February 8, 2021

Chairman Tonko and Ranking Member McKinley, Subcommittee on Environment and Climate Change of the House Committee on Energy and Commerce

Re: Materials for February 9, 2021 Hearing on "Back In Action: Restoring Federal Climate Leadership"

Dear Chairman Tonko and Ranking Member McKinley,

On behalf of Our Children's Trust ("OCT"), a nonprofit organization dedicated to securing the legal right to a stable climate system for youth and future generations, please find enclosed herewith materials for your consideration relevant to the Subcommittee on Environment and Climate Change of the House Committee on Energy and Commerce's February 9, 2021 hearing, "Back In Action: Restoring Federal Climate Leadership." We applaud the Subcommittee for promptly utilizing this "renewed opportunity to meaningfully and thoughtfully tackle the climate crisis." This submission will inspire you with the stories of courageous children and provide resources critical to developing science-based, technically and economically feasible solutions to the climate crisis.

In fact, the House concurrent resolution on Children's Fundamental Rights and Climate Recovery supporting the *Juliana v. United States ("Juliana")* youth plaintiffs requests exactly this – it states that "renewed United States leadership is needed immediately to act to address the human-caused climate crisis that is disproportionately affecting the health, economic opportunity, and fundamental rights of our Nation's children" and recognizes the need of the United States to develop a national, comprehensive, science-based and just climate recovery plan to phase out fossil fuel emissions, protect and enhance natural sequestration, and put the United States on a path towards stabilizing the climate system. This resolution, sponsored by Representative Schakowsky and co-led by Representative Rush and originally introduced in September 2020, had the support of 61 cosponsors from both chambers and it will be reintroduced shortly.

Through youth-led constitutional legal actions, including *Juliana* – the landmark federal constitutional climate case filed by twenty-one youth plaintiffs, including eleven Black, Brown and Indigenous youth – OCT supports youth seeking to hold their governments accountable for policies and actions that have caused, and continue to cause, the climate crisis. Through these actions, youth seek science-based remedies to reduce greenhouse gas emissions at rates necessary to protect their fundamental human rights.

It is OCT's understanding that the materials submitted for the February 9 hearing will inform the Committee's forthcoming legislation to rebuild the economy and decarbonize the economy as it works in tandem with President Biden's bold actions. Given our mission, OCT has a substantial interest in ensuring that any such legislation is consistent with what the best available science dictates is necessary to stabilize the climate system and protect the fundamental rights of youth and future generations. We invite you to consult the materials enclosed herewith, which demonstrate that climate change is *already harming* the fundamental rights of young people in the United States and legislation which ensures emissions reductions and sequestration of excess CO_2 is necessary for the protection of the fundamental rights of American children. Please note in Exhibit C below, the prescription to stabilize the atmosphere is a return to atmospheric CO_2 levels to 350 ppm by 2100, limiting global warming to less than 1 degree Celsius by 2100. This requires that net negative CO_2 emissions is achieved before mid-century.

Specifically, enclosed as **Exhibit A** is a summary of *Juliana*, including plaintiffs' profiles. Enclosed as **Exhibit B** you will find a document entitled "Government Climate and Energy Actions, Plans, and Policies Must Be Based on a Maximum Target of 350 ppm Atmospheric CO_2 and 1°C by 2100 to Protect Young People and Future Generations." This document details the scientific basis underlying, and prescription for, stabilization of the climate system as necessary to protect the fundamental human rights of youth and future generations relative to the climate crisis and explains that allowing warming of up to 1.5°C *is not safe*. Enclosed as **Exhibit C** include reports published by the energy experts at Evolved Energy Research. **Exhibit C.1** is an executive summary entitled "350 PPM Pathways for the United States," which demonstrates multiple technologically and economically feasible pathways for transitioning to a 100 percent clean energy economy consistent with the science-based prescription for stabilizing the atmosphere and securing the fundamental rights of youth and future generations. Enclosed as **Exhibit C.2** is an executive summary entitled "350 PPM Pathways for Florida," which focuses on Florida, mirrors the national study's target and includes updated national data beginning on page 71 as the U.S. model was upgraded to reflect the newer and even lower costs for renewable technologies.

The remaining reports are from three expert witnesses in *Juliana*. Enclosed as **Exhibit D** is the expert report of Dr. Jim Williams, Director of the Deep Decarbonization Pathways Project. This expert report includes policy recommendations to achieve rapid and deep decarbonization in the United States. Enclosed as **Exhibit E** is the expert report of Dr. Mark Jacobson, Professor of Civil and Environmental Engineering at Stanford University. This expert report summarizes research, conclusions, and implications of studies he and his colleagues previously performed to develop 100% clean, renewable all-sector (electricity, transportation, heating/cooling, industry)

roadmaps for the 50 states and the United States as a whole. Enclosed as **Exhibit F** is the expert report of Dr. G. Philip Robertson, University Distinguished Professor of Ecosystem Ecology in the Department of Plant, Soil and Microbial Sciences at Michigan State University and Scientific Director for the Department of Energy's Great Lakes Bioenergy Research Center at the University of Wisconsin and Michigan State University. This expert report estimates the potential for increased carbon sequestration from U.S. forest, range, and agricultural land management and concludes that over the period 2020-2100, changes to land management practices in the U.S. could mitigate more than 30 GtC_{eq}, which is over 30% of the negative and avoided emissions needed, after phasedown of fossil fuel emissions, to stabilize the Earth's climate system.

Legislation which ensures emissions reductions and sequestration of excess CO_2 consistent with what the best available science dictates is necessary for the protection of the fundamental rights of young people and future generations. The information in Exhibits A through E are additionally relevant to the forthcoming Children's Fundamental Rights and Climate Recovery resolution which will be reintroduced shortly.

Should you have any questions regarding the enclosed materials, please feel free to contact Liz Lee, OCT's government affairs staff attorney at liz@ourchildrenstrust.org.

Sincerely,

/s Julia Olson
Julia Olson
Executive Director
Our Children's Trust

Enclosures:
Exhibit A: *Juliana v. United States* Summary and Plaintiffs' Profiles
Exhibit B: Government Climate and Energy Actions, Plans, and Policies Must Be Based on a Maximum Target of 350 ppm Atmospheric CO_2 and 1°C by 2100 to Protect Young People and Future Generations
Exhibit C.1: 350 PPM Pathways for the United States, Executive Summary
Exhibit C.2: 350 PPM Pathways for Florida, Executive Summary and U.S. data
Exhibit D: Expert Report of Dr. Jim Williams
Exhibit E: Expert Report of Dr. Mark Jacobson
Exhibit F: Expert Report of Dr. G. Philip Robertson

Exhibit A:

Juliana v. United States Summary and Plaintiffs' Profiles

Our Children's Trust
Youth v. Gov

Juliana v. United States

Young Americans Fight for Their Constitutional Rights and Climate Recovery

Background

Represented by attorneys at Our Children's Trust, **21 young Americans filed their constitutional climate lawsuit, *Juliana v. United States*, against the executive branch of the U.S. government in 2015.** They assert that the government's affirmative actions causing climate change have violated their constitutional rights to life, liberty, property, and equal protection of the laws, and impaired essential public trust resources. They seek a court-ordered, science-based climate recovery plan, to put the U.S. on track to bring atmospheric carbon dioxide levels back to 350 parts per million (ppm) by 2100, which would limit long-term warming to less than 1° Celsius, which scientists say is the safe target to stabilize the planet's climate system.

In May 2019, a team of renowned energy experts, Jim Williams, Ben Haley, and Ryan Jones, published a report that demonstrates the technical and economic viability of the U.S. to meet this standard by 2100. An October 2020 report on specific pathways for Florida to meet this standard also provides updated U.S. data.

History

The U.S. District Court has repeatedly found that the youth plaintiffs have legitimate claims for trial. **In a groundbreaking decision in November 2016, the court found that the U.S. Constitution secures the fundamental right to a climate system capable of sustaining life;** that plaintiffs' injuries give them standing to bring their claims; and that the Court has authority to remedy the youth's injuries.

Since that historic ruling, the defendants have relentlessly attempted to prevent *Juliana v U.S.* from going to trial. **Three times in 2018, the Ninth Circuit Court of Appeals ruled resoundingly against government attempts to stop the case**. **The U.S. Supreme Court has also ruled in favor of the youth, twice refusing to halt the case.**

Looking Forward

On January 17, 2020, a divided panel of the Ninth Circuit Court of Appeals found for the plaintiffs in nearly every respect, but ultimately ruled that the courts cannot stop the executive branch of government from harming children with its policies that cause climate change. **A petition for rehearing was filed on March 2, 2020 by the youth plaintiffs' attorneys, followed by ten *amicus curiae* briefs filed on March 12, 2020 by 24 members of Congress and experts in constitutional law, climate change, public health, and human rights. The briefs urge the Ninth Circuit Court of Appeals to grant the petition and convene a new panel to review the case, arguing that the judicial branch has a responsibility to protect the youth's constitutional rights and the children have legal standing to be heard at trial.** Plaintiffs and their attorneys are currently awaiting a decision.

Support These Brave Plaintiffs

The youth plaintiffs deserve to have their constitutional claims heard at trial, and need your support now. Please publicly support their right to have their constitutional claims heard and decided by a court of law. Support the congressional resolution recognizing children's fundamental rights and the need for a national, science-based climate recovery plan at ourchildrenstrust.org/congressionalresolution. The resolution, originally introduced on September 23, 2020, was supported by 63 members of Congress. Also, join future *amicus curiae* briefs in support of their constitutional rights and the judiciary exercising its Article III powers in their case. **Show our nation's children you care about their future, and the future of all generations to come.**

info@ourchildrenstrust.org | www.ourchildrenstrust.org

Our Children's Trust
Youth v. Gov

Juliana v. United States: Meet the Plaintiffs

Meet all 21 Juliana plaintiffs at ourchildrenstrust.org/federal-plaintiffs
Learn more about their stories in this 60 minutes segment (bit.ly/60minsjuliana) and their visit to Congress in this video (bit.ly/yearsprojectjuliana) from The YEARS Project

For over five years, these young plaintiffs, all of whom have been personally impacted by climate change, have been leading the game-changing litigation campaign to secure the legal right to a stable climate for young people, based on the best available science. In 2015, they filed their constitutional climate lawsuit against the U.S. government in the U.S. District Court for Oregon.

Kelsey Juliana, 24, Eugene, OR

Fighting climate change since she was 10, Kelsey has been increasingly exposed to hazardous wildfire smoke in her hometown. As a teenager, she participated in the Great March for Climate Action, marching 1,600 miles from Nebraska to D.C. Time Magazine recognized Kelsey as a Rising Star in its list of the Next 100 Most Influential People in the World.

Vic Barrett, 21, White Plains, NY

A Garifuna American, Vic has spoken about environmental justice issues and how his climate anxiety is increased because his identities — first generation, trans, indigenous, Latinx, Black, youth — make him uniquely vulnerable to the climate crisis. In 2019, he testified at a historic joint hearing of the House Foreign Affairs and Select Committee on the Climate Crisis alongside Greta Thunberg.

