedbacks. The reason scenarios leave out carbon-cycle feedback uncertainties is that about half of the climate modelling groups do not currently include the biogeochemical cycles needed to model carbon-cycle feedback changes. Including uncertainties in future carbon cycle feedbacks results

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[11] For more details see Forster, P., et al. 2020. Why low-end 'climate sensitivity' can now be ruled out. *Carbon Brief*. Available: https://www.carbonbrief.org/guest-post-why-low-end-climate-sensitivity-can-now-be-ruled-out

[12] For more on the new generation of climate models, see: Hausfather, Z. 2019. CMIP6: the next generation of climate models explained. *Carbon Brief*. Available: https://www.carbonbrief.org/cmip6-the-next-generation-of-climate-models-explained

[13] Nijsse, F.J.M.M., et al., 2020. Emergent constraints on transient climate response (TCR) and equilibrium climate sensitivity (ECS) from historical warming in CMIP5 and CMIP6 models. *Earth System Dynamics*. Available: https://esd.copernicus.org/articles/11/737/2020/

[14] Zhu, J. et al. 2020. High climate sensitivity in CMIP6 model not supported by paleoclimate. *Nature Climate Change*. Available: https://www.nature.com/articles/s41558-020-0764-6

[15] Tokarska, K.B., et al. 2020. Past warming trend constrains future warming in CMIP6 models. *Sci. Adv.*

[16] Flynn, C.M., and Mauritsen, T. 2020. On the climate sensitivity and historical warming evolution in recent coupled model ensembles. *Atmospheric Chemistry and Physics*.

[17] Brunner, L., et al. 2020. Reduced global warming from CMIP6 projections when weighting models by performance and independence. *Earth System Dynamics*.

[18] Ribes, A., et al. 2021. Making climate projections conditional on historical observations. *Sci. Adv.*

[19] Zhu, J. et al. 2021. Assessment of Equilibrium Climate Sensitivity of the Community Earth System Model Version 2 Through Simulation of the Last Glacial Maximum.

in as much as 13 percent less warming or 25 percent more warming than estimates based on climate sensitivity alone.[20]

What we do and do not know about climate impacts

Continued climate change is expected to result in substantial negative impacts to both human and natural systems. The degree of impact will in large part be determined by our future emissions. One important finding from climate models is that the climate as a whole is not particularly prone to tipping points, at least within the range of emissions we would reasonably expect to occur this century. Climate models show that warming is proportional to our cumulative emissions, but there is no discernable point at which we end up getting "runaway" climate change. Despite the popular portrayal by some in the media, global climate targets like well-below 2ºC do not represent a "point of no return" where "climate change, intensified by various feedback loops, spins completely out of control".[21]

Rather, targets like well-below 2ºC are themselves largely political constructs informed by the climate impacts literature.[22] We know that impacts on both human and natural systems increase sharply as the climate warms, at 2ºC is a point at which impacts across a number of human and natural systems are likely to have become severe enough that they are best avoided if possible. However, climate change is ultimately a matter of degrees rather than thresholds; the world does not suddenly experience runaway global warming if a particular threshold is passed, but the magnitude of impacts continues to accelerate as the world warms.

That is not to say that tipping points in the climate system are not concerning. There are clear thresholds associated with natural systems, and a world of increasing future emissions is one in which most coral reef ecosystems cease to exist, parts of the Amazon rainforest may permanently shift into a savannah-type ecosystem, ocean circulation may significantly slow, greenhouse gas releases from Arctic permafrost will accelerate, summer Arctic sea ice may cease to exist, and the world will lock-in multiple meters of sea level rise from melting ice sheets over the next millennium. These are all serious impacts, but at the same time there is relatively limited evidence that they could result in substantial additional warming compared to what is already projected in modern climate models.

At the same time, we should also be humbled by what we do not know about the Earth's climate. Models are necessarily imperfect representations of reality, and large and not-fully-explained changes to the climate in the distant past should make us cautious. The

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[20] For details see Hausfather, Z., and Betts, R. 2020. Analysis: How 'carbon-cycle feedbacks' could make global warming worse. *Carbon Brief*.
[21] See Chrobak, U. 2019. Can we still prevent an apocalypse? What Jonathan Franzen gets wrong about climate change. *Popular Science*. Available: https://www.popsci.com/climate-change-new-yorker-franzen-corrections/
[22] Victor, D., and Kennel, C. 2015. Climate policy: Ditch the 2°C warming goal. *Nature*. Available: https://www.nature.com/news/climate-policy-ditch-the-2-c-warming-goal-1.16018

more we push the Earth out of the climate that it has experienced over the past few million years, the larger the chance that we encounter "unknown unknowns".[23]

Beyond concerns over climate tipping points, there are many impacts that are clearly detectable and attributable to the climate changes we have already experienced. Extreme heat events are becoming more common as the Earth warms, with many more all-time heat records being set than cold records across the world. A warming world increases the amount of water vapor in the atmosphere, resulting in more extreme precipitation events. Higher temperatures result in lower soil moisture and contribute to exacerbating drought conditions. Melting ice sheets and glaciers combined with the thermal expansion of water drive higher sea levels, contributing to higher and more damaging storm surges when storms hit coastal areas. Higher ocean temperatures contribute to the formation of more intense hurricanes and tropical cyclones. Sea ice loss and melting permafrost result in dramatic changes in the Arctic. Dryer vegetation due to high temperatures enables the rapid spread of devastating wildfires.[24]

However, despite the increases in extreme events due to climate change, the risk of death from extreme events worldwide has declined dramatically – by around two orders of magnitude – over the past century. This is because our adaptive capacity has increased, through the use of technology to construct more resilient structures, better storm forecasts, cooler interior environments, more thorough communications and stronger institutions to provide disaster relief.[25] Back in the 1970s major cyclones hitting Bangladesh would result in hundreds of thousands of deaths; today storms of a similar magnitude result in only hundreds.[26] Human adaptive capacity is an important factor to account for in determining climate change impacts, and a more equitable, prosperous world is likely one where climate impacts are much less severe, all things being equal. This does not mean that climate change impacts on human systems are not real or severe; a world without climate change but with the same level of adaptive capacity would be one with notably smaller impacts. It is also possible that impacts of climate change will outpace our ability to adapt to them.[27]

One of the particularly pernicious aspects of climate change is that those least responsible tend to be most vulnerable; its poorer countries with vanishingly small per-capita CO_2 emissions that

[23] Schmidt, G.A. 2006. Runaway tipping points of no return. *RealClimate*. Available: http://www.realclimate.org/index.php/archives/2006/07/runaway-tipping-points-of-no-return/comment-page-2/

[24] For a comprehensive summary of climate change attribution studies across different types of extreme events, see: Pidcock, R., and McSweeney, R., 2021. Mapped: How climate change affects extreme weather around the world. Available: https://www.carbonbrief.org/mapped-how-climate-change-affects-extreme-weather-around-the-world

[25] Formetta, G., and Feyen, L. 2019. Empirical evidence of declining global vulnerability to climate-related hazards. *Global Environmental Change*. Available: https://www.sciencedirect.com/science/article/pii/S0959378019300378

[26] Haque, U., et al. 2012. Reduced death rates from cyclones in Bangladesh: what more needs to be done? *Bulletin of the World Health Organization*. Available: https://www.who.int/bulletin/volumes/90/2/11-088302/en/

[27] Mehrabi, Z., et al. Can we sustain success in reducing deaths to extreme weather in a hotter world?. *World Development Perspectives*. Available: https://www.sciencedirect.com/science/article/abs/pii/S2452292918301449

are the most severely affected by increases in extreme events because they lack the adaptive capacity that we in the US take for granted. There need not be a tradeoff between climate mitigation and development, but we should work to ensure that decarbonization policies support rather than inhibit poorer countries and disadvantaged communities from pursuing prosperity.

While human systems are often quite adaptable on short timescales, the same is not true for the natural environment. The timeframe over which plants and animal species evolve to respond to changes in their environment is orders of magnitude slower than the rate of changes we are seeing to many environments today. A high warming future could consign many of the world's species to extinction. It is quite possible to imagine a humanity that adapts to – but does not thrive in – a high-warming future amid the ruin of natural ecosystems. Even here other human activities make an important difference in the capacity of natural ecosystems to respond to climate change. Deforestation, air quality, water pollution and other environmentally damaging activities make the natural world more vulnerable to disruptions from climate change. Addressing them can help make nature more resilient.

Climate change impacts pose a serious threat to our way of life, but are unlikely to lead to human extinction. However, existential risks are an unnecessarily high bar to take action; nearly every other challenge we have dealt with in the past – poverty, war, hunger, disease, conventional environmental pollution, etc. – did not literally threaten the survival of our species. The impetus to mitigate climate change is less about enabling humanity to survive and more about enabling it to thrive, and to leave our children a natural world that, while far from untouched, is at least largely intact.

The need for net-zero emissions

Our best estimate is that approximately all of the observed global mean surface temperature warming since the 1950s is due to human emissions of CO_2 and other greenhouse gases. Natural climate "forcings" such as changing solar output, variations in the Earth's orbit, and volcanic activity would have likely led to a slight cooling over the past 70 years in the absence of human influences on the climate.[28]

CO_2 increases are the primary driver of recent warming, and have the same effect on the climate no matter where in the world it is emitted. CO_2 accumulates in the Earth's atmosphere, and the amount of warming that the Earth has and will experience is approximately proportional to our total cumulative emissions.[29] This means that the total cumulative emissions since the

[28] This is the finding of both the IPCC 5th Assessment Report and the recent US Fourth National Climate Assessment. For more details and an independent assessment of the different drivers of warming since 1850 see Hausfather, Z. 2017. Analysis: Why scientists think 100% of global warming is due to humans. *Carbon Brief*. Available: https://www.carbonbrief.org/analysis-why-scientists-think-100-of-global-warming-is-due-to-humans

[29] For a good review of the cumulative emissions-temperature relationship see: Matthews, H.D., et al. 2018. Focus on cumulative emissions, global carbon budgets and the implications for climate mitigation targets. *Environmental Research Letters*. Available: https://iopscience.iop.org/article/10.1088/1748-9326/aa98c9/meta

industrial revolution are driving current global temperatures rather than the emissions of any given year. The long atmospheric lifetime of CO_2 perturbations means that emissions would need to be cut fairly dramatically – by around 80 percent or so – for atmospheric CO_2 concentrations to stabilize.

However, stable atmospheric CO_2 concentrations do not necessarily result in stable global temperatures. The Earth is currently out of equilibrium; that is, more heat is being trapped by greenhouse gases in the Earth system than is being reradiated back to space. The oceans are slowly absorbing this extra heat, and will continue to slowly heat up even if CO_2 levels begin to fall. It turns out – rather conveniently – that if emissions of CO_2 are brought all the way down to net-zero, the cooling from falling atmospheric concentrations of CO_2 is nearly perfectly balanced out by warming "in the pipeline" as the oceans continue towards equilibrium, and global temperatures remain relatively flat.[30]

This has a number of important implications. First, it means that even if we get emissions all the way down to net-zero, global temperatures will not fall for many centuries to come. To actually reduce global temperatures we need net-negative emissions – sucking more CO_2 out of the atmosphere than is going in. To put it another way, if we ever wanted to bring the Earth back to the temperatures of the 1970s, we would have to actively remove an amount of CO_2 from the atmosphere roughly equal to all of our emissions since the 1970s. Second, it means that we have significant influence over future warming through the control of our emissions; there is likely not a large amount of additional warming that is inevitable, and we can effectively stop the world from warming any further by reaching net-zero emissions. But as long as emissions remain above net-zero, the world will continue to warm.

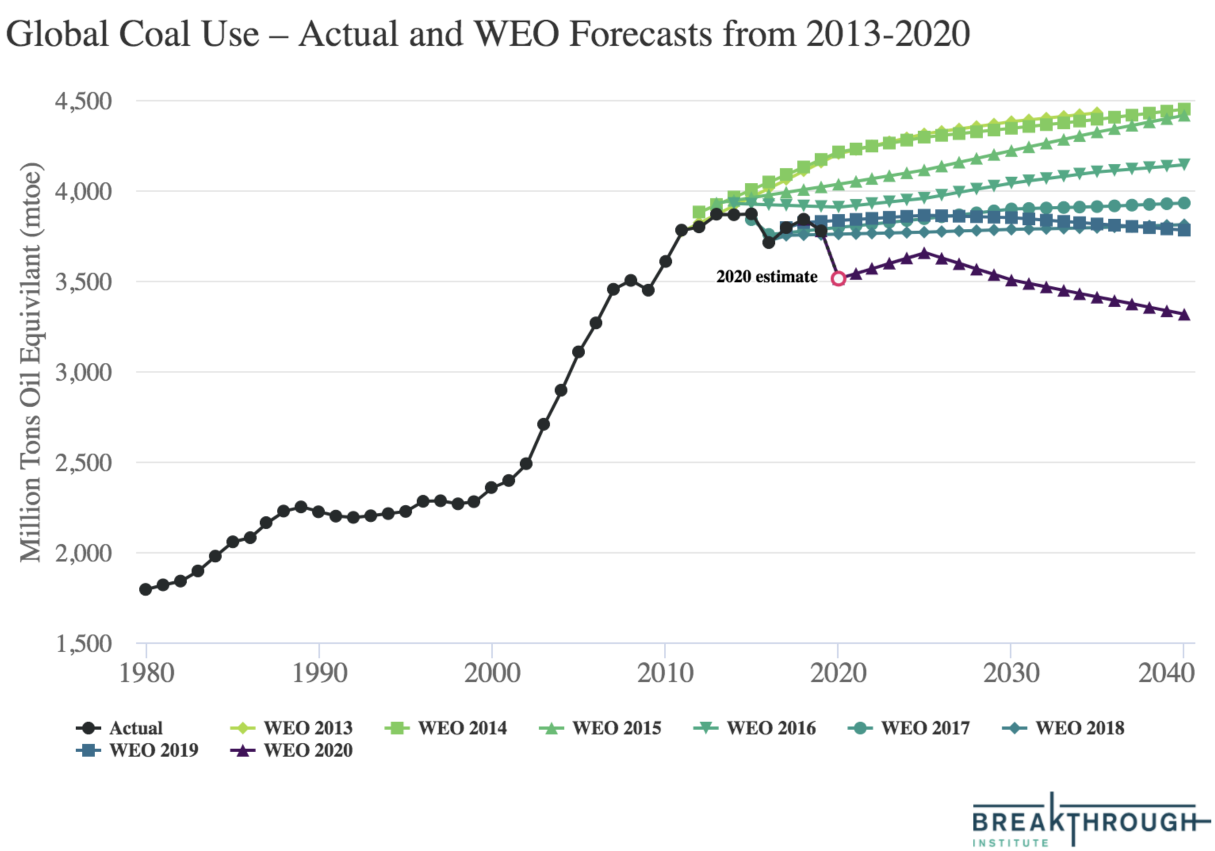
[30] MacDougall, A.H., et al. 2020. Is there warming in the pipeline? A multi-model analysis of the Zero Emissions Commitment from CO_2. *Biogeosciences*. Available: https://bg.copernicus.org/articles/17/2987/2020/

The accelerating energy transition

Moving toward a clean energy future

A decade ago global CO_2 emissions were rising rapidly. Global use of coal – the most CO_2-intensive fossil fuel per unit of energy – had nearly doubled between 2000 and 2010, driven in large part by a massive expansion in China, where a new coal plant opened every few days.[31] A continuation of this dramatic expansion of coal seemed like a plausible path the world could take, and many global energy system models saw a 21st century dominated by coal in the absence of much stronger climate policies enacted by countries.

A decade later, we live in a very different world. Rather than continuing to grow, global coal use likely peaked in 2013 and has been declining since. Global coal use is in "structural decline" for the foreseeable future according to the International Energy Agency's recent 2020 World Energy Outlook (WEO). Actual coal use has nearly always turned out to be lower than forecasts, as shown in Figure 7, below.



[31] Evans, S., and Pearce, R., 2020. Mapped: The world's coal power plants. *Carbon Brief*. Available: https://www.carbonbrief.org/mapped-worlds-coal-power-plants

Figure 7: Global coal use (black line, in million tons oil equivalent) compared with IEA World Energy Outlook forecasts for each year between 2013 and 2020.

Declines in coal use for electricity have been even more rapid; the world now produces more of its electricity from clean energy sources – wind, solar, hydro, and nuclear – than from coal.[32]

The trajectory of coal in the US is even more dramatic; despite continued projections of a coal renaissance by the Department of Energy's Energy Information Agency (EIA) – which has long been a key resource to the climate and energy community – coal use for electricity generation has fallen to less than half its 2007 peak even before the COVID-19 pandemic created a host of new challenges for the industry.[33] Both renewables and nuclear each produced more electricity than coal in the US in 2020. The speed of the energy transition in the US power sector – driven by a combination of cheap natural gas and renewables – shows how quickly things can change when clean(er) energy sources become the more cost-effective option.

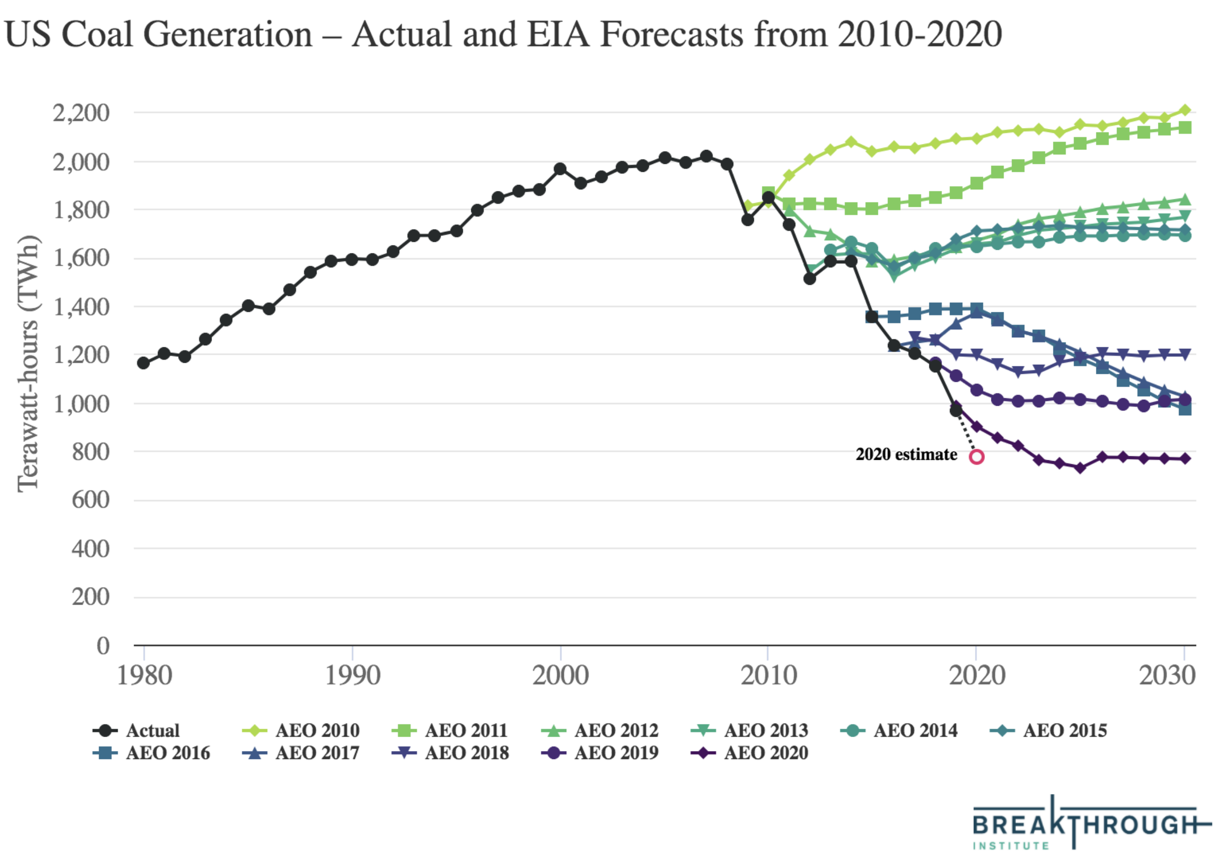


Figure 8: US coal generation (black line, in terawatt-hours) compared with EIA Annual Energy Outlook (AEO) forecasts for each year between 2010 and 2020.

[32] IEA World Energy Outlook 2020. Available: https://www.iea.org/reports/world-energy-outlook-2020
[33] EIA 2020. U.S. Energy-Related Carbon Dioxide Emissions, 2019. Available: https://www.eia.gov/environment/emissions/carbon/

It is also remarkable that coal's decline in the US not only continued but accelerated during the Trump administration, despite the rollback of a number of regulations that could have increased the cost of coal generation. This is a testament to the power of making clean energy cheap, as it produces a transition that is somewhat resilient to policy choices.[34]

Cheap renewables (and – in the US – cheap natural gas) have contributed to both an acceleration of coal retirements and a significant decline in coal capacity factors worldwide. For example, in the US coal plants only ran 40 percent of the time on average in 2020, compared to 67 percent a decade ago.[35] Similarly, the capacity factor of Chinese coal generation has declined from 60 percent in 2011 to 49 percent today, though overcapacity in the sector played a larger role there.[36]

The decline in power sector emissions in the US has been one of the larger – but by no means the only – drivers of reduction in overall US CO_2 emissions.[37] US emissions from fossil fuels were down by 24 percent below 2005 levels in 2020, down from 14 percent below 2005 levels in 2019. While emissions are expected to recover as the economy rebounds, the EIA expects emissions to remain well below 2019 levels at least through 2022, as shown in Figure 9. Given the historically pessimistic nature of EIA CO_2 emissions forecasts, it is quite possible that US CO_2 emissions will be even lower over the next few years.