Jaime Butler, 20, Flagstaff, AZ

Jaime is of the Tangle People Clan, born of the Bitterwater Clan. She grew up in Cameron, Arizona on the Navajo Nation Reservation, but had to move due to water scarcity and failed attempts at dryland farming. Jaime knows firsthand the cultural and spiritual impacts of climate change as she and her tribe struggle to participate in their traditional ceremonies due to climate-related impacts.

Levi Draheim, 13, Satellite Beach, FL

Levi has lived most of his life on a barrier island in Florida, barely above sea level and literally washing away due to sea level rise and storms made worse by climate change. In 2019, Levi addressed a youth stakeholder's meeting with members of the Senate Democrats' Special Committee on the Climate Crisis at the United Nations Foundation. His baby sister is a source of motivation and inspiration.

Xiuhtezcatl Martinez, 20, Boulder, CO

Xiuhtezcatl is a renowned hip-hop artist and activist. He is also the former Youth Director and now Co-Chair of the executive board for Earth Guardians. He has experienced extreme weather events that have been exacerbated due to climate change, such as catastrophic flooding. Raised in the Aztec tradition, Xiuhtezcatl has spoken at the United Nations several times, including in English, Spanish, and his Native language, Nahuatl.

Exhibit B:

Government Climate and Energy Actions, Plans, and Policies Must Be Based on a Maximum Target of 350 ppm Atmospheric CO_2 and 1°C by 2100 to Protect Young People and Future Generations

Government Climate and Energy Actions, Plans, and Policies Must Be Based on a Maximum Target of 350 ppm Atmospheric CO_2 and 1°C by 2100 to Protect Young People and Future Generations

INTRODUCTION

Human laws can adapt to nature's laws, but the laws of nature will not bend for human laws. Government climate and energy policies **must** be based on the best available climate science to protect our climate system and vital natural resources on which human survival and welfare depend, and to ensure that young people's and future generations' fundamental and inalienable human rights are protected.

Because carbon dioxide (CO_2) is the primary driver of climate destabilization and ocean warming and acidification, all government policies regarding CO_2 pollution and CO_2 sequestration should be aimed at reducing global CO_2 concentrations **below 350 parts per million (ppm) by 2100**. Global atmospheric CO_2 levels, as of 2019, are approximately 407 ppm and rising.[1] An emission reductions and sequestration pathway back to 350 ppm could limit peak warming to approximately 1.3°C this century and stabilize long-term heating at 1°C above pre-industrial temperatures.

As explained in more detail below, there are numerous scientific bases and lines of evidence supporting setting 350 ppm and 1°C by 2100 as the uppermost safe limit for atmospheric CO_2 concentrations and global warming. Beyond 2100, atmospheric CO_2 may need to return to below 300 ppm to prevent the complete melting of Earth's ice sheets and protect coastal cities from sea level rise. Fortunately, it is still not only technically and economically feasible to return to those levels, but transitioning to renewable energy sources will provide significant economic and public health benefits and improve quality-of-life.

WHY 350 PPM AND 1°C LONG-TERM WARMING?

Three lines of robust and conclusive scientific evidence, based on the paleo-climate record and real-world observations show that above an atmospheric CO_2 concentration of 350 ppm there is: 1) significant global energy imbalance; 2) massive ice sheet destabilization and sea level rise; and 3) ocean warming and acidification resulting in the bleaching death of coral reefs and other marine life.

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[1] Ed Dlugokencky & Pieter Tans, NOAA/ESRL, www.esrl.noaa.gov/gmd/ccgg/trends/.

1) Energy Balance

Earth's energy flow is out of balance. Because of a buildup of CO_2 in our atmosphere, due to human activities, primarily the burning of fossil fuels and deforestation,[2] more solar energy is retained in our atmosphere and less energy is released back into space.[3] The energy imbalance of the Earth is roughly equivalent to 2500 Camp Creek[4] fires **per day** burning around the world.[5] Returning CO_2 concentrations to below 350 ppm would restore the energy balance of Earth by allowing as much heat to escape into space as Earth retains, an important historic balance that has kept our planet in the sweet spot for the past 10,000 years, supporting stable sea levels, enabling productive agriculture, and allowing humans and other species to thrive.[6] The paleo-climate record shows that CO_2 levels, temperature, and sea level all move together (see Figure 1). Humans have caused CO_2 levels to shoot off the chart (circled in red), rising to levels unprecedented over the past 3 million years, and causing the energy imbalance.[7]

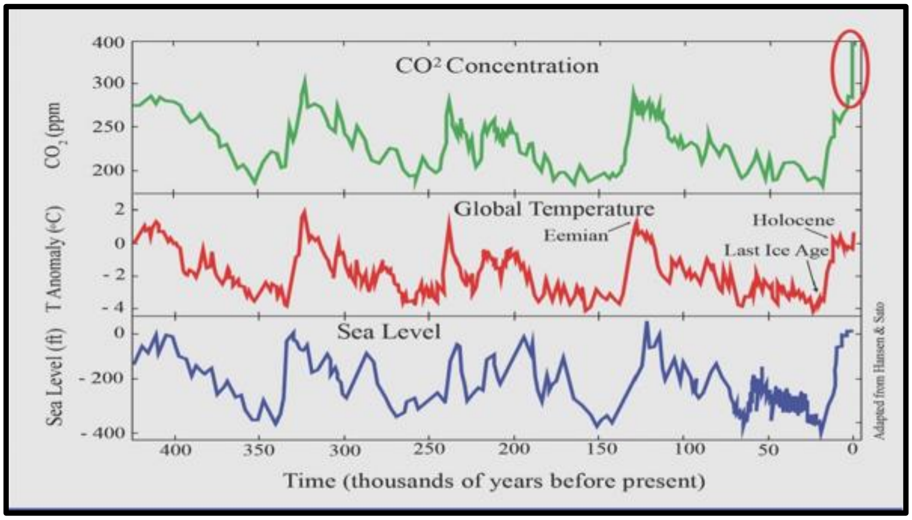

Figure 1: Evidence from the paleo-climate record showing the relationship between CO_2 concentration, global temperature, and sea level.

2) Ice Sheets and Sea Level Rise

The last time the ice sheets appeared stable in the modern era was in the 1980s when the atmospheric CO_2 concentration was below 350 ppm. The consequences of > 350 ppm and 1°C of warming are already visible, significant, and dangerous for humanity. With just 1°C of warming, glaciers in all regions of the world are shrinking, and the rate at which they are melting is accelerating.[8] Large parts of the Greenland and Antarctic ice sheets, which required millennia to grow, are teetering on the edge

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[2] Intergovernmental Panel on Climate Change, *Summary for Policymakers, Climate Change 2014: Impacts, Adaptation, and Vulnerability* 5 (2014).

[3] James Hansen et al., *Assessing "Dangerous Climate Change": Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature*, PLOS ONE 8:12 (2013) [hereinafter Assessing "*Dangerous Climate Change*"].

[4] The Camp Creek fire was the 2018 California fire, the deadliest and most destructive in the state's history, that burned over 150,000 acres (almost 240 square miles).

[5] Steven W. Running, *Declaration in Support of Plaintiffs, Juliana v. United States*, No. 18-36082, Doc. 21-12 (9th Cir. Feb. 7, 2019).

[6] James Hansen, Storms of My Grandchildren 166 (2009).

[7] Willeit et al., *Mid-Pleistocene transition in glacial cycles explained by declining CO2 and regolith removal*. Science Advances (2019).

[8] Zemp et al., *Global glacier mass changes and their contributions to sea-level rise from 1961-2016.* Nature (2019); B. Menounos, *Heterogeneous Changes in Western North American Glaciers Linked to Decadal Variability in Zonal Wind Strength*, Geophysical Research Letters (2018).

of irreversible disintegration, a point that if reached, would lock-in major ice sheet mass loss, sea level rise of many meters, and worldwide loss of coastal cities – a consequence that would be irreversible on any timescale relevant to humanity (see Figure 2).[9] Greenland's ice sheet melt is currently occurring faster than anytime during the last three and a half centuries, with a 33% increase alone since the 20th century.[10] The paleo-climate record shows the last time atmospheric CO_2 levels were over 400 ppm, the seas were **70 feet higher** than they are today and that heating consistent with CO_2 concentrations as low as 450 ppm may have been enough to melt almost all of Antarctica.[11] While many experts are predicting multi-meter sea level rise this century, even NOAA's modest estimate of 3-6 feet by 2100 would impact between 4 and 13 million Americans (see Figure 3).[12]

Figure 2: Antarctic melt water from the Nansen ice shelf.

Most climate models represent sea level rise as a gradual linear response to melting ice sheets, but the historic climate record shows something very different. In reality, seas do not rise slowly and predictably but rather in quick pulses as ice sheets destabilize.[13] Scientists believe we have a chance to preserve the large ice sheets of Greenland and Antarctica and most of our shorelines and ecosystems if we limit long-term warming by the end of the century to no more than 1°C above pre-industrial levels (short-term warming will inevitably exceed 1°C but must not exceed 1°C for more than a short amount of time).

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[9] Hansen, Assessing "Dangerous *Climate Change*," at 13; *see also* James Hansen et al., *Ice Melt, Sea Level Rise and Superstorms; Evidence from Paleoclimate Data, Climate Modeling, and Modern Observations that 2 °C Global Warming Could be Dangerous*, Atmos. Chem. & Phys. 16, 3761 (2016) [hereinafter *Ice Melt, Sea Level Rise and Superstorms*].

[10] Trusel, L. D., et al., *Nonlinear rise in Greenland runoff in response to post-industrial Arctic warming*, Nature (2018).

[11] Dec. of Dr. James E. Hansen, *Juliana et al., v. United States et al.*, No. 6:15-cv-01517-TC, 14 (D. Or. Aug. 12, 2015); Intergovernmental Panel on Climate Change: 2007 Working Group I: The Physical Science Basis, Chapter 6.3.2, What Does the Record of the Mid-Pliocene Show?; Dowsett & Cronin, *High eustatic sea level during the middle Pliocene: Evidence from the southeastern U.S. Atlantic Coastal Plain*, Geology (1990); Shackleton et al., *Pliocene stable isotope stratigraphy of ODP Site 846*, Proceedings of the Ocean Drilling Program, Scientific Results (1995).

[12] NOAA, Examining Sea Level Rise Exposure for Future Populations, https://coast.noaa.gov/digitalcoast/stories/population-risk.

[13] Wanless, H.R., et al., *Dynamics and Historical Evolution of the Mangrove/Marsh Fringe Belt of Southwest Florida, in Response to Sea-level History, Biogenic Processes, Storm Influences and Climatic Fluctuations*. Semi-annual Research Report (June 1993 to February 1994); Hansen, *Ice Melt, Sea Level Rise and Superstorms*, at 3761; Hansen, *Assessing "Dangerous Climate Change,"* at 20.