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[34] Hausfather, Z., and Anderson, L. 2019. Trump's War on Coal. *Breakthrough Institute*. Available: https://thebreakthrough.org/issues/energy/trumps-war-on-coal

[35] EIA Electric Power Monthly. 2021. Table 6.07.A. Available: https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_a

[36] Myllyvirta, L., et al. 2020. Analysis: Will China build hundreds of new coal plants in the 2020s? *Carbon Brief*. Available: https://www.carbonbrief.org/analysis-will-china-build-hundreds-of-new-coal-plants-in-the-2020s

[37] For more details on the different drivers of US CO_2 reductions, see Hausfather, Z. 2017. Analysis: Why US carbon emissions have fallen 14% since 2005. *Carbon Brief*. Available: https://www.carbonbrief.org/analysis-why-us-carbon-emissions-have-fallen-14-since-2005

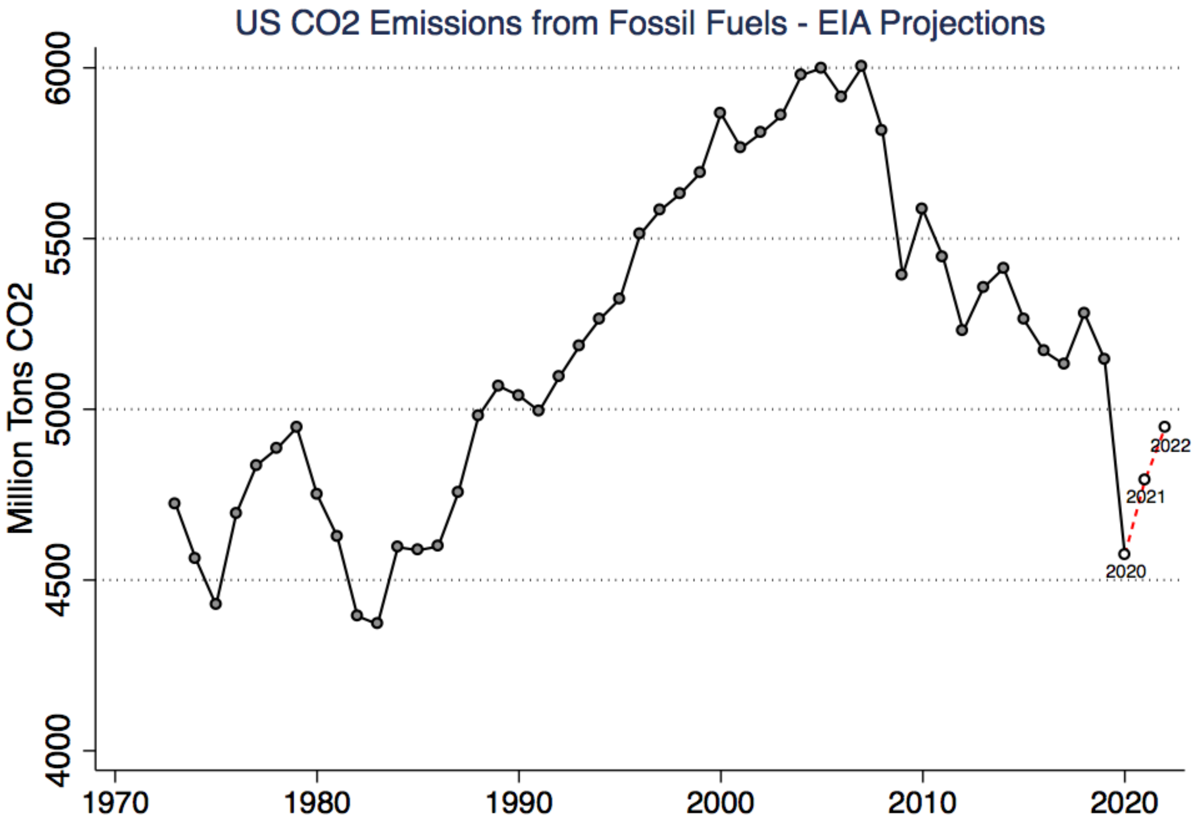

Figure 9: US CO_2 emissions from fossil fuels (in million tons) from 1973-2020, along with 2021 and 2022 projections from the EIA Short Term Energy Outlook (STEO).[38]

The decline of coal use and the rise of clean energy – both in the US and globally – has been driven by a combination of technology and policy. The two are strongly interrelated, as policy has played a role in driving down technology costs both through investing heavily in early research, development, and deployment (RD&D) and driving economies of scale through tax incentives and other subsidies.[39] Solar photovoltaics (PV), wind, and batteries have seen the most dramatic cost declines in recent years. Back in 2009 solar PV cost approximately $350 per megawatt-hour (MWh); since then it has fallen by a factor of 10x, down to $35 per MWh. Electricity generated by wind turbines has fallen from around $140 per MWh to around $40 per MWh.[40] At the same time, battery costs – which are important both to enable higher levels of variable renewable energy use and make electric vehicles more cost-effective – have fallen from $1200 per kilowatt-hour (kWh) to $137, a decline of nearly a factor of 10x.[41]

[38] EIA Short Term Energy Outlook. February 2021. Available: https://www.eia.gov/outlooks/steo/
[39] Jenkins, J., et al., 2010. Where Good Technologies Come From. *The Breakthrough Institute*. Available: https://thebreakthrough.org/articles/american-innovation
[40] Lazard 2020. Levelized Cost of Energy and Levelized Cost of Storage – 2020. Available: https://www.lazard.com/perspective/levelized-cost-of-energy-and-levelized-cost-of-storage-2020/
[41] BloombergNEF 2020 Battery Price Survey.

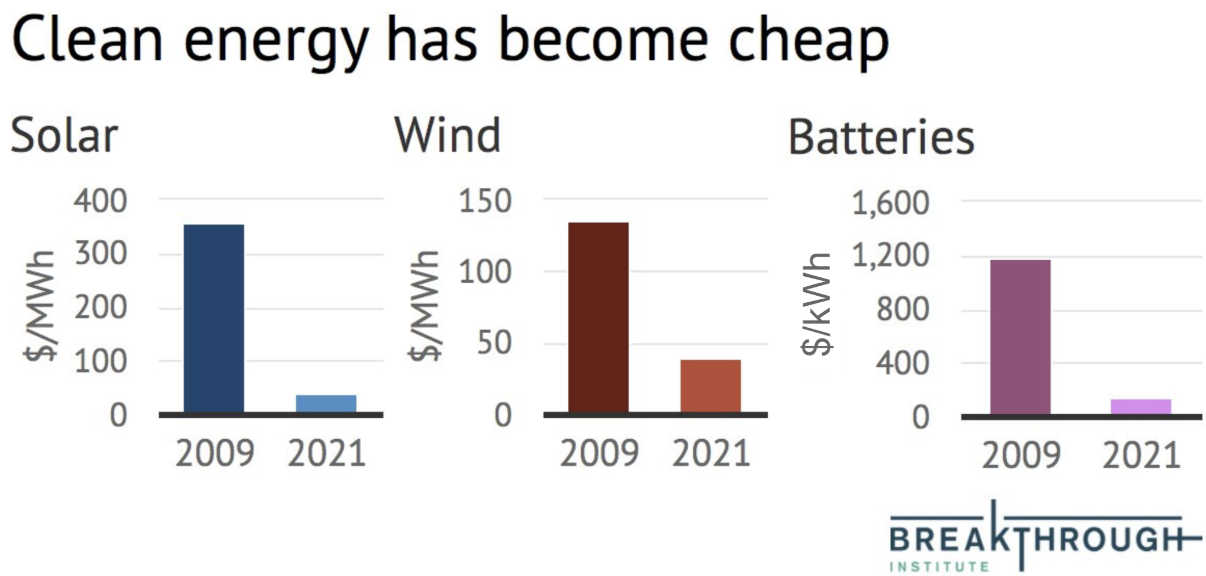

Figure 10: Levelized cost of energy from solar photovoltaics, onshore wind, and lithium ion batteries in 2009 and 2021. Data from Lazard and BloombergNEF.

Non-hydro renewables – primarily wind and solar PV – now produce 10.4 percent of the world's electricity, up from 3.5 percent in 2010 and 1.4 percent in 2000. In 2019, non-hydro renewables accounted for 48 percent of new electricity generation globally, with natural gas accounting for 31 percent, new nuclear accounting for 14 percent, and hydro accounting for 7 percent (both coal and oil generation declined globally in 2019).[42]

Cheap renewables by themselves are not a panacea for decarbonization; as discussed below, clean firm electricity generation like nuclear and additional technological innovation in hard-to-decarbonize sectors like industrial processes, long-distance transportation, and agriculture are needed to cost-effectively fully decarbonize the economy.[43] But cheap renewables coupled with electrification can get us a good part of the way there, and will likely be the largest driver of global decarbonization for at least the next decades or two.[44]

In many ways, technology enables policy. While decarbonizing the US economy seemed like a very costly endeavor a decade ago, falling prices of renewables, electric vehicles, and other technologies makes it appear far less costly today. Cost-effective pathways to decarbonization

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[42] BP Statistical Review of World Energy 2020. Available: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html

[43] Electricity generation in grid decarbonization models can broadly be divided into fuel-saving resources like wind and solar that have near-zero operational costs and displace other higher-cost resources when available, fast-burst balancing resources such as batteries and demand response, and clean firm generation such as nuclear, hydro, gas with carbon capture, and geothermal that can be counted on to meet demand when needed in all seasons and over long durations. For details see: Sepulveda, N.A., et al. 2018. The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. Joule. Available: https://www.sciencedirect.com/science/article/pii/S2542435118303866

[44] Larson, E., et al., 2021. Net-Zero America: Potential Pathways, Infrastructure, and Impacts. Princeton University. Available: https://acee.princeton.edu/rapidswitch/projects/net-zero-america-project/

are driving a slew of new net-zero commitments by countries worldwide. Making clean energy cheap also has important spillover effects; the fact that renewables are the cheapest form of new electricity at the margin in many parts of the world is helping drive large-scale development in middle-income countries like India and China that will account for the bulk of 21st century increases in CO_2 emissions. If we want to ensure that the rest of the world follows the US in reducing CO_2 emissions, there is no better step that we can take than making clean energy cheaper than fossil fuel alternatives. Making clean energy cheap can set the US up to be a leader in developing and selling clean energy technologies to the rest of the world while building new industries at home.

Implications for future emissions pathways

A decade ago the world seemed to be on track for a best estimate of around 4ºC (7F) global mean surface temperature warming by the year 2100, compared to preindustrial levels.[45] To put this in perspective, the peak of the last ice age – which was a drastically different planet than we have today – was only around 6ºC (11F) cooler than preindustrial temperatures.[46]

Today there is cause for some cautious optimism regarding our climate future. We have bent down the curve of future emissions, and seem on track for warming closer to 3ºC (5.4F) in a current policy world and 2.5ºC (4.5F) if additional near-term pledges and targets by counties – such as those included in the Paris Agreement – are met.[47] We are no longer in a "business as usual" world, and the combination of technology and policy has made outcomes where global emissions double or triple by the end of the century far less likely.