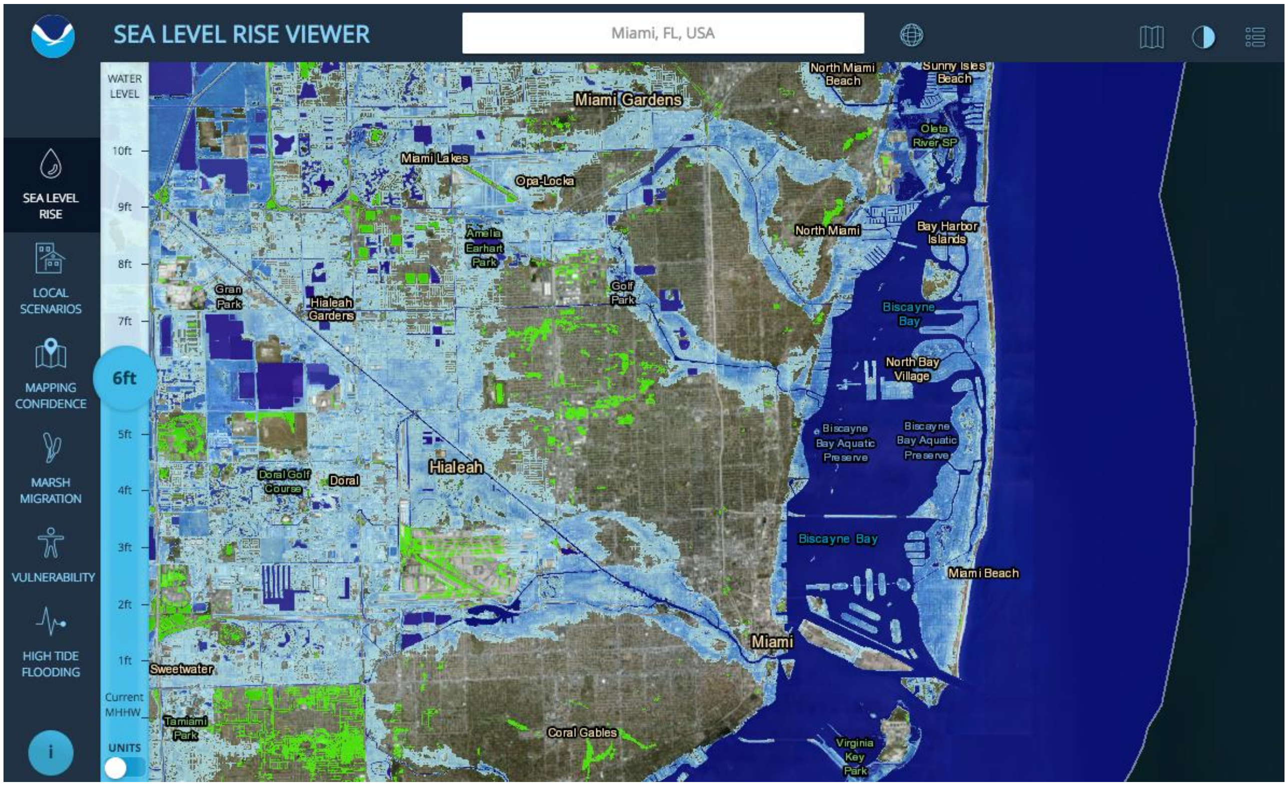

Figure 3: South Florida, including Miami, will face significant inundation with 6 feet of sea level rise.

3) <u>Ocean Warming and Acidification</u>

Our oceans have absorbed 93% of the excess heat in the atmosphere trapped by greenhouse gases (see Figure 4) as well as approximately 30% of CO_2 emitted into the atmosphere, causing ocean temperatures to surge and the ocean to become more acidic.[14] Indeed, our oceans are warming much more rapidly than previously-thought.[15] Many marine ecosystems, and particularly coral reef ecosystems, cannot tolerate the increased warning and acidity of ocean waters that result from increased CO_2 levels.[16] At today's CO_2 concentration, around 407 ppm,[17] critically important ocean ecosystems, such as coral reefs, are rapidly declining and will be irreversibly damaged from high ocean temperatures and repeated mass bleaching events if we do not quickly curtail emissions (see Figures 5 and 6).[18] According to the Intergovernmental Panel on Climate Change, bleaching events are occurring more frequently than the IPCC previously projected and 70-90% of the world's coral

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[14] Hansen, *Assessing "Dangerous Climate Change,"* at 1; *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge University Press, 2013); Cheng et al., *How fast are the oceans warming?* 363 Science 128 (2019); National Oceanic and Atmospheric Administration, *What is Ocean Acidification?*, https://oceanservice.noaa.gov/facts/acidification.html.

[15] Cheng, L. et al., How fast are the oceans warming?, 363 *Science* 128 (2019).

[16] Hughes et al., *Global warming impairs stock-recruitment dynamics of corals*, Nature (2019).

[17] Ed Dlugokencky and Pieter Tans, NOAA/ESRL, www.esrl.noaa.gov/gmd/ccgg/trends/.

[18] Frieler, K. et al., *Limiting global warming to 2 degrees C is unlikely to save most coral reefs*. Nature Climate Change 3:165-170. (2013); Veron, J., et al; *The coral reef crisis: The critical importance of< 350ppm CO2*. Marine Pollution Bulletin 58:1428-1436 (2009); Hughes, T. et al., *Spatial and temporal patterns of mass bleaching of corals in the Anthropocene*, Science 359: 80–83 (2018); Hughes, T. et al. *Global warming impairs stock–recruitment dynamics of corals*, Nature (2019).

reefs could disappear as soon as 2030 (the IPCC also predicts 99% of coral reefs will die with 2°C warming).[19] Even the recent National Climate Assessment acknowledged that coral reefs in Florida, Hawaii, Puerto Rico, and the U.S. Virgin Islands have been harmed by mass bleaching and coral diseases and could disappear by mid-century as a result of warming waters.[20] Scientists believe we can protect marine life and prevent massive bleaching and die-off of coral reefs only by rapidly returning CO_2 levels to below 350 ppm.[21]

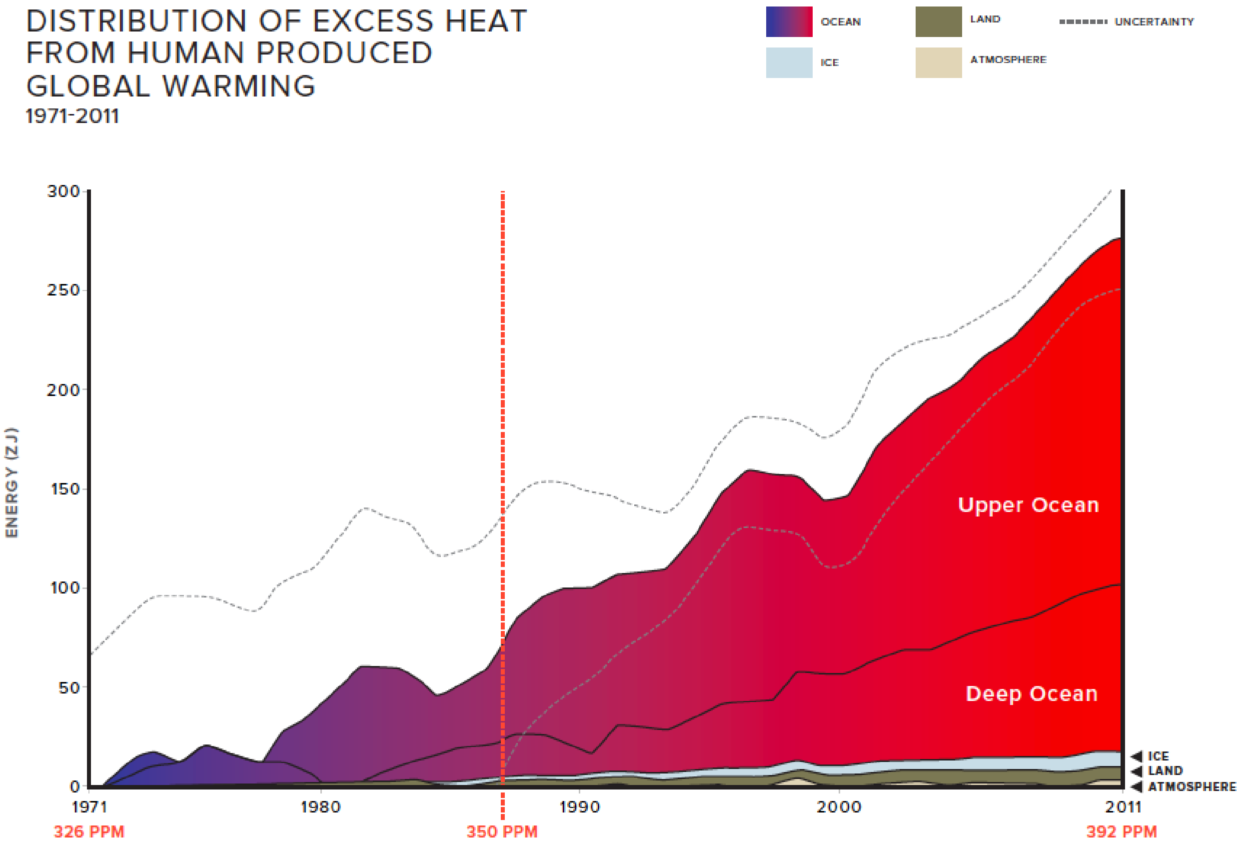

Figure 4: Over 90% of the excess energy from human caused climate change has been absorbed by the oceans, adding energy to storms and harming coral reefs around the globe.

No scientific institution, including the IPCC, has ever concluded that 2°C warming or 450 ppm would be safe for ocean life. According to Dr. Ove Hoegh-Guldberg, one of the world's leading experts on ocean warming and acidification, and a Coordinating Lead Author on the "Oceans" chapter of the IPCC's Fifth Assessment Report and on the "Impacts of 1.5ºC global warming on natural and human systems" of the IPCC's Special Report on 1.5°C:

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[19] Hoegh-Guldberg, Ove, et al., *Impacts of 1.5ºC Global Warming on Natural and Human Systems*. In *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* at pp. 225-226 (2018); IPCC, Summary for Policymakers of IPCC Special Report on Global Warming of 1.5°C Approved by Governments (2018).

[20] Pershing, A. J., et al., *Oceans and Marine Resources.* In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*, USGCRP (2018);

[21] Veron, J., et al., *The coral reef crisis: The critical importance of <350 ppm CO2*, 58 *Marine Pollution* Bulletin 1428 (2009).

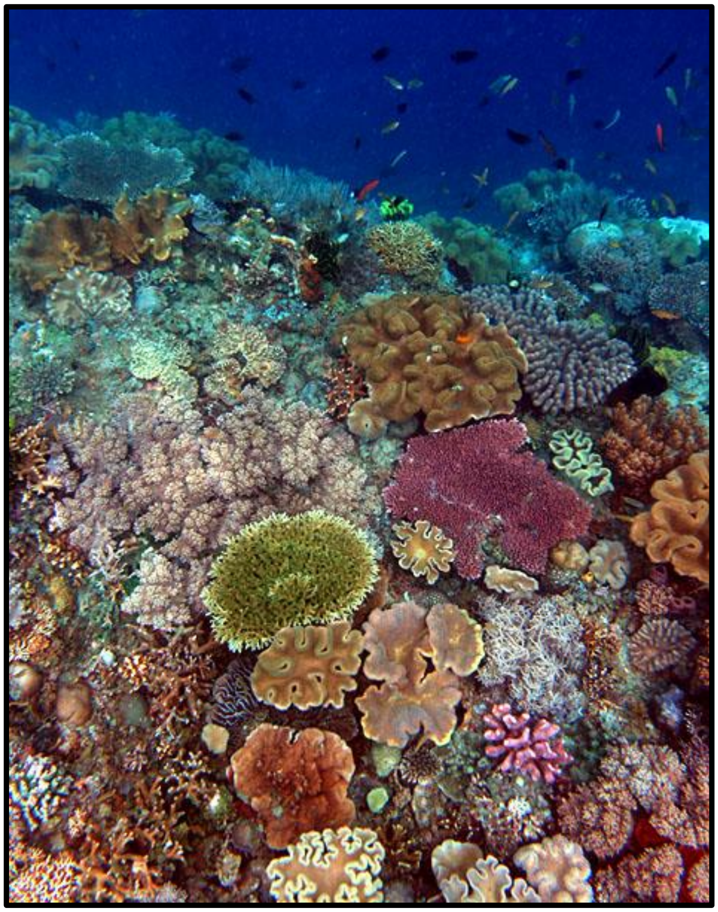

Figure 5: Healthy coral like this are already gravely threatened and will likely die with warming of 1.5°C.