[45] Note that RCP8.5-type outcomes with ~5ºC warming were always intended to be the upper end of possible emissions outcomes, and reflected roughly the 90th percentile of no policy baseline emissions scenarios in the literature. The median no policy baseline estimates are generally closer to 4ºC (e.g. the new SSP3-7.0 scenario). For more details see: Hausfather, Z. 2019. Explainer: The high-emissions 'RCP8.5' global warming scenario. *Carbon Brief*. Available: https://www.carbonbrief.org/explainer-the-high-emissions-rcp8-5-global-warming-scenario

[46] Tierney, J.E., et al. 2020. Glacial cooling and climate sensitivity revisited. *Nature*. Available: https://www.nature.com/articles/s41586-020-2617-x

[47] Current policies are reasonably in-line with a RCP6.0 outcome, while near-term pledges and targets are in-line with a RCP4.5 outcome. For more see: Hausfather, Z., and Ritchie, J. 2019. A 3C World Is Now "Business as Usual". *The Breakthrough Institute*. Available: https://www.nature.com/articles/d41586-020-00177-3

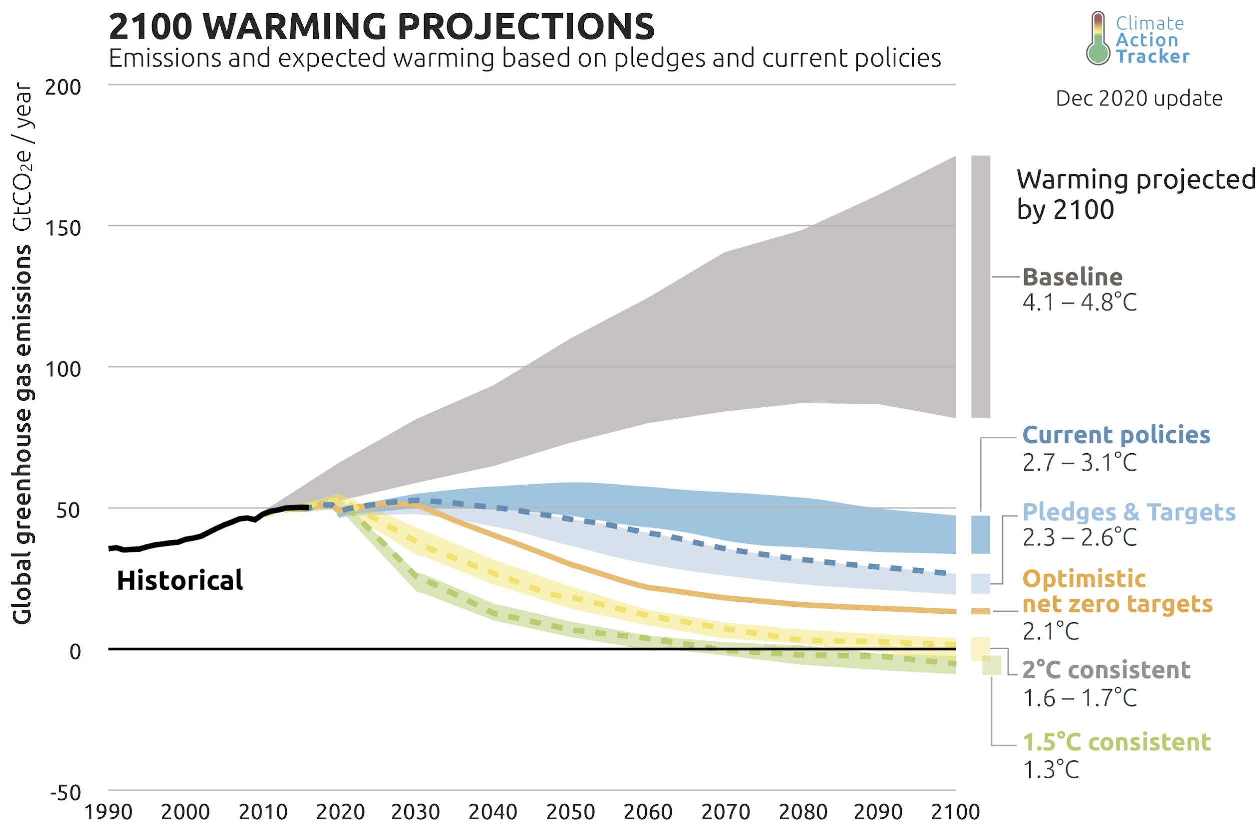

Figure 11: Mean expected global surface temperature warming across various future emissions scenarios. Note that the warming ranges here only reflect emissions uncertainties, and do not include climate sensitivity or carbon cycle feedback uncertainties. Figure from Climate Action Tracker.[48]

There is even a reasonable chance that global emissions may have already peaked in 2019, as the rate of decarbonization was already on track to overtake the rate of global economic growth by the mid-2020s.[49] Even if 2019 did not represent peak emissions, it is clear that global emissions are on a path to plateau this decade.[50] China is likely on track to peak emissions in the next five years, and has pledged to reach net-zero by 2060.[51] In fact, in recent years there has been an explosion of new net-zero pledges, which taken all together would put the world at a best estimate of 2.1ºC (3.8F) above preindustrial levels by 2100.

Today countries representing 43 percent of global emissions have now pledged to reach net-zero by 2050 or 2060, with countries representing another 11 percent of global emissions

[48] Climate Action Tracker 2020. 2100 Warming Projections. Available: https://climateactiontracker.org/global/temperatures/
[49] Hausfather, Z. 2020. CO2 Emissions from Fossil Fuels May Have Peaked in 2019. Available: https://thebreakthrough.org/issues/energy/peak-co2-emissions-2019
[50] IEA World Energy Outlook 2020.
[51] BBC, March 4th 2021. Climate change: Will China take a 'great leap' to a greener economy? Available: https://www.bbc.com/news/science-environment-56271465

actively discussing implementing targets.[52] This includes the European Union, United Kingdom, China, Brazil, Japan, South Korea, Canada, South Africa, Argentina and Mexico, as well as the Biden Administration's net-zero target. This is also notably up from the number of countries that had similar commitments at this point in 2019.[53] It is still unclear how seriously these 2050/2060 net-zero targets should be taken, as long-term targets are easy to put on paper but may prove much harder to achieve. The extent to which long-term commitments are reflected in nearer-term policy goals will prove an early test.

These long-term commitments are a promising development, and if countries prove serious in achieving them it will lead to substantial new investment in technology for sectors of the economy that are difficult to decarbonize today, with large global spillover effects. While the Paris Agreement goal of limiting warming to well-below 2ºC remains challenging, the fact that current commitments in aggregate get us close to that point makes much more plausible than it appeared even a few years ago.

Worst-case emissions outcomes increasingly unlikely

The falling price of clean energy and enactment of climate policies have moved the world away from worst-case outcomes where coal dominates the 21st century energy mix. At the same time, however, a sizable part of the climate impacts literature still tends to focus on the high-end RCP8.5 emissions scenario, where global coal use increases 500 percent by 2100 and global emissions nearly triple. In a piece we published in the journal *Nature* last year, Glen Peters of Norway's CICERO and I argued that researchers should focus on modeling the world as it is today, rather than a counterfactual where all of the progress made over the last decade is erased.[54] It can be useful to examine worst case outcomes, and current policies represent neither a ceiling nor a floor on future emissions outcomes; however, we need to be sure not to conflate what is a worst case outcome with what is "business as usual" today.

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[52] Bloomberg New Energy Finance 2021 Executive Factbook. Available: https://about.bnef.com/blog/bloombergnef-2021-executive-factbook/
[53] UNEP. 2020. Emissions Gap Report 2020. Available: https://www.unep.org/emissions-gap-report-2020
[54] Hausfather, Z., and Peters, G. 2020. Emissions – the 'business as usual' story is misleading. Nature. Available: https://www.nature.com/articles/d41586-020-00177-3

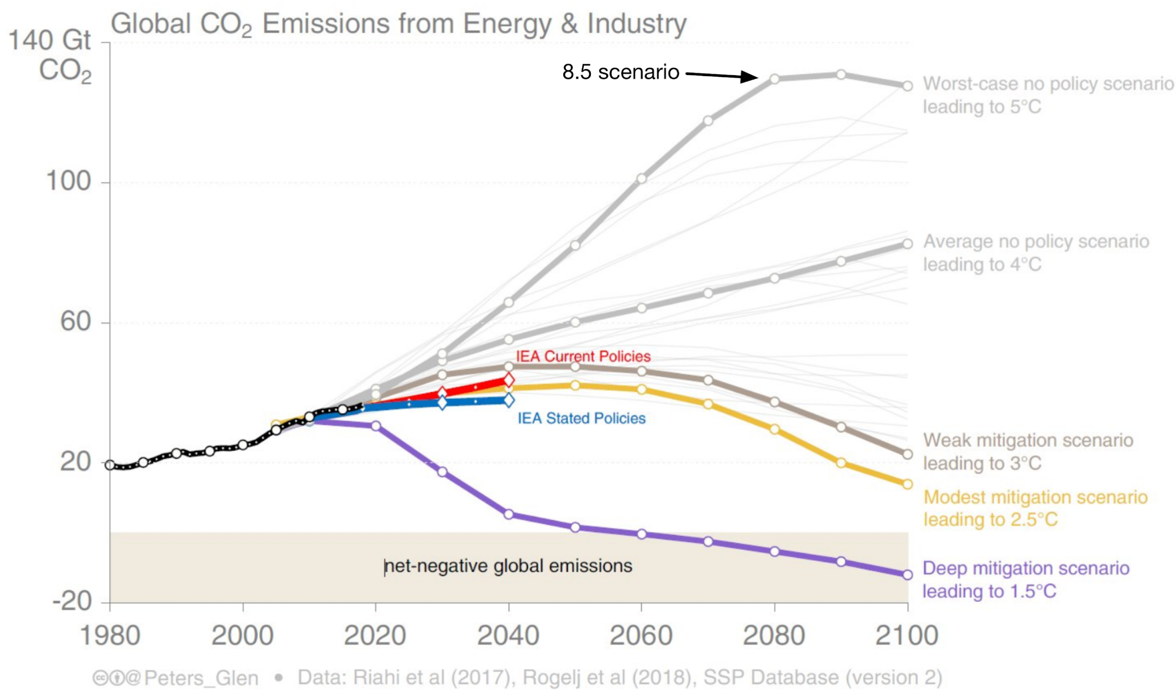

Figure 12: Comparison of emission scenarios featured in the upcoming IPCC 6th Assessment Report to near term current policy and stated policy (e.g. near-term pledges and targets) projections from the IEA 2019 World Energy Outlook. Adapted from Hausfather and Peters 2020.

As the world makes progress on tackling climate change we will necessarily exclude higher-end no-policy emissions outcomes. This is a good thing, but at the same time we need to be cognizant that there are still severe climate impacts to human and natural systems in a 3ºC world, even if they are not as potentially catastrophic as in a 4ºC or 5ºC one. The impetus to limit warming to well-below 2ºC does not depend on a high warming counterfactual, and even current commitments by countries fall short of what would be needed to avoid 2ºC+ warming by 2100.[55]

While the world has moved away from high-end future emissions scenarios, we cannot be as confident in ruling out high levels of future warming. We need to avoid being too deterministic about temperature outcomes based on emissions scenarios; as discussed earlier, there are additional large uncertainties from climate sensitivity and carbon cycle feedbacks. This means that while current policies and pledges and targets put us on track for a best estimate of 3ºC and 2.5ºC warming, respectively, we cannot rule out warming of up to 5ºC and 4ºC, respectively, if both climate sensitivity and carbon cycle feedbacks end up at the highest end of our estimates. The small chance of extremely severe warming outcomes serves as a strong incentive to pursue aggressive emissions mitigation.

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[55] For more details on how current commitments compare with 1.5ºC and 2ºC pathways, see: Hausfather, Z. 2020. UNEP: Net-zero pledges provide an 'opening' to close growing emissions 'gap'. *Carbon Brief*. Available:
https://www.carbonbrief.org/unep-net-zero-pledges-provide-an-opening-to-close-growing-emissions-gap

The world also does not end in 2100, even if most of our climate and energy system models stop there. As long as emissions remain above net-zero, the world will continue to warm. If emissions remain at current levels, RCP8.5-type outcomes could occur in the 22nd century, though not in the 21st. Regardless of what level of warming we feel is achievable in the 21st century, we still need to plan to ultimately bring emissions down to net-zero.

The 1.5ºC target is likely out of reach – but not the 2ºC one

Every year that global emissions remain close to current levels narrows the range of possible futures, making both high-end warming outcomes and low-end warming outcomes less likely. While technological development and climate policy has moved the world away from RCP8.5-type trajectories, delays in reducing global emissions have also put the 1.5ºC aspirational goal of the Paris Agreement increasingly out of reach.

Global surface temperatures in 2020 were between 1.2ºC and 1.4ºC above preindustrial levels, depending on the dataset used. While the 1.5ºC target is defined based on long-term average warming rather than any individual year (which are subject to short-term natural variability from El Niño events, for example), we still have a very small amount of additional warming allowable before the 1.5ºC target is reached.