"Allowing a temperature rise of up to 2°C would seriously jeopardize ocean life, and the income and livelihoods of those who depend on healthy marine ecosystems. Indeed, the best science available suggests that coral dominated reefs will completely disappear if carbon dioxide concentrations exceed much more than today's concentrations. Failing to restrict further increases in atmospheric carbon dioxide will eliminate coral reefs as we know them and will deny future generations of children from enjoying these wonderful ecosystems."[22]

Figure 6: Bleached coral from warmer ocean temperatures.

ADDITIONAL OBSERVATIONS ILLUSTRATE THE DANGERS OF INCREASED WARMING

In addition to the evidence discussed above which illustrates the necessity of ensuring that the atmospheric CO_2 concentration returns to no more than 350 ppm, based on present day observations about climate impacts occurring **now**, it is clear that the present level of 1°C is already causing significant climate impacts and additional warming will exacerbate these already dangerous impacts. Climate impacts that are already being experienced today include:

- Declining snowpack and rising temperatures are increasing the length and severity of drought conditions, especially in the western United States and Southwest, causing problems for agriculture users, forcing some people to relocate, and leading to water restrictions.[23]
- In the western United States, the wildfire season is now almost three months longer (87 days) than it was in the 1980s.[24]

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[22] *Id.*

[23] Steven W. Running, *Declaration in Support of Plaintiffs, Juliana v. United States*, No. 18-36082, Doc. 21-12 (9th Cir. Feb. 7, 2019).

[24] Steven W. Running, *Declaration in Support of Plaintiffs, Juliana v. United States*, No. 18-36082, Doc. 21-12 (9th Cir.

- Extreme weather events, such as intense rainfall events that cause flooding, are increasing in frequency and severity because a warmer atmosphere holds more moisture.[25] What are supposedly 1-in-1000-year rainfall events are now occurring with alarming frequency – in 2018 there were at least five such events.[26]
- Tropical storms and hurricanes are increasing in intensity, both in terms of rainfall and windspeed, as warmer oceans provide more energy for the storms (we saw this with Hurricanes Harvey, Irma, and Maria in 2017) (Figure 7).[27]
- Terrestrial ecosystems are experiencing compositional and structural changes, with major adverse consequences for ecosystem services.[28]
- Terrestrial, freshwater, and marine species are experiencing a significant decrease in population size and geographic range, with some going extinct and others are facing the very real prospect of extinction – the rapid rate of extinctions has been called the 6th mass extinction.[29]

Figure 7: Flooding in Port Arthur, Texas on August 13, 2018 after Hurricane Harvey.

- Human health and well-being are already being affected by heat waves, floods, droughts, and extreme events; infectious diseases; quality of air, food, and water.[30] Doctors and leading medical institutions are calling climate change a "health emergency."[31] Children are being uniquely impacted by climate change.[32]
- In addition to physical harm, climate change is causing mental health impacts, ranging from stress to suicide, due to exposure to climate impacts, displacement, loss of income, chronic stress, and other impacts of climate change.[33]

Feb. 7, 2019).

[25] Kevin E. Trenberth, *Declaration in Support of Plaintiffs, Juliana v. United States*, No. 18-36082, Doc. 21-3 (9th Cir. Feb. 7, 2019).

[26] Belles, F., *America's 'One-in-1,000-Year' Rainfall Events in 2018*, The Weather Channel (Sept. 27, 2018).

[27] Kevin E. Trenberth, *Declaration in Support of Plaintiffs, Juliana v. United States*, No. 18-36082, Doc. 21-3 (9th Cir. Feb. 7, 2019).

[28] Nolan et al., *Past and future global transformation of terrestrial ecosystems under climate change*, Science (2018).

[29] G. Ceballos, et al., *Accelerated modern human–induced species losses: Entering the sixth mass extinction*, Science Advances (2015); Steven W. Running, *Expert Report, Juliana v. United States*, No. 6:15-cv-01517-TC, Doc. 264-1 (D. Or. June 28, 2018).

[30] Ebi, K. L., et al., *Human Health.* In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*, USGCRP (2018).

[31] Solomon, C. G. & LaRocque R. C., *Climate Change – A Health Emergency*, N. Engl. J. Med. 380:3 (2019).

[32] May, C., et al., *Northwest.* In *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II*, USGCRP (2018); Watts, N., et al., *The 2018 report of the* Lancet *Countdown on health and climate change: shaping the health of nations for centuries to come*, Lancet, Vol. 392 at 2482 (2018); *Brief of Amici Curiae Public Health Experts, Public Health Organizations, and Doctors in Support of Plaintiffs*, No. 18-36082, Doc. 47 (9th Cir. Mar. 1, 2019).

[33] Lise Van Susteren, *Expert Report, Juliana v. United States*, No. 6:15-cv-01517-TC, Doc. 271-1 (D. Or. June 28, 2018).

Figure 8: Offutt Air Force Base was impacted by flood waters during flooding in Nebraska during spring 2019.

- As Congress has recognized, "climate change is a direct threat to the national security of the United States and is impacting stability in areas of the world both where the United States Armed Forces are operating today, and where strategic implications for future conflict exist."[34] Senior military leaders have called climate change "*the* most serious national security threat facing our Nation today,"[35] a conclusion similarly recognized by our Nation's intelligence community.[36] Climate change is increasing food and water shortages, pandemic disease, conflicts over refugees and resources, and destruction to homes, land, infrastructure, and military assets, directly threatening our military personnel and the "Department of Defense's ability to defend the Nation" (see Figure 8).[37]
- Climate change is already causing vast economic harm in the United States. Since 1980 the United States has experienced 246 climate and weather disasters that each caused damages in excess of $1 billion, for a total cost of $1.6 trillion.[38] In 2018 alone, Congress appropriated more than $130 billion for weather and climate related disasters.[39]

These already serious impacts will grow in severity and will impact increasingly large numbers of people and parts of the world if CO_2 concentrations continue to rise. If we want our children and grandchildren to have a safe planet to live on, full of health and biodiversity rather than chaos and conflict, we must follow the best scientific prescription to restore Earth's energy balance and avoid the destruction of our planet's atmosphere, climate, and oceans.

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[34] *National Defense Authorization Act for Fiscal Year 2018*, Pub. L. No. 115-91, 131 Stat. 1358.

[35] Vice Admiral Lee Gunn, USN (Ret.), *Declaration in Support of Plaintiffs, Juliana v. United States*, No. 18-36082, Doc. 21-17 (9th Cir. Feb. 7, 2019) (emphasis in original); *see also* CNA Military Advisory Board, *National Security and the Accelerating Risks of Climate Change* (2014), https://www.cna.org/cna_files/pdf/MAB_5-8-14.pdf.

[36] National Intelligence Council, *Implications for US National Security of Anticipated Climate Change* (Sept. 2016), https://www.dni.gov/files/documents/Newsroom/Reports%20and%20Pubs/Implications_for_US_National_Security_of_Anticipated_Climate_Change.pdf.

[37] U.S. Dep't of Defense, *2014 Climate Change Adaptation Roadmap* (2014), https://www.acq.osd.mil/eie/downloads/CCARprint_wForward_e.pdf.

[38] NOAA, *Billion Dollar U.S. Weather/Climate Disasters 1980-2019* (2019), http://www.ncdc.noaa.gov/billions/events.pdf.

[39] U.S. House of Representatives Committee on the Budget, *The Budgetary Impact of Climate Change* 2 (Nov. 27, 2018).

INTERNATIONAL POLITICAL TARGETS OF 1.5°C OR 2°C ARE NOT SCIENCE-BASED AND ARE NOT SAFE

International, politically-recognized targets like 1.5°C or "well below" 2°C – which are commonly-associated with long-term atmospheric CO_2 concentrations of 425 and 450 ppm, respectively – have not been and are not presently considered safe or scientifically-sound targets for present or future generations.

Importantly, the Intergovernmental Panel on Climate Change ("IPCC") has never established nor endorsed a target of 1.5°C or 2°C warming as a limit below which the climate system will be stable.[40] It is beyond the IPCC's declared mandate to endorse a particular threshold of warming as "safe" or "dangerous." As the IPCC makes clear, "each major IPCC assessment has examined the impacts of [a] multiplicity of temperature changes but has left [it to the] political processes to make decisions on which thresholds may be appropriate."[41]

Neither 1.5°C nor 2°C warming above pre-industrial levels has ever been considered "safe" from either a political or scientific point of view. The 2°C figure was originally adopted in the political arena "from a set of heuristics," and it has retained predominantly political character ever since.[42] It has recently been all-but-abandoned as a credible policy goal, in light of the findings in IPCC's 1.5°C Special Report, and the mounting evidence leading up to its publication, that 2°C would be catastrophic relative to lower, still-achievable levels of warming.[43]

On the other hand, the idea of a 1.5°C target was first raised by the Association of Small Island States (AOSIS) in the negotiations leading up to the ill-fated 2009 UNFCCC Conference of Parties in Copenhagen.[44] AOSIS, however, was explicitly advocating a *well below* 1.5°C and *well below* 1°C target, on the basis of the research of Dr. James Hansen and his colleagues.[45] Political compromise on this science-based target then led to the adoption of a goal of "pursuing efforts to limit the

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[40] Dec. of Dr. James E. Hansen, *Juliana et al., v. United States et al*., No. 6:15-cv-01517-TC, 5 (D. Or. Aug. 12, 2015).

[41] IPCC, *Climate Change 2014: Mitigation of Climate Change, Contribution of Working Group III to the Fifth Assessment Report*, 125 (2014), http://report.mitigation2014.org/report/ipcc_wg3_ar5_chapter1.pdf.

[42] Randalls, S. *History of the 2°C Temperature Target*. 1. WIREs Climate Change 598, 603 (2010); Jaeger, C. and J. Jaeger, *Three views of two degrees*. 11(Suppl 1) Regional Environmental Change S15 (2011).

[43] IPCC, *Summary for policymakers* at 13-14, Climate Change 2014: Impacts, Adaptation, and Vulnerability (2014), http://www.ipcc.ch/pdf/assessment-report/ar5/wg2/ar5_wgII_spm_en.pdf; UNFCCC, *Report on the structured expert dialogue on the 2013–2015 review*, 18 (2015), http://unfccc.int/resource/docs/2015/sb/eng/inf01.pdf; Petra Tschakert, *1.5 °C or 2 °C: a conduit's view from the science-policy interface at COP20 in Lima, Peru*, Climate Change Responses 8 (2015), http://www.climatechangeresponses.com/content/2/1/3; IPCC, *Global warming of 1.5°C: An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* (2018), https://www.ipcc.ch/sr15/.

[44] See Webster, R. *A brief history of the 1.5C target*. Climate Change News (December 10, 2015), http://www.climatechangenews.com/2015/12/10/a-brief-history-of-the-1-5c-target/; *Submission from Grenada on behalf of AOISIS to the Ad Hoc Working Group on Further Commitments for Annex I Parties Under the Kyoto Protocol*, U.N. Doc. FCCC/KP/AWG/2009/MISC.1/Add.1 (25 March 2009), https://unfccc.int/sites/default/files/resource/docs/2009/awg7/eng/misc01a01.pdf.

[45] *Submission from Grenada on behalf of AOISIS to the Ad Hoc Working Group on Further Commitments for Annex I Parties Under the Kyoto Protocol*, U.N. Doc. FCCC/KP/AWG/2009/MISC.1/Add.1 (25 March 2009), https://unfccc.int/sites/default/files/resource/docs/2009/awg7/eng/misc01a01.pdf, citing Hansen, J. et al. *Target Atmospheric CO_2: Where Should Humanity Aim?* 2 The Open Atmospheric Science Journal 217 (2008).

temperature increase to 1.5°C above pre-industrial levels" in Article 2 of the Paris Agreement. Yet the 2018 IPCC Special Report on 1.5°C has made clear that allowing a temperature rise of 1.5°C:

> is **not considered 'safe'** for most nations, communities, ecosystems, and sectors and poses significant risks to natural and human systems as compared to current warming of 1°C (*high confidence*) . . . .[46]

Dr. James Hansen warns that "distinctions between pathways aimed at 1°C and 2°C warming are much greater and more fundamental than the numbers 1°C and 2°C themselves might suggest. These fundamental distinctions make scenarios with 2°C or more global warming far more dangerous; so dangerous, we [James Hansen et al.] suggest, that aiming for the 2°C pathway would be foolhardy."[47] This target is at best the equivalent of "flip[ping] a coin in the hopes that future generations are not left with few choices beyond mere survival. This is not risk management, it is recklessness and we must do better."[48]

Tellingly, more than 45 eminent scientists from over 40 different institutions have published in peer-reviewed journals finding that the maximum level of atmospheric CO_2 consistent with protecting humanity and other species is 350 ppm, and no one, including the IPCC, has published any scientific evidence to counter that 350 is the maximum safe concentration of CO_2.[49]

A 1.5° OR 2°C TARGET RISKS LOCKING-IN DANGEROUS FEEDBACKS

The longer the length of time atmospheric CO_2 concentrations remain at dangerous levels (i.e., above 350 ppm) and there is an energy imbalance in the atmosphere, the risk of triggering, and locking-in, dangerous warming-driven feedback loops increases. The 1.5°C or 2°C target reduces the likelihood that the biosphere will be able to sequester CO_2 due to carbon cycle feedbacks and shifting climate zones.[50] As temperatures warm, forests burn and soils warm, releasing their carbon. These natural carbon "sinks" become carbon "sources" and a portion of the natural carbon sequestration necessary to drawdown excess CO_2 simply disappear. Another dangerous feedback includes the release of methane, a potent greenhouse gas, as the global tundra thaws.[51] These feedbacks might show little change in the short-term, but can hit a point of no return, even at a 1.5°C or 2°C temperature increase, which will trigger accelerated heating and sudden *and irreversible* catastrophic impacts. Moreover,

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[46] Roy, J., et al., *Sustainable Development, Poverty Eradication and Reducing Inequalities.* In *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty* at 447 (2018) (emphasis added).

[47] *Id.* at 15.

[48] Matt Vespa, *Why 350? Climate Policy Must Aim to Stabilize Greenhouse Gases at the Level Necessary to Minimize the Risk of Catastrophic Outcomes*, 36 Ecology Law Currents 185, 186 (2009), http://www.biologicaldiversity.org/publications/papers/Why_350.pdf.

[49] James Hansen, et al., *Target Atmospheric CO_2: Where Should Humanity Aim?* (2008); James Hansen, et al., *Assessing "Dangerous Climate Change": Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature* (2013); James Hansen, et al., *Ice Melt, Sea Level Rise and Superstorms: Evidence From Paleoclimate Data, Climate Modeling, and Modern Observations That 2ºC Global Warming Could Be Dangerous* (2016); James Hansen, et al., *Young People's Burden: Requirement of Negative CO_2* Emissions (2017); Veron, J., et al., *The Coral Reef Crisis: The Critical Importance of <350 ppm CO_2* (2009); Frieler, K., et al., *Limiting global warming to 2 ◦C is unlikely to save most coral reefs* (2012).

[50] *Id.* at 15, 20.

[51] *Id.*

an emission reduction target aimed at 2°C would "yield a larger eventual warming because of slow feedbacks, probably at least 3°C."[52] Once a temperature increase of 2°C is reached, there will already be "additional climate change 'in the pipeline' even without further change of atmospheric composition."[53]

IT IS TECHNOLOGICALLY AND ECONOMICALLY FEASIBLE TO REDUCE CO_2 LEVELS TO 350 PPM BY 2100

There are two steps to reducing CO_2 levels to 350 ppm by the end of the century: 1) reducing CO_2 emissions; and 2) sequestering excess CO_2 already in the atmosphere. Carbon dioxide emission reductions of approximately 80% by 2030 and close to 100% by 2050 (in addition to the requisite CO_2 sequestration) are necessary to keep long-term warming to 1°C and the atmospheric CO_2 concentration to 350 ppm. Emission reduction targets that seek to reduce CO_2 emissions by 80% by 2050 are consistent with long-term warming of 2°C and an atmospheric CO_2 concentration of 450 ppm, which, as described above, would result in catastrophic and irreversible impacts for the climate system and oceans. Importantly, it is economically and technologically feasible to transition the entire U.S. energy system to a zero-CO_2 energy system by 2050 and to drawdown the excess CO_2 in the atmosphere through reforestation and carbon sequestration in soils.[54]

Deep Decarbonization Pathways Project and Evolved Energy Research recently completed research and very sophisticated modeling describing a nearly complete phase out of fossil fuels in the U.S. by 2050.[55] They describe six different technologically feasible pathways to drastically, and quickly, cut our reliance on fossil fuels and achieve the requisite level of emissions reductions in the U.S. while meeting our nation's forecasted energy needs. All of the 350 ppm pathways rely on four pillars of action: a) investment in energy efficiency; b) electrification of everything that can be electrified; c) shifting to very low-carbon and primarily renewable electricity generation; and d) carbon dioxide capture as fossil fuels are phased out. The six scenarios are used to evaluate the ability to meet the targets even absent one key technology. For example, one scenario describes a route to 350 absent construction of new nuclear facilities; another illustrates getting to 350 with extremely limited biomass technology; still another describes a way to 350 without any carbon capture and storage. Even absent a key technology, each of these six routes are viable and cost effective.

The study also concludes that the cost of the energy system transition is affordable. The total cost of supplying and using energy in the U.S. in 2016 was about 5.6% of GDP (see Figure 9).[56] A transition from fossil fuels to low carbon energy sources is expected to increase those costs by no more than an additional two to three percent of GDP. Even with this small and temporary added expense, the cost would still be well below the 9.5% of GDP spent on the energy system in 2009 (not to mention well below the harm to the economy caused by climate change). Once the transition is complete, the cost

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[52] Hansen, Assessing "Dangerous *Climate Change*," at 15.

[53] *Id.* at 19.

[54] *See* Mark Z. Jacobson et al., *100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for the 50 United States*, 8 Energy & Envtl. Sci. 2093 (2015) (for plans on how the United States and over 100 other countries can transition to a 100% renewable energy economy see www.thesolutionsproject.org); *see also* Arjun Makhijani, Carbon-Free, Nuclear-Free: A Roadmap for U.S. Energy Policy (2007); B. Haley et al., *350 ppm pathways for the United States* (2019).

[55] B. Haley et al., *350 ppm pathways for the United States* (2019).

[56] B. Haley et al., *350 ppm pathways for the United States* (2019).

of energy will remain low and stable because we will no longer be dependent on volatile global fossil fuel markets for our energy supplies. As Nobel Laureate Economist Dr. Joseph Stiglitz has stated: "[t]he benefits of making choices today that limit the economic costs of climate change far outweigh any economic costs associated with limiting our use of fossil fuels."[57]

Other experts have already prepared plans for all 50 U.S. states as well as for over 139 countries that demonstrate the technological and economic feasibility of transitioning off of fossil fuels toward 100% of energy, for all energy sectors, from clean and renewable energy sources: wind, water, and sunlight by 2050 (with 80% reductions in fossil fuels by 2030).[58]

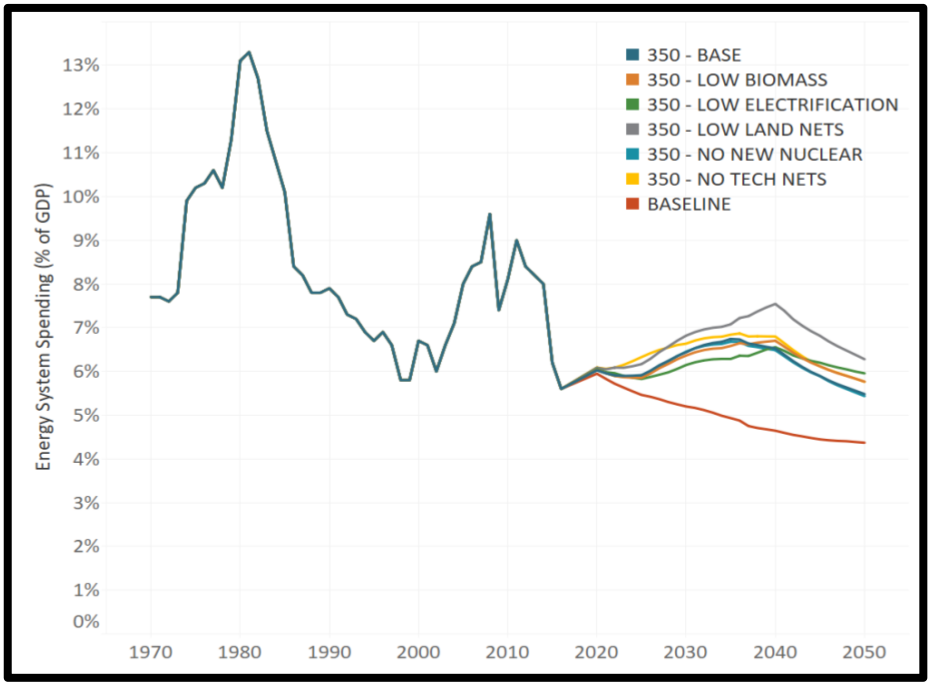

Figure 9: Historic and Projected Costs of Energy in the U.S.