The relationship between cumulative emissions and warming allows the creation of simplified "carbon budgets" that can inform us about the remaining allowable emissions under different climate targets. While the topic of carbon budgets is not without its controversies and uncertainties, budgets can be a useful tool.[56,57] Figure 13, below, shows a set of simplified emissions pathways for various proposed warming targets, in the absence of net-negative emissions (e.g. below-zero global emissions). It includes scenarios where the best estimate of future warming is either 1.5ºC or 2ºC (e.g. with a 50 percent chance), as well as scenarios that have a two-thirds (66 percent) chance of avoiding 1.5ºC or 2ºC warming based on uncertainties in climate sensitivity.

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[56] Peters, G. 2018. Beyond carbon budgets. *Nature Geosciences*. Available: https://www.nature.com/articles/s41561-018-0142-4

[57] Geden, O. 2018. Politically informed advice for climate action. *Nature Geosciences*. Available: https://www.nature.com/articles/s41561-018-0143-3

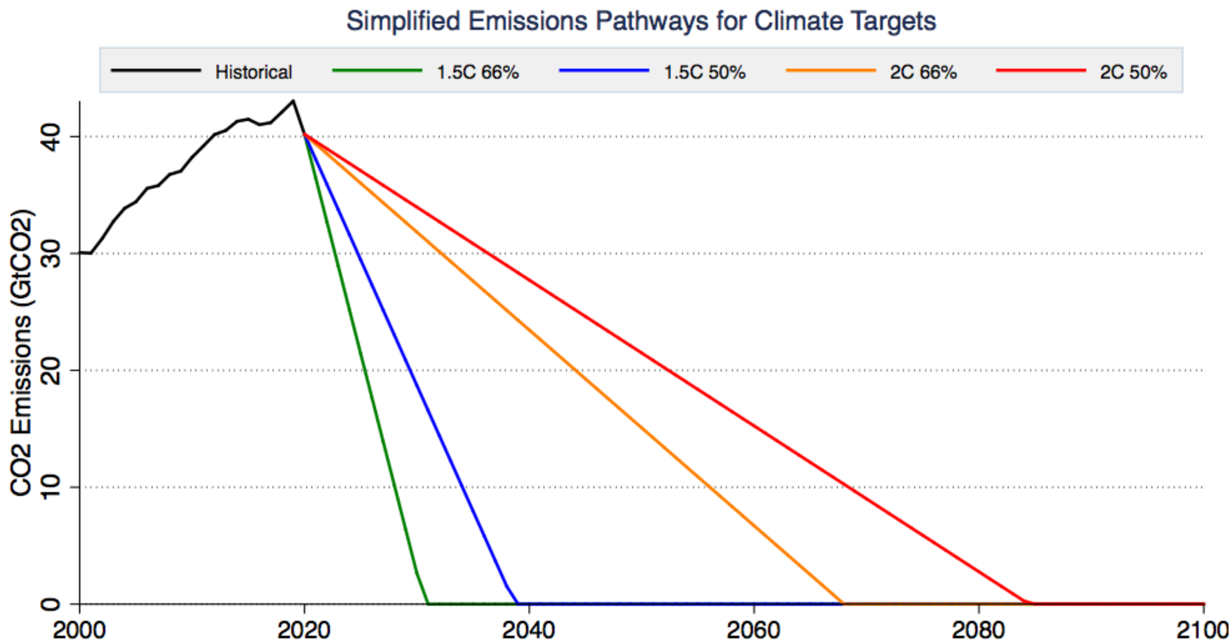

Figure 13. Simplified global emissions pathways associated with a 66% and 50% chance of limiting warming to 1.5ºC or 2ºC above preindustrial levels in the absence of net-negative global emissions. Historical emissions from the Global Carbon Project; cumulative carbon budgets for each scenario from the 2020 CONSTRAIN report.[58]

To limit warming to 1.5ºC would require getting all global emissions to zero by the year 2031 (for a 66 percent chance of avoiding 1.5ºC) or by 2039 (for a 50 percent chance). While it might be possible – in theory – for rich countries to get their emissions all the way down to zero in the next 10 to 20 years, this would come at a huge cost as large amounts of existing infrastructure (cars, furnaces in homes, industry, power plants, etc.) would have to be prematurely retired. It is unclear if we will have viable zero-carbon alternatives for aviation, industrial heat, and agriculture in that short a timeframe. It seems implausible that low and middle-income countries – whose near-term priorities are focused on poverty alleviation – would be willing to make the magnitude of sacrifices needed for such rapid near-term mitigation. The current commitments by countries to reach net-zero emissions by 2050 or 2060 are inconsistent with the 1.5ºC carbon budget.

In order to find possible pathways to 1.5ºC, energy system models trade more gradual near-term reductions in emissions for large-scale net-negative emissions later in the century. These scenarios have a more gradual target – say, net zero in the 2050s – coupled with planetary scale engineering late in the century to remove tens of gigatons of CO_2 from the atmosphere every year. To give a sense of the staggering scale of assumed negative emissions, some of these models devote an amount of land equal to the entire United States (including

[58]CONSTRAIN 2020. Zero in on a new generation of climate models, COVID-19, and the Paris Agreement. Available: https://constrain-eu.org/wp-content/uploads/2020/12/Constrain-Report-2020-Final.pdf

Alaska and Hawaii) to bioenergy with carbon capture and storage – growing energy crops to absorb CO_2 from the atmosphere, turning them into useful energy, and capturing the CO_2 for underground storage.[59]

This is not to suggest that large-scale negative emissions technologies are not something we should pursue, just that planning to remove greater and greater amounts of CO_2 in the future with largely-unproven technology should not be used to justify temperature targets that would otherwise be much less plausible to achieve.

A world where temperatures are kept well-below 2ºC in line with Paris Agreement targets – e.g. where there is a 66 percent chance of avoiding more than 2ºC warming relative to preindustrial temperatures – without the use of net-negative emissions requires that global emissions reach zero in the late 2060s. This outcome is broadly consistent with the long term net-zero goals that have been adopted by countries. If global temperatures are limited to 2ºC with a 50 percent chance – rather than well-below 2ºC – the required global emissions pathway is more permissive, requiring the net-zero be reached by the mid-2080s in the absence of net-negative emissions.

While the 1.5ºC target has slipped out of reach as global emissions have failed to fall in the aftermath of the Paris Agreement – at least in the absence of remarkable breakthroughs in our ability to remove CO_2 from the atmosphere later in the century – a well-below 2ºC outcome seems a lot more plausible today than even a few years ago. The price declines in clean energy and the willingness of countries to commit to net-zero emissions targets are putting a world of only 2ºC warming within reach. However, actually achieving global net zero emissions in the next 50 to 60 years will require significant advances in technology as well as greater political will by countries than has been in evidence to date.

[59] For details on carbon budgets and the amount of negative emissions used in models, see Hausfather, Z., 2018. Analysis: Why the IPCC 1.5C report expanded the carbon budget. *Carbon Brief*. Available: https://www.carbonbrief.org/analysis-why-the-ipcc-1-5c-report-expanded-the-carbon-budget

A broad range of solutions

Some – but not all – of the technologies we need

There is a widespread view by some in the environmental community that we have all the technology we need to solve climate change today, and that all we lack is the political will to deploy it at the scale needed. It is true that many technologies that will play a key role in decarbonization – including variable renewable energy sources like wind and solar, as well as electric vehicles – are increasingly cost-competitive with fossil fuels.

At the same time, there is a real need for additional innovation, both in terms of clean firm generation and complementary technologies that will allow us to cost-effectively fully decarbonize the power sector,[60] and for parts of the economy like industrial heat, agriculture, and long-distance transportation where cost-effective alternatives to fossil fuels are not readily available.[61] Advocates of renewables or nuclear often treat them like a silver bullet to climate change, whereas in reality we need an all-of-the-above approach to decarbonization, recognizing that the most effective approaches will differ based on geographic location, resource availability, and may change over time as the costs of new technologies decrease.

Currently around a quarter of US greenhouse gas emissions comes from the power sector, a quarter comes from transportation, a quarter from industry, and the remaining quarter is split between commercial and residential building and agriculture.[62] We are making significant progress in the first two of these sectors – representing roughly half our emissions. As discussed earlier, coal use in the US has fallen in half over the past decade, replaced by lower-emission natural gas and renewable sources. In the transportation sector many automakers are putting massive investments behind electric light vehicles, and planning to phase out the sale of internal combustion engine light vehicles over the next two decades. While it may be a bit of a bubble, the fact that Tesla had a valuation equal to all the oil supermajors combined is a sign of what the market sees as the future of transportation.

Even in these sectors where solutions are cost-effective today, challenges remain. One consistent finding from the energy modeling community is that the lowest cost decarbonization pathways include a sizable amount of clean firm generation in addition to variable renewables. Variable renewables are predictably unreliable; their primary role today is as fuel-saving technologies that enable expensive-to-run gas and coal plants to curtail generation when the sun is shining and wind is plentiful. Energy system planners have to keep sufficient dispatchable

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[60] Sepulveda, N.A., et al. 2018. The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. *Joule*. Available: https://www.sciencedirect.com/science/article/pii/S2542435118303866
[61] Davis, S.J., et al. 2018. Net-zero emissions energy systems. *Science*. Available: https://science.sciencemag.org/content/360/6396/eaas9793
[62] US EPA. 2021. Sources of Greenhouse Gas Emissions. Available: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

resources in reserve for when variable renewable generation declines, and need to plan for the rare combination of extreme demand and low renewable resource availability, as we saw recently in Texas when extreme cold conditions coincided with low-wind conditions and low seasonal solar output (though in that case large amounts of firm capacity from natural gas, coal, and nuclear went offline unexpectedly).

Renewable generation varies both short-term and seasonally. Solar generation has a predictable daily and annual cycle, while wind conditions can vary both within and across days. There are also large differences in seasonal generation, with solar producing only half as much electricity in the winter than in the summer in areas like California. The variable nature of renewables makes them subject to a phenomenon called value deflation. Because they cannot be turned on and off when needed (e.g. are not dispatchable), it is quite possible to have more renewables than the grid can effectively use during periods of low demand and high generation. High mid-day generation from solar already causes electricity prices to drop closer to zero (or even go negative) in California in the Spring and Fall months; Texas similarly sees increasingly common negative electricity prices from high wind generation.

This value deflation means that the value of a renewable resource tends to decrease the more is installed on the grid, particularly at higher levels of installation; we already see this in California, where solar represents around 20 percent of total state-wide electricity generation, and is about 35 percent less valuable today compared to other sources of electricity than it was in 2014.[63] Value deflation to-date has been largely countered by continued decline in solar PV module costs, though if cost declines will win the race against value deflation over the longer term remains an open question.[64]

While value deflation – and day-to-day variability – can be mitigated in part by investments in complementary technologies like energy storage, long distance transmission, and demand response, seasonal variations in renewable generation represent a larger challenge to high variable renewable electricity systems. Seasonal energy storage is currently extremely costly, given the need to have batteries or other storage technologies sitting idle for much of the year until needed during winter periods when renewable generation is lower. Here clean firm generation can play a critical role; technologies like advanced nuclear, gas with carbon capture and storage, and next-generation geothermal are all able to reliably provide firm, dispatchable generation but are largely not cost-competitive today.