Products already exist that enable new construction or retrofits that result in zero greenhouse gas buildings. We have the technology to meet all electricity needs with zero-emission electric generation. We know how to achieve zero-emission transportation, including aviation. These actions result in other benefits, such as improved health, job creation, and savings on energy costs.

The amount of natural carbon sequestration required is also proven to be feasible. Researchers have evaluated the potential to drawdown excess carbon dioxide in the atmosphere by increasing the carbon stored in forests, soils, and wetlands, and have found significant potential for these natural systems to support a return to 350 ppm by the end of the century.[59] We know the agricultural, rangeland, wetland, and forest management practices that decrease greenhouse gas emissions and increase sequestration.

There is no scientific, technological, or economic reason to *not* adopt a 350 ppm and 1°C by 2100 target. There are abundant reasons for doing so, not the least of which is to do our best through human laws to respect the laws of nature and create a safe and healthy world for children and future generations who will walk this Earth.

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[57] Joseph E. Stiglitz, Ph.D., *Declaration in Support of Plaintiffs, Juliana v. United States*, No. 18-36082, Doc. 21-14 (9th Cir. Feb. 7, 2019).

[58] Mark Z. Jacobson et al., *100% Clean and Renewable Wind, Water, and Sunlight (WWS) All-Sector Energy Roadmaps for the 50 United States*, 8 Energy & Envtl. Sci. 2093 (2015). For a graphic depicting the overview of the plan for the United States see: https://thesolutionsproject.org/why-clean-energy/#/map/countries/location/USA.

[59] Benson W. Griscom et al., *Natural Climate Solutions*, Proceedings of the National Academies of Sciences (2017); Joseph E. Fargione et al., *Natural Climate Solutions for the United States*, Science Advances (2018).

Exhibit C.1:
350 PPM Pathways for the United States
Executive Summary

EXECUTIVE SUMMARY

350 PPM PATHWAYS FOR THE UNITED STATES

May 8, 2019

EVOLVED ENERGY RESEARCH

Prepared by

Ben Haley, Ryan Jones, Gabe Kwok, Jeremy Hargreaves & Jamil Farbes

Evolved Energy Research

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Sustainable Development Solutions Network

DEEP DECARBONIZATION PATHWAYS PROJECT

DDPP

Executive Summary

This report describes the changes in the U.S. energy system required to reduce carbon dioxide (CO_2) emissions to a level consistent with returning atmospheric concentrations to 350 parts per million (350 ppm) in 2100, achieving net negative CO_2 emissions by mid-century, and limiting end-of-century global warming to 1°C above pre-industrial levels. The main finding is that 350 ppm pathways that meet all current and forecast U.S. energy needs are technically feasible using existing technology, and that multiple alternative pathways can meet these objectives in the case of limits on some key decarbonization strategies. These pathways are economically viable, with a net increase in the cost of supplying and using energy equivalent to about 2% of GDP, up to a maximum of 3% of GDP, relative to the cost of a business-as-usual baseline. These figures are for energy costs only and do not count the economic benefits of avoided climate change and other energy-related environmental and public health impacts, which have been described elsewhere.[1]

This study builds on previous work, *Pathways to Deep Decarbonization in the United States* (2014) and *Policy Implications of Deep Decarbonization in the United States* (2015), which examined the requirements for reducing GHG emissions by 80% below 1990 levels by 2050 ("80 x 50").[2] These studies found that an 80% reduction by mid-century is technically feasible and economically affordable, and attainable using different technological approaches. The main requirement of the transition is the construction of a low carbon infrastructure characterized by high energy efficiency, low-carbon electricity, and replacement of fossil fuel combustion with decarbonized electricity and other fuels, along with the policies needed to achieve this transformation. The findings of the present study are similar but reflect both a more stringent emissions limit and the consequences of five intervening years without aggressive emissions reductions in the U.S. or globally.

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[1] See e.g. *Risky Business: The Bottom Line on Climate Change,* available at https://riskybusiness.org/

[2] Available at http://usddpp.org/.

The 80 x 50 analysis was developed in concert with similar studies for other high-emitting countries by the country research teams of the Deep Decarbonization Pathways Project, with an agreed objective of limiting global warming to 2°C above pre-industrial levels.[3] However, new studies of climate change have led to a growing consensus that even a 2°C increase may be too high to avoid dangerous impacts. Some scientists assert that staying well below 1.5°C, with a return to 1°C or less by the end of the century, will be necessary to avoid irreversible feedbacks to the climate system.[4] A recent report by the IPCC indicates that keeping warming below 1.5°C will likely require reaching net-zero emissions of CO_2 globally by mid-century or earlier.[5] A number of jurisdictions around the world have accordingly announced more aggressive emissions targets, for example California's recent executive order calling for the state to achieve carbon neutrality by 2045 and net negative emissions thereafter.[6]

In this study we have modeled the pathways – the sequence of technology and infrastructure changes – consistent with net negative CO_2 emissions before mid-century and with keeping peak warming below 1.5°C. We model these pathways for the U.S. for each year from 2020 to 2050, following a global emissions trajectory that would return atmospheric CO_2 to 350 ppm by 2100, causing warming to peak well below 1.5°C and not exceed 1.0°C by century's end.[7] The cases modeled are a 6% per year and a 12% per year reduction in net fossil fuel CO_2 emissions after 2020. These equate to a cumulative emissions limit for the U.S. during the 2020 to 2050 period of 74 billion metric tons of CO_2 in the 6% case and 47 billion metric tons in the 12% case. (For comparison, current U.S. CO_2 emissions are about 5 billion metric tons per year.) The emissions in both cases must be accompanied by increased extraction of CO_2 from the atmosphere using land-based negative emissions technologies ("land NETs"), such as reforestation, with greater extraction required in the 6% case.

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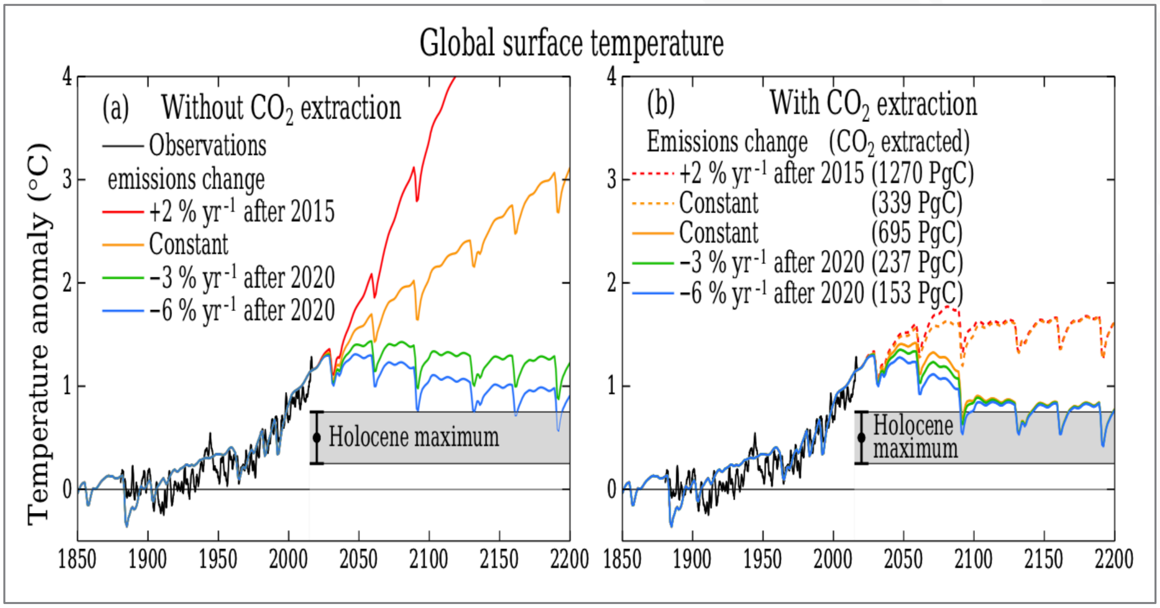
[3] Available at http://deepdecarbonization.org/countries/.
[4] James Hansen, et al. (2017) "Young people's burden: requirement of negative CO2 emissions," *Earth System Dynamics*, https://www.earth-syst-dynam.net/8/577/2017/esd-8-577-2017.html.
[5] Available at https://www.ipcc.ch/sr15/.
[6] Available at https://www.gov.ca.gov/wp-content/uploads/2018/09/9.10.18-Executive-Order.pdf.
[7] Hansen et al. (2017).

Figure ES1 Global surface temperature and CO2 emissions trajectories. Hansen et al, 2017.



We studied six different scenarios: five that follow the 6% per year reduction path and one that follows the 12% path. All reach net negative CO_2 by mid-century while providing the same energy services for daily life and industrial production as the *Annual Energy Outlook (AEO)*, the Department of Energy's long-term forecast. The scenarios explore the effects of limits on key decarbonization strategies: bioenergy, nuclear power, electrification, land NETs, and technological negative emissions technologies ("tech NETs"), such as carbon capture and storage (CCS) and direct air capture (DAC).

Table ES1. Scenarios developed in this study

Scenario	Average annual rate of CO_2 emission reduction	2020-2050 maximum cumulative fossil fuel CO_2 (million metric tons)	Year 2050 maximum net fossil fuel CO_2 (million metric tons)	Year 2050 maximum net CO_2 with 50% increase in land sink (million metric tons)
Base	6%	73,900	830	-250
Low Biomass	6%	73,900	830	-250
Low Electrification	6%	73,900	830	-250
No New Nuclear	6%	73,900	830	-250
No Tech NETS	6%	73,900	830	-250
Low Land NETS	12%	57,000	-200	-450

The scenarios were modeled using two new analysis tools developed for this purpose, EnergyPATHWAYS and RIO. As extensively described in the Appendix, these are sophisticated models with a high level of sectoral, temporal, and geographic detail, which ensure that the scenarios account for such things as the inertia of infrastructure stocks and the hour-to-hour dynamics of the electricity system, separately in each of fourteen electric grid regions of the U.S. The changes in energy mix, emissions, and costs for the six scenarios were calculated relative to a high-carbon baseline also drawn from the *AEO*.