Currently the US has an energy technology that is widely deployed and provides a good complement to variable renewable energy: natural gas. Gas turbines tend to have low capital costs and high operational costs; they are well suited to reduce generation when large amounts of renewable energy is available and electricity costs are low, and ramp up generation when renewable generation is lower and electricity costs are high. However, we need to be cognizant

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[63] Based on a soon-to-be-published analysis of the differences between solar and non-solar hourly energy prices in CAISO between 2014 and 2020. Data available here: http://oasis.caiso.com/mrioasis/logon.do
[64] Sivaram, V., & Kann, S. (2016). Solar power needs a more ambitious cost target. Nature Energy, 1(4), 16036. https://doi.org/10.1038/nenergy.2016.36

that high renewable systems will put more pressure on thermal generators; ramping up only when needed creates a higher likelihood of failure than near-constant operation, and we need to have redundancies in place to avoid blackouts when some thermal generators fail.

Natural gas is also still a significant source of emissions, albeit one that is only about half the CO_2 per unit of electricity generated than coal – and is still better than coal even when fugitive methane emissions are taken into account.[65] But "better than coal" is a distinctly low bar when it comes to fully decarbonizing the power sector; while gas will likely serve as a key element to enable accelerated variable renewable energy deployment over the next two decades, new technological advances are needed to fully replace its role in a decarbonized power system.

Nuclear currently provides around 20 percent of US electricity generation. These existing power plants are fully paid off, and represent relatively low cost firm clean generation. Unfortunately, a combination of cheap natural gas and the absence of subsidies to reflect the benefits of their low-carbon generation has put a sizable portion of the US nuclear fleet at risk of premature retirement. Around 38 TWh of nuclear generation has already been retired in recent years, with another 90 TWh scheduled to retire. An additional 135 TWh of nuclear is at risk of premature retirement, primarily due to competition from cheap natural gas.[66] To put these numbers in perspective, the amount of nuclear scheduled to retire is roughly equal to all the US solar power generated in 2018. The amount either scheduled to retire or at risk of retirement is equal to two thirds of current US wind generation. Decarbonizing the US power sector will be difficult enough without losing a sizable portion of our existing clean energy generation, and one of our only sources of clean firm generation.

In the transportation sector it seems increasingly clear that electric vehicles will be the dominant future technology for both light and medium-duty vehicles. There are still challenges, however, in electrifying heavy duty freight, and relatively few options for electrifying long-distance shipping or aviation. It is likely that some combination of electrification, biofuels, synfuels from captured carbon, and hydrogen will ultimately replace fossil fuels for these applications, but substantial additional RD&D efforts are needed before these technologies can be deployed at scale.

In the industrial sector, a sizable portion of energy use comes in the form of heat. Industrial heat is used in making concrete, steel, glass, ammonia, and many other products.[67] While electric heating is increasingly cost-effective for buildings, reaching temperatures in excess of thousands of degrees Fahrenheit using electricity is prohibitively costly. Options for industrial heat decarbonization include direct combustion of natural gas with carbon capture, use of hydrogen produced from natural gas with carbon capture of from clean energy sources such as

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[65] Hausfather, Z. 2015. Bounding the climate viability of natural gas as a bridge fuel to displace coal. *Energy Policy*. Available: https://www.sciencedirect.com/science/article/abs/pii/S0301421515300239
[66] Hausfather, Z. 2018. Mapped: The US nuclear power plants 'at risk' of shutting down. *Carbon Brief*. Available: https://www.carbonbrief.org/mapped-the-us-nuclear-power-plants-at-risk-of-shutting-down
[67] Friedman, J., et al. 2019. Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today. Available: https://www.energypolicy.columbia.edu/research/report/low-carbon-heat-solutions-heavy-industry-sources-options-and-costs-today

nuclear or renewables, biomass, or high-temperature small and modular nuclear reactors. Again, significant additional technological advancements are required to bring down the costs of these technologies to make them cost-competitive with current fossil fuel usage for industrial heat.

In the residential and commercial sectors, most of the non-electricity usage comes in the form of space and water heating (gas ranges and ovens are a relatively minor end-use). Heat pumps can serve as a cost-effective way to electricity building heating, though there are still some challenges to cost-effectively using heat pumps in cold climates, and additional RD&D efforts are working toward improving the technology at the same time that further deployment is driving down costs.

Agriculture will be one of the most challenging sectors to fully decarbonize. While ammonia production for fertilizers without emissions is possible, it requires both high temperatures and a ready source of hydrogen. Current production is largely from natural gas, though other sources of hydrogen can also be used. Emissions from ruminants (e.g. methane from cows) will be a particularly difficult source to decarbonize. While plant-based meat alternatives are gaining market share and numerous companies are working on cell-based meat alternatives (e.g. lab-grown steaks), the technologies are still fairly early-stage. Much of the environmental impact of agriculture is associated with land use; when forested areas are turned into fields a lot of CO_2 is released. Intensive agriculture – producing more food on less land – can be an important tool to reduce impacts and free up areas for reforestation.[68]

We will likely also need at least some carbon removal technology – such as afforestation/reforestation, direct air capture or bioenergy with carbon capture and storage – to remove excess CO_2 from the atmosphere. There may well be some hard-to-decarbonize sectors, such as aviation, where it will prove more cost-effective to offset emissions through capturing CO_2, at least in the near-to-medium term. CO_2 removal is not a replacement for emissions reductions writ large, but could play a role in some cases if costs can be reduced to lower levels than are possible are present.

The next decade will be critical to reach the US's decarbonization goals, both to accelerate the deployment of existing clean energy technologies and heavily invest in RD&D for maturing and improving a range of technologies that will be needed longer-term — such as advanced nuclear, gas with carbon capture and storage, enhanced geothermal, blue/green hydrogen, and direct air capture.

Private sector forces and innovation have gone a long way toward making deep decarbonization plausible. But the private sector cannot achieve this alone. Government energy RD&D spending has historically played a critical role in bringing energy technologies to the market, from solar panels to hydraulic fracturing to the diamond drill bits now enabling enhanced geothermal

[68] Nordhaus, T. 2018. No Sustainability Without Intensification. *The Breakthrough Institute*. Available: https://thebreakthrough.org/issues/food/no-sustainability-without-intensification

power.[69] Well-designed government policies are needed to accelerate smart deployment of wind and solar energy, drive zero-carbon technology innovation, and ensure the needed cuts in emissions.

In December, Congress passed a sweeping bipartisan spending package that authorizes billions of dollars for investments in clean energy, vital energy R&D, grid modernization, energy efficiency, and phasing down superwarming hydrofluorocarbons.[70] This represents perhaps the single most impactful congressional bill to-date that accelerates the energy transition and mitigates greenhouse gas emissions. It shows the potential for "quiet climate policy" – bipartisan energy solutions that both reduce emissions and create jobs.

In the current legislative session there are opportunities for cooperation on further energy innovation funding, grid modernization and interconnection, EV charging infrastructure, and agricultural innovation, as we propose in a newly released report: Saying the Quiet Part Out Loud: Quiet Climate Policy in a Post-Covid World.[71] Longer-term, it may make sense to phase out federal subsidies for mature clean energy technologies such as wind and solar in exchange for a technology-neutral mitigation policy like a clean electricity standard.[72]

Statements that "we have the technology we need and just need to build it" get it half right — we do need to build clean energy much more quickly than we are today. But we will need continued innovation and investment in supporting technologies like long-distance transmission and storage in addition to this multi-decade buildout of existing clean energy technologies. Clean energy policy is not zero-sum. Keeping this in mind as the US designs energy policy and debates the merits of various decarbonization options will help ensure we pursue more cost-effective and socially-acceptable pathways going forward.

What we can learn from decarbonization scenarios

The future of the energy system is difficult to foresee perfectly, and history is a graveyard of failed energy model predictions. All models are wrong, as the saying goes, but some are useful. A slew of new net-zero studies have been published in recent months, including Princeton's Net Zero America (NZA) project,[73] the Vibrant Clean Energy Zero By Fifty scenario,[74] and by a team

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[69] Jenkins, J., et al., 2010. Where Good Technologies Come From. The Breakthrough Institute. Available: https://thebreakthrough.org/articles/american-innovation

[70] Larson, J., et al. 2020. Climate Progress in the Year-End Stimulus. *Rhodium Group*. https://rhg.com/research/climate-progress-in-the-year-end-stimulus/

[71] Blaustein-Rejto, D., et al. 2021. Saying the Quiet Part Out Loud: Quiet Climate Policy in a Post-Covid World. *The Breakthrough Institute*. Available: https://thebreakthrough.org/articles/press-release-qcp

[72] Trembath, A., et al. 2020. Reforming Federal Policy to Support Innovation and Clean Energy in the U.S. Power Sector. *The Breakthrough Institute*. Available: https://thebreakthrough.org/articles/renewables-grid-memo

[73] Larson, E., et al., 2021. Net-Zero America: Potential Pathways, Infrastructure, and Impacts. Princeton University. Available: https://acee.princeton.edu/rapidswitch/projects/net-zero-america-project/

[74] Vibrant Clean Energy. 2021. Insights from Modeling the Decarbonization of the United States Economy by 2050. Initial results; available: https://vibrantcleanenergy.com/wp-content/uploads/2021/01/VCE-UCSD-01272021.pdf

of researchers led by Jim Williams at USF.[75] All three of these take a deep-dive into how the US could reach net-zero emissions by 2050, down to the level of where each new generating facility might be located, where new transmission lines would be built, and how electricity generation sources can meet hourly grid demand in different regions of the country.

Figure 14, below, shows the current 2020 US electricity generation mix, as well as the projected generation mix in 2030, 2040, and 2050 across each of the three models.

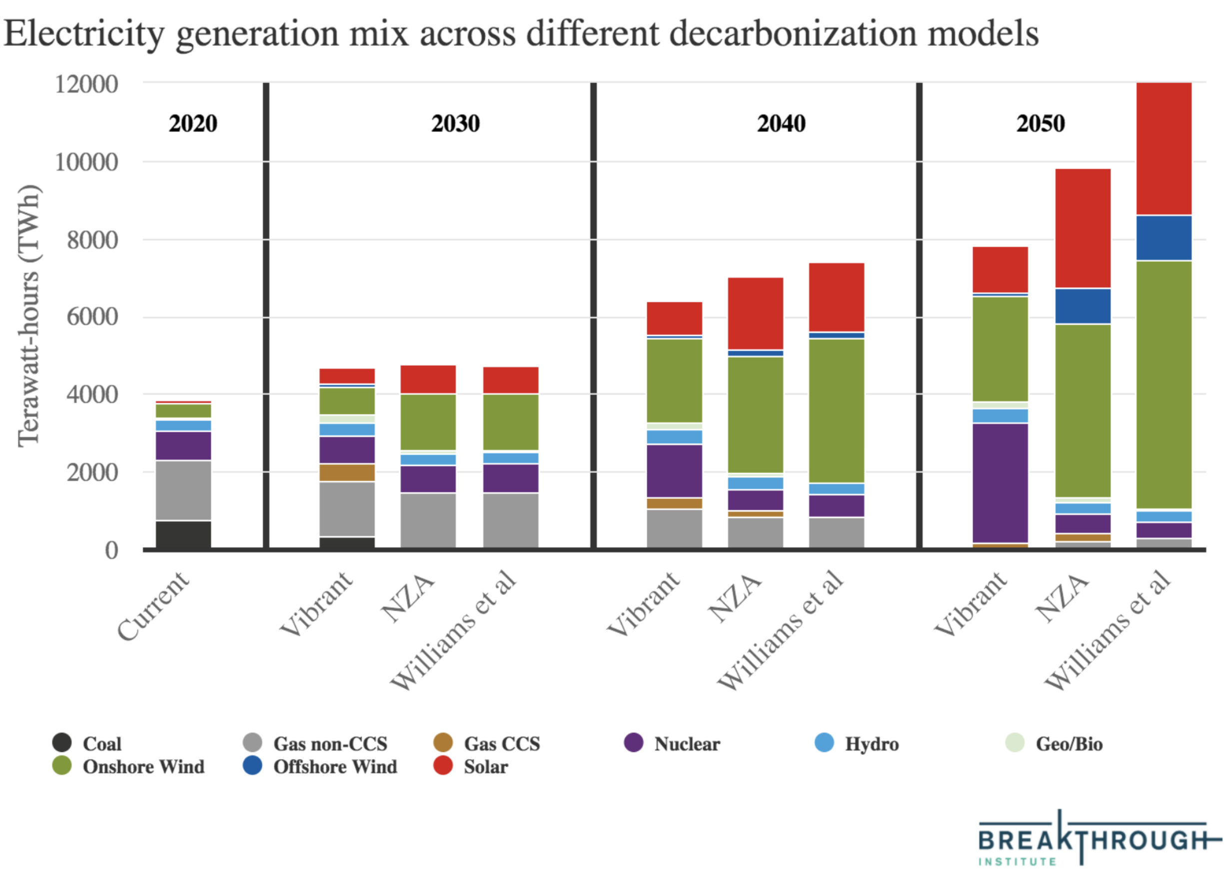

Figure 14. Annual US electricity generation (in TWh) in the initial year of each decade. 2020 values from the February 2021 EIA Short Term Energy Outlook. 2030, 2040, and 2050 values from the respective Vibrant, NZA, and Williams et al. scenarios examined. Note that CCS in the legend refers to carbon capture.