Relative to 80 x 50 trajectories, a 350 ppm trajectory that achieves net negative CO_2 by mid-century requires more rapid decarbonization of energy plus more rapid removal of CO_2 from the atmosphere. For this analysis, an enhanced land sink 50% larger than the current annual sink of approximately 700 million metric tons was assumed.[8] This would require additional sequestration of 25-30 billion metric tons of CO_2 from 2020 to 2100. The present study does not address the cost or technical feasibility of this assumption but stipulates it as a plausible value for calculating an overall CO_2 budget, based on consideration of the scientific literature in this area.[9]

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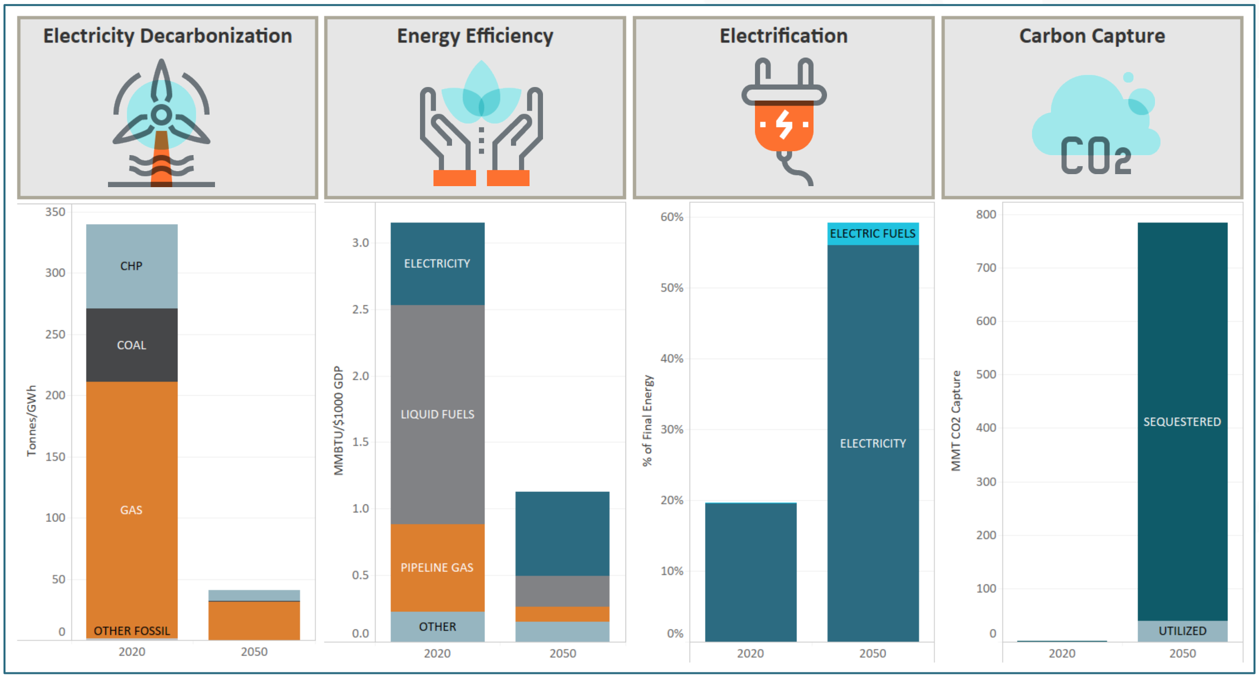
[8] U.S. EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016,* available at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016

[9] Griscom, Bronson W., et al. (2017) "Natural climate solutions." *Proceedings of the National Academy of Sciences* 114.44 (2017): 11645-11650; Fargione, Joseph E., et al. (2018) "Natural climate solutions for the United States." *Science Advances* 4.11: eaat1869.

Figure ES2 Four pillars of deep decarbonization - Base case



Energy decarbonization rests on the four principal strategies ("four pillars") shown in Figure ES2: (1) electricity decarbonization, the reduction in emissions intensity of electricity generation by about 90% below today's level by 2050; (2) energy efficiency, the reduction in energy required to provide energy services such as heating and transportation, by about 60% below today's level; (3) electrification, converting end-uses like transportation and heating from fossils fuels to low-carbon electricity, so that electricity triples its share from 20% of current end uses to 60% in 2050; and (4) carbon capture, the capture of otherwise CO_2 that would otherwise be emitted from power plants and industrial facilities, plus direct air capture, rising from nearly zero today to as much as 800 million metric tons in 2050 in some scenarios. The captured carbon may be sequestered or may be utilized in making synthetic renewable fuels.

Achieving this transformation by mid-century requires an aggressive deployment of low-carbon technologies. Key actions include retiring all existing coal power generation, approximately doubling electricity generation primarily with solar and wind power and electrifying virtually all passenger vehicles and natural gas uses in buildings. It also includes creating new types of infrastructure, namely large-scale industrial facilities for carbon capture and storage, direct air capture of CO_2, the production of gaseous and liquid biofuels with zero net lifecycle CO_2, and the production of hydrogen from water electrolysis using excess renewable electricity. The scale of the infrastructure buildout by region is indicated in Figure ES3.

Figure ES3 Regional infrastructure requirements (Low Land NETS scenario)

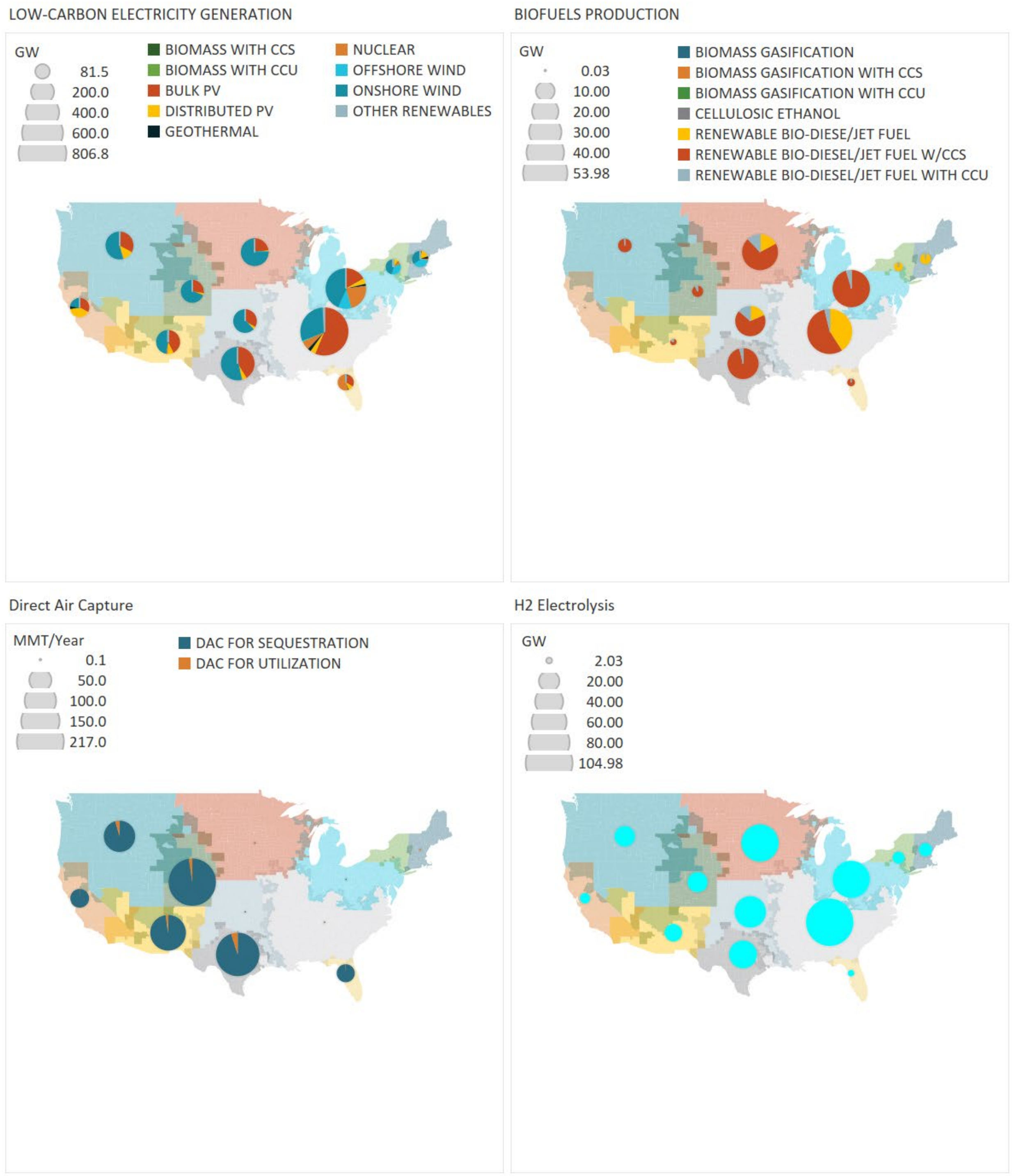


Figure ES4 shows that all scenarios achieve the steep reductions in net fossil fuel CO_2 emissions to reach net negative emissions by the 2040s, given a 50% increase in the land sink, including five that are limited in one key area. This indicates that the feasibility of reaching the emissions goals is robust due to the ability to substitute strategies. At same time, the more limited scenarios are, the more difficult and/or costly they are relative to the base case with all options available. Severe limits in two or more areas were not studied here but would make the emissions goals more difficult to achieve in the mid-century time frame.

Figure ES4 2020-2050 CO_2 emissions for the scenarios in this study

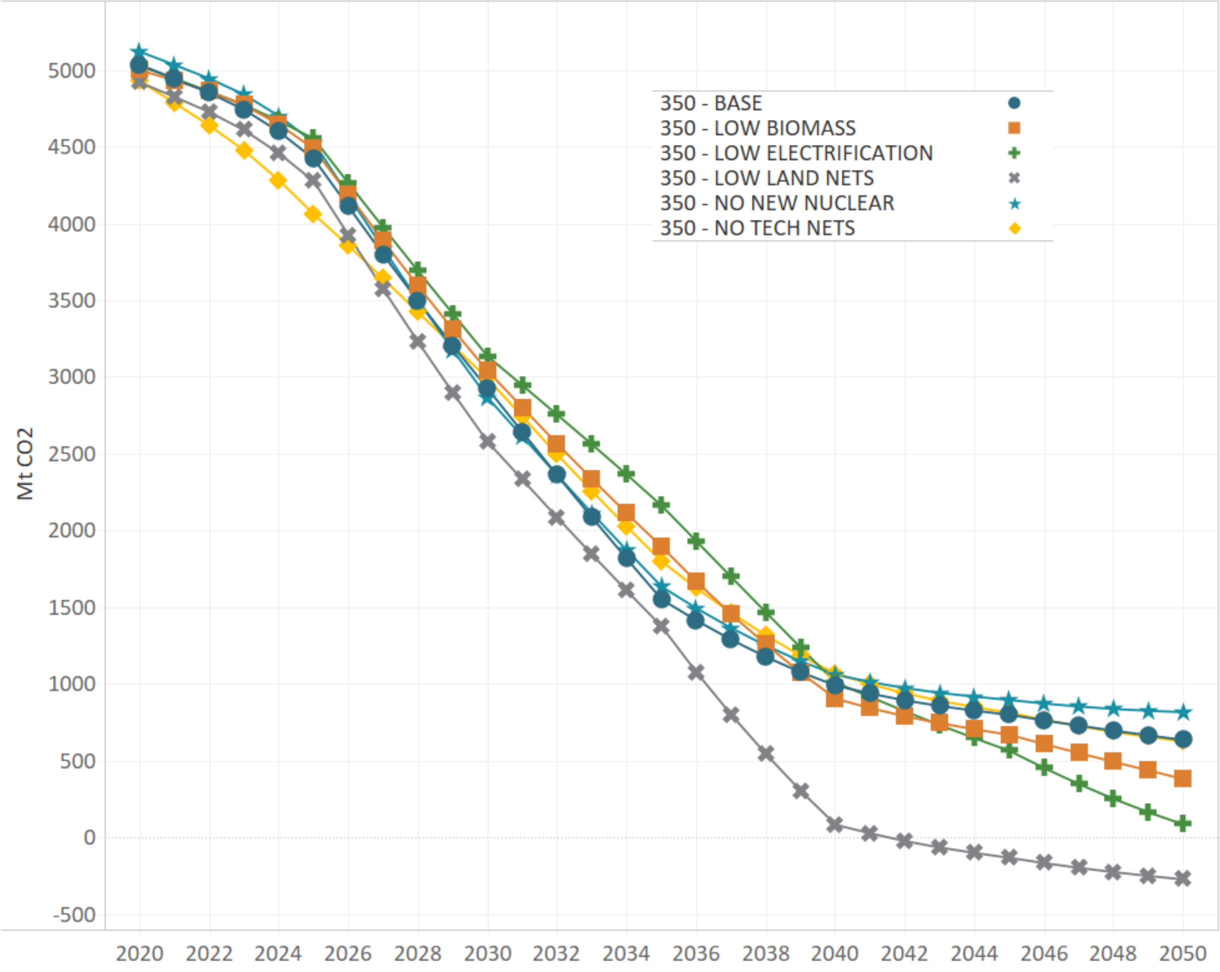
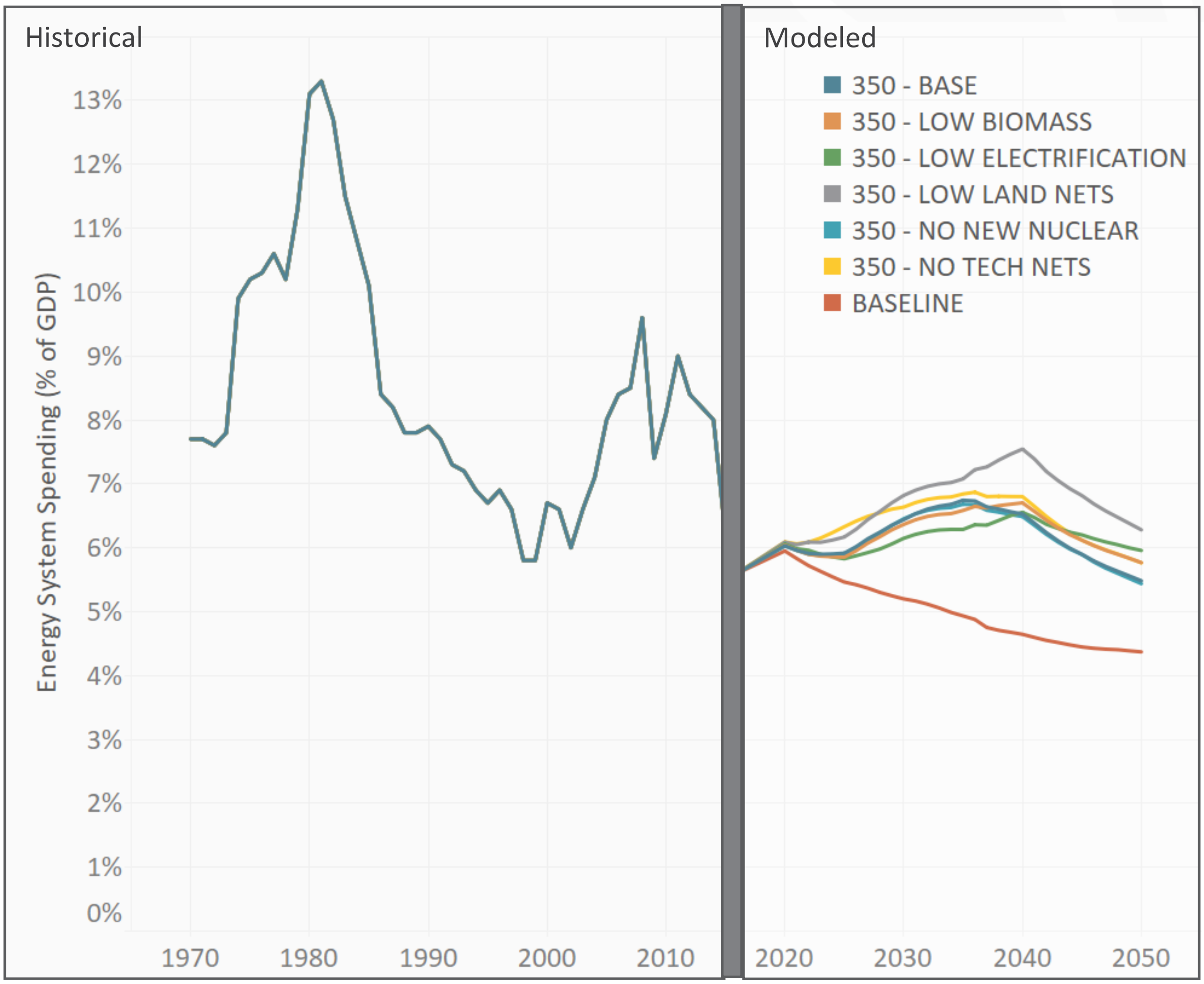


Figure ES5 shows U.S. energy system costs as a share of GDP for the baseline case and six 350 ppm scenarios in comparison to historical energy system costs. While the 350 ppm scenarios have a net cost of 2-3% of GDP more than the business as usual baseline, these costs are not out of line with historical energy costs in the U.S. The highest cost case is the Low Land NETs scenario, which requires a 12% per year reduction in net fossil fuel CO_2 emissions. By comparison, the 6% per year reduction cases are more closely clustered. The lowest increase is the Base scenario, which incorporates all the key decarbonization strategies. These costs do not include any potential economic benefits of avoided climate change or pollution, which could equal or exceed the net costs shown here.

Figure ES5. Total energy system costs as percentage of GDP, modeled (R.) and historical (L.)



A key finding of this study is the potentially important future role of "the circular carbon economy." This refers to the economic complementarity of hydrogen production, direct air capture of CO_2, and fuel synthesis, in combination with an electricity system with very high levels of intermittent renewable generation. If these facilities operate flexibly to take advantage of periods of excess generation, the production of hydrogen and CO_2 feedstocks can provide an economic use for otherwise curtailed energy that is difficult to utilize with electric energy storage technologies of limited duration. These hydrogen and CO_2 feedstocks can be combined as alternatives for gaseous and liquid fuel end-uses that are difficult to electrify directly like freight applications and air travel. While the CO_2 is eventually emitted to the atmosphere, the overall process is carbon neutral as it was extracted from the air and not emitted from fossil reserves. A related finding of this work is that bioenergy with carbon capture and storage (BECCS) for power plants appears uneconomic, while BECCS for bio-refineries appears highly economic and can be used as an alternative source of CO_2 feedstocks in a low-carbon economy.

There are several areas outside the scope of this study that are important to provide a full picture of a low greenhouse gas transition. One important area is better understanding of the potential and cost of land-based NETs, both globally and in the U.S. Another is the potential and cost of reductions in non-CO_2 climate pollutants such as methane, nitrous oxide, and black carbon. Finally, there is the question of the prospects for significant reductions in energy service demand, due to lifestyle choices such as bicycling over cars, structural changes such as increased transit and use of ride-sharing, or the development of less-energy intensive industry, perhaps based on new types of materials.

“Key Actions by Decade” below provides a blueprint for the physical transformation of the energy system. From a policy perspective, this provides a list of the things that policy needs to accomplish, for example the deployment of large amounts of low carbon generation, rapid electrification of vehicles, buildings, and industry, and building extensive carbon capture, biofuel, hydrogen, and synthetic fuel synthesis capacity.

Some of the policy challenges that must be managed include: land use tradeoffs related to carbon storage in ecosystems and siting of low carbon generation and transmission; electricity market designs that maintain natural gas generation capacity for reliability while running it very infrequently; electricity market designs that reward demand side flexibility in high-renewables electricity system and encourage the development of complementary carbon capture and fuel synthesis industries; coordination of planning and policy across sectors that previously had little interaction but will require much more in a low carbon future, such as transportation and electricity; coordination of planning and policy across jurisdictions, both vertically from local to state to federal levels, and horizontally across neighbors and trading partners at the same level;

mobilizing investment for a rapid low carbon transition, while ensuring that new investments in long-lived infrastructure are made with full awareness of what they imply for long-term carbon commitment; and investing in ongoing modeling, analysis, and data collection that informs both public and private decision-making. These topics are discussed in more detail in *Policy Implications of Deep Decarbonization in the United States.*

Key Actions by Decade

This study identifies key actions that are required in each decade from now to mid-century in order to achieve net negative CO_2 emissions by mid-century, at least cost, while delivering the energy services projected in the *Annual Energy Outlook*. Such a list inherently relies on current knowledge and forecasts of unknowable future costs, capabilities, and events, yet a long-term blueprint remains essential because of the long lifetimes of infrastructure in the energy system and the carbon consequences of investment decisions made today. As events unfold, technology improves, energy service projections change, and understanding of climate science evolves, energy system analysis and blueprints of this type must be frequently updated.

2020s

- Begin large-scale electrification in transportation and buildings
- Switch from coal to gas in electricity system dispatch
- Ramp up construction of renewable generation and reinforce transmission
- Allow new natural gas power plants to be built to replace retiring plants
- Start electricity market reforms to prepare for a changing load and resource mix
- Maintain existing nuclear fleet
- Pilot new technologies that will need to be deployed at scale after 2030
- Stop developing new infrastructure to transport fossil fuels
- Begin building carbon capture for large industrial facilities

2030s

- Maximum build-out of renewable generation
- Attain near 100% sales share for key electrified technologies (e.g. EVs)
- Begin large-scale production of bio-diesel and bio-jet fuel
- Large scale carbon capture on industrial facilities
- Build out of electrical energy storage
- Deploy fossil power plants capable of 100% carbon capture if they exist

Maintain existing nuclear fleet

2040s

- Complete electrification process for key technologies, achieve 100% stock penetration
- Deploy circular carbon economy using DAC and hydrogen to produce synthetic fuels
- Use synthetic fuel production to balance and expand renewable generation
- Replace nuclear at the end of existing plant lifetime with new generation technologies
- Fully deploy biofuel production with carbon capture

Exhibit C.2:
350 PPM Pathways for Florida
Executive Summary and U.S. data

350 PPM PATHWAYS FOR FLORIDA

October 6, 2020

EVOLVED
ENERGY
RESEARCH

350 PPM Pathways for Florida

Prepared by

Ben Haley, Gabe Kwok, and Ryan Jones

Evolved Energy Research

October 6, 2020

Executive Summary

This study evaluates multiple scenarios to radically reduce the greenhouse gas emissions that result from Florida's energy system, and can serve as a tool to inform statewide energy system decisions.

We detail five technically and economically feasible pathways to reduce carbon dioxide emissions and remain within a small enough "carbon budget" to enable a return to 350 parts per million of carbon dioxide in the atmosphere by 2100, a level identified by scientists as a safe limit necessary to preserve a stable climate. These scenarios limit emissions while providing the same energy services for daily life and industrial production as the Department of Energy's long-term forecast.

This study builds upon the research conducted by Evolved Energy Research and the Sustainability Development Solutions Network (SDSN) and published on May 8, 2019, titled *350 PPM Pathways for the United States.*

Scenarios

This study evaluates five energy decarbonization[1] scenarios for the energy system of Florida:

Central: The least constrained scenario, this uses all options to decarbonize the energy system.

Low