While the models differ in important ways, they all paint a broadly similar picture:

- Overall energy use increases to double or triple currently levels as other sectors of the economy such as transportation and building heating electrify.
- Wind and solar expand rapidly in the next three decades, accounting for between 51% and 91% of US electricity generation in 2050 across the three models.
- US coal use falls off a cliff, reaching zero by 2030 or 2035.

[75] Williams, J.H., et al. 2021. Carbon-Neutral Pathways for the United States. AGU Advances. Available: https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2020AV000284

- Natural gas use stays rather flat — or even increases modestly — between 2020 and 2030, as it serves a key role in filling in the gaps in variable renewable generation. Gas capacity actually increases in two of the three decarbonization models through 2050, though capacity factors — how often the gas plants are run — fall rapidly, and gas increasingly becomes a blend of hydrogen and methane closer to 2050.
- Existing nuclear reactors are kept online as long as possible, and in one of the three models is eventually replaced by advanced nuclear in the form of small and modular reactors and larger molten salt reactors. In the Vibrant model nuclear provides more electricity generation than any other energy source by 2050.
- All three scenarios also feature large-scale expansion of transmission, energy storage, and demand management to help support higher levels of intermittent generation. They demonstrate that the supporting technologies around renewable energy are in many ways just as important as the renewable energy itself.
- Carbon capture and CO_2 removal technologies all play a big role in these models' scenarios – albeit in different ways.

The difference between the trajectories of coal and gas in these decarbonization models is particularly notable. Figure 15, below, shows both coal use (solid lines) and the natural gas (dashed lines; excluding CCS) over time across the three models.

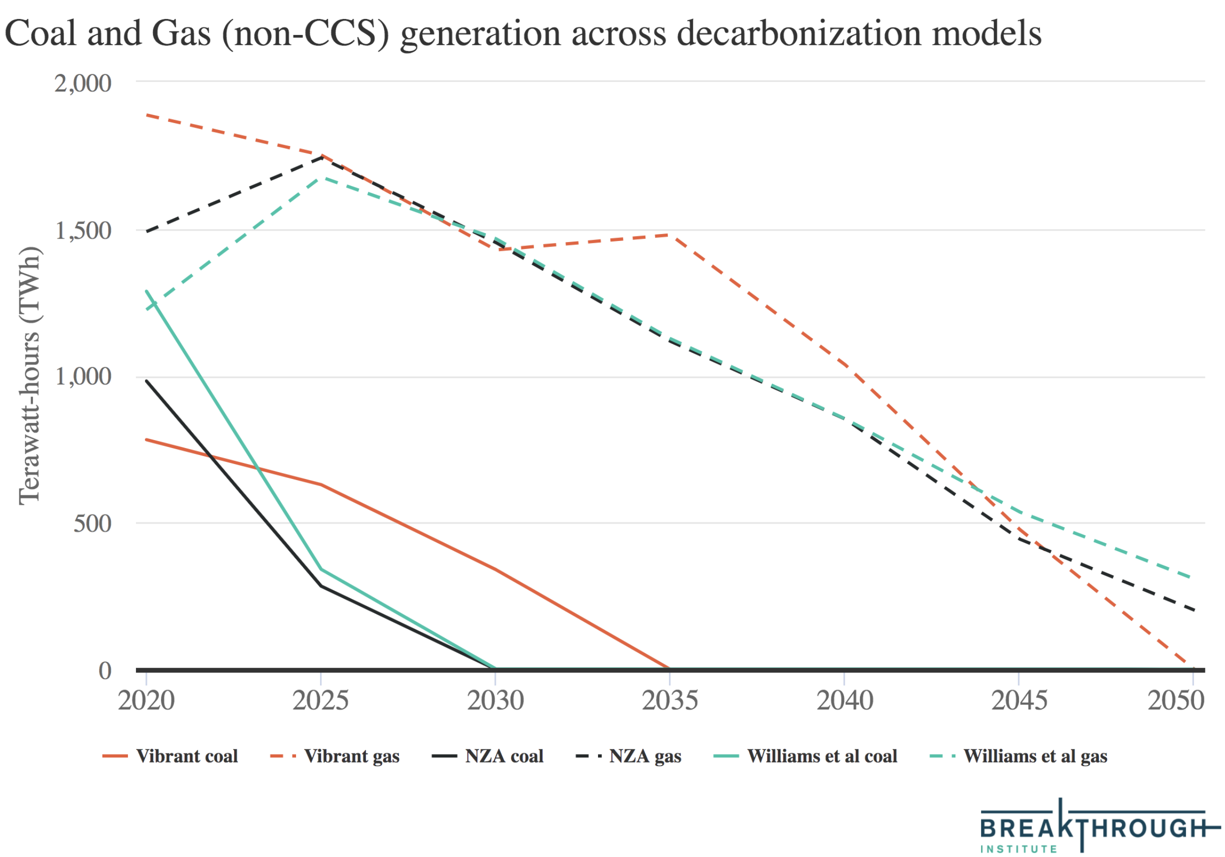

Figure 15. Annual US electricity generation (in TWh) by year from coal and natural gas (excluding carbon capture) in the Vibrant, NZA, and Williams et al. scenarios examined. Note that none of the scenarios include any meaningful coal use with carbon capture.

US coal generation falls dramatically from current levels, reaching zero between 2030 and 2035. Natural gas generation, by contrast, stays close to today's levels through 2030 and remains around 50% below current levels by 2040. It is only by 2050 that gas without carbon capture is mostly gone in the models. Modest amounts of gas with carbon capture is also used in two of the three models (Vibrant and NZA).

High natural gas capacity plays an important role in all three models to fill in the gaps in variable renewable generation as more wind and solar energy are installed on the grid. In the longer term, transmission expansion, storage, and development of alternative clean firm generation sources result in falling capacity factors, as gas increasingly operates as a peaking resource, reserved for either periods of exceptional demand or long periods of abnormally low variable renewable generation.

Current technologies can get us a long way toward power sector decarbonization, but if we ever want to fully decarbonize — and move away from our reliance on natural gas — we need technologies such as grid-scale storage, advanced nuclear, gas with CCS, or hydrogen that are not mature today. We need to both accelerate the deployment of current cost-effective clean energy resources and invest considerably more in future technologies that will simultaneously lower system costs and enable deep decarbonization. As the NZA report argues, "the 2020s is the decade to invest in maturing and improving a range of technologies that improve options for the long term."

These decarbonization models give us a sense of what may be needed. We should not fixate too much on the specific generation mixes in any particular scenario, but we should take heed of where the models agree: on the importance of near-term renewables deployment, the medium-term role of gas capacity to fill in the gaps, and the importance of clean firm generation and complementary technologies to wean the power system off its dependence on natural gas in the longer term.

Stranded assets in a post peak-oil future

A rapid transition is occurring in the world's automotive industry. Electric vehicles are rapidly approaching cost-parity with conventional internal combustion engine vehicles. Major automakers are committing to invest many tens of billions in electric vehicle manufacturing over the next decade, and General Motors recently announced that it will phase out all internal combustion vehicles after 2035.[76] This is not only a US phenomenon, with electric vehicle sales

[76] Boudette, N.E., and Davenport, C. 2021. G.M. Will Sell Only Zero-Emission Vehicles by 2035. *New York Times*. January 21st. Available: https://www.nytimes.com/2021/01/28/business/gm-zero-emission-vehicles.html

accelerating rapidly in both Europe and China. Due in large part to this trend – but also other broader market forces – many groups including BP, Equinor, Rystad, and Bernstein Energy project that global oil production has either already peaked or will peak in the next decade.[77] While fears of peak oil in the past inaccurately worried about running out of low-cost production, we are now faced with a very different – and more plausible – scenario: peak oil driven by declining global demand.

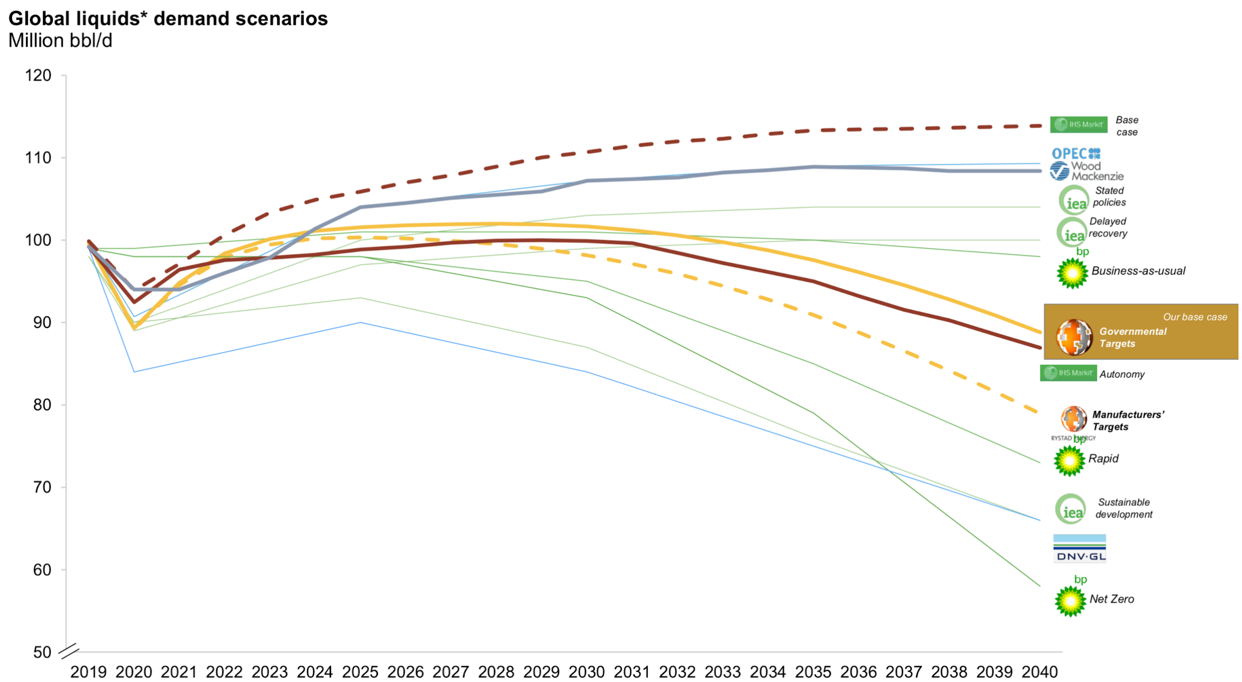

Figure 16: Projections of global oil demand between 2020 and 2040. From a Rystad Energy analysis undertaken for The Breakthrough Institute.

Even in the absence of strong additional climate policy, it is unlikely that US oil producing regions will be able to develop all of their resources. The US has substantially higher oil production costs than the Middle East, which would be favored in a demand constrained world. In a scenario where automakers meet their stated EV targets, a Rystad Energy analysis undertaken for The Breakthrough Institute finds that 32% of total US oil resources would be uneconomic to produce. Some parts of the US with higher oil production costs will be even harder hit; in Colorado and California about half of resources would be uneconomic to produce, while in North Dakota, Alaska, and Oklahoma it would be roughly a third of resources.

[77] Reuters. 2020. Pandemic brings forward predictions for peak oil demand. November 27th. Available: https://www.reuters.com/article/us-oil-demand-factbox/factbox-pandemic-brings-forward-predictions-for-peak-oil-demand-idUSKBN2870NY

Figure 17: Portion of oil resources that could be cost-effectively developed in a scenario with limited new climate policy but where stated auto manufacturer EV targets are met. From a Rystad Energy analysis undertaken for The Breakthrough Institute.

Many regions whose economies depend on oil production today may be left behind in a world of rapidly expanding electric vehicle sales, regardless of any congressional action to tackle climate change. It is important that these regions plan ahead to a world of lower future oil demand. Diversifying local economies is a smart hedge given real uncertainties around the extent to which oil demand is coming back – and how robustly. Coal country can serve as a cautionary tale here; the fact that coal use has fallen by more than 50 percent in just a decade shows just how fast things can change when driven by technological progress.

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EXPERIENCE

THE BREAKTHROUGH INSTITUTE, Oakland, CA
Director of Climate and Energy, August 2019 – Present

At Breakthrough I lead a team of researchers doing cutting-edge work on climate science and energy system transitions associated with emissions mitigation.

CARBON BRIEF, London, UK
US Analyst, June 2017 – Present

My role at Carbon Brief involves reporting developments in climate science and energy, writing fact checks, and conducting novel analyses of issues including negative emissions, energy system models, climate sensitivity, and model/observation comparisons. My work has a strong focus on data analysis and interactive visualization.

BERKELEY EARTH, Berkeley, CA
Research Scientist, January 2012 – Present

As a research scientist at Berkeley Earth I helped develop a novel estimate of global surface temperatures utilizing five times more observational data than groups like NOAA and NASA, as well as a daily homogenized land temperature record.

ESSESS, Boston, MA
Lead Data Scientist, January 2014 – June 2017

At Essess I led the development of energy analytics and program design/evaluation for vehicle-mounted thermal imaging systems used to collect and deliver home thermal characteristics data to residential, utility, commercial, and military customers. I participated extensively in software development, product management, sales, and client engagement.

PROJECT DRAWDOWN, Sausalito, CA
Senior Climate Analyst, July 2014 – August 2015

At Project Drawdown I worked with Paul Hawken to help research and write a book highlighting mitigation technologies that collectively hold the potential to begin reducing atmospheric concentrations of greenhouse gases. I developed their underlying climate model, converting mitigated GHGs into reduced atmospheric concentrations and avoided warming. I also developed a number of featured solutions including solar photovoltaics, and managed fellows researching numerous other solutions.

C3 ENERGY (NOW C3.AI), Redwood City, CA
Chief Scientist, April 2012 – February 2013

At C3 I led the development of analytics for the residential, small/medium business, and large commercial and industrial platforms after Efficiency 2.0 was acquired by C3, managing a team of energy and data scientists. I worked both with product managers developing specifications and coders writing algorithms, as well as working directly with clients on feature development and data integration. I also developed the EM&V processes to rigorously evaluate program performance and calculate energy savings/GHG reductions.

EFFICIENCY 2.0, New York, NY
Co-Founder and Chief Scientist, September 2007 – April 2012

I co-founded Efficiency 2.0, and managed a team of energy analysts and data scientists to develop an industry leading energy end-use model for disaggregating and quantifying residential and small business energy use characteristics and reduction opportunities for use in behavior-based energy efficiency programs. I worked in numerous areas across the company including analytics, program EM&V, product management, and sales.

EDUCATION

UNIVERSITY OF CALIFORNIA, BERKELEY, ENERGY AND RESOURCES GROUP, Berkeley, CA
PHD, Focus on Climate Science and Energy Systems Modeling, December 2019.
Honors: National Science Foundation Fellowship

YALE SCHOOL OF FORESTRY & ENVIRONMENTAL STUDIES, New Haven, CT
M.E.M., Focus on Climate and Energy Economics & Policy, May 2008
Activities: Industrial Environmental Management and Energy Group, Co-President
Yale Climate Connections, Climate Science and Policy Writer (2007 – 2017)
Journal of Industrial Ecology, Research Assistant

VRIJE UNIVERSITEIT, Amsterdam, Netherlands
M.S., Cum Laude, Environment and Resource Management, August 2006
Honors: Fulbright Fellowship

GRINNELL COLLEGE, Grinnell, IA
B.A., Phi Betta Kappa, Political Science with concentration in Global Development Studies, May 2005
Activities: Free the Planet, Co-President
Honors: Grinnell Mortar Board Honor Society and Trustees Honor Scholarship

QUANTITATIVE TOOLS

Python (numpy, pandas, sklearn, scipy, statsmodels, NetCDF, basemap, matplotlib), Stata, CDO, Highcharts, OmniGraffle, and Excel/Google Sheets.

PROFESSIONAL ACTIVITIES

Contributing Author, Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report.
World Meteorological Organization Ad-Hoc Advisory Board for the recognition of long-term observing stations - U.S. Representative.
Memberships: American Meteorological Society; American Geophysical Union
Reviewer for: Nature; Science; Geophysical Research Letters; Journal of Geophysical Research; Environmental Research Letters; Energy Policy; International Journal of Climatology, among others.

PUBLIC OUTREACH

TV: CNN, NBC
Radio: BBC, NPR (Science Friday, Marketplace, Here and Now, Living On Earth), CBC
Print: New York Times, Washington Post, AP, San Francisco Chronicle, LA Times, Christian Science Monitor, Science, Popular Science, Scientific American, The Atlantic, The Guardian, National Geographic, etc.
Online: BBC News, ABC News, PBS NewsHour, Huffington Post, Inside Science, AAAS, Slate, Ars Technica, Axios, FactCheck.org, Politifact, Snopes, Vox, etc.

ADDITIONAL CONSULTING WORK

- Future Building Climate Conditions, Praedictix, 2018-2019.
- Solar Demand Modeling, Powerscout, 2016.
- Energy Efficiency Modeling, Sealed Inc, 2013.
- Carbon Reduction Measure Modeling, Oroeco, 2013.
- Pipeline Abandonment Research, SIS International, 2013.
- Parking Spot Detection / Street Cleaning Alerts, Pirouette Software, 2013.
- Electric Vehicle Fast Charging, E-Hwys, 2012-2013.

PEER-REVIEWED PUBLICATIONS

Rohde, R.A., Hausfather, Z. 2020. The Berkeley Earth Land/Ocean Temperature Record. *Earth System Science Data*.

Hausfather, Z., Peters, G.P. 2020. RCP8.5 is a problematic scenario for near-term emissions. *Proceedings of the National Academy of Sciences*.

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Hausfather, Z., Drake, H.F., Abbott, T., Schmidt, G.A. 2019. Evaluating the performance of past climate model projections. *Geophysical Research Letters*.

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Haustein, K., ..., Hausfather, Z. et al. 2019. A limited role for unforced internal variability in twentieth-century warming. *Journal of Climate*

Cheng, L., Abraham, J., Hausfather, Z., and Trenberth, K.E. 2019. How fast are the oceans warming? *Science*.

Mayer, A., Hausfather, Z., Jones, A.D., and Silver, W.L. 2018. The potential of agricultural land management to lower global surface temperatures. *Science Advances*.

Thorne, P.W., …, Hausfather, Z. et. al., 2018. Towards a global land surface climate fiducial reference measurements network. *International Journal of Climatology.*

Cowtan, K., Rohde, R., and Hausfather, Z. 2018. Evaluating biases in Sea Surface Temperature records using coastal weather stations. *Quarterly Journal of the Royal Meteorological Society*.

Hausfather, Z., Cowtan, K., Clarke, D.C., Jacobs, P., Richardson, M., and Rohde, R. 2017. Assessing recent warming using instrumentally homogeneous sea surface temperature records. *Science Advances*.

Hausfather, Z., Cowtan, K., Menne, M.J., and Williams, C.N. 2016. Evaluating the impact of US Historical Climatology Network homogenization using the US Climate Reference Network. *Geophysical Research Letters*.

Thorne, P.W., …, Hausfather, Z. et. al, 2016. Reassessing changes in diurnal temperature range: Intercomparison and evaluation of existing global data set estimates. *Journal of Geophysical Research: Atmospheres.*

Zhang, X., Myhrvold, N. Hausfather, Z., and Caldeira, K. 2016. Climate Benefits of Natural Gas as a Bridge Fuel and Potential Delay of Near-Zero Energy Systems. *Applied Energy*.

Hausfather, Z. 2015. Bounding the Climate Viability of a Natural Gas as a Bridge Fuel to Displace Coal. *Energy Policy*.

Cowtan, K., Hausfather, Z., Hawkins, E., Jacobs, P., Mann, M.E., Miller, S.K., Steinman, B.A., Stolpe, M.B., and Way, R.G. 2015. Robust comparison of climate models with observations using blended land air and ocean sea surface temperatures. *Geophysical Research Letters*.

Richardson, M., Hausfather, Z., Nuccitelli, D.A., Rice, K., and Abraham, J.P. 2015. Misdiagnosis of earth climate sensitivity based on energy balance model results. *Science Bulletin*.

Thomas, B., Hausfather, Z., and Azevedo, I. 2014. A Regional Model of Direct and Indirect Rebound Effects. *Environmental Research Letters*.

Willett, K., et. al., 2014. A framework for benchmarking of homogenisation algorithm performance on the global scale. *Geoscientific Instrumentation, Methods and Data Systems*.

Hausfather, Z., Menne, M.J., Williams, C.N., Masters, T., Broberg, R., and Jones, D. 2013. Quantifying the Effect of Urbanization on U.S. Historical Climatology Network Temperature Records. *Journal of Geophysical Research*.

Lifset, R., Eckelman, M., Harper, E., Hausfather, Z., and Urbina, G. 2012. Metal lost and found: dissipative uses and releases of copper in the United States 1975-2000. *The Science of the Total Environment*.

Min, J, Hausfather, Z, and Lin, Q. 2010. A High-Resolution Statistical Model of Residential Energy End Use Characteristics for the United States. *Journal of Industrial Ecology*.

Hausfather, Z. 2005. India's Shark Trade: An Analysis of Indian Shark Fisheries Based on Shark Fin Exports. *Maritime Studies.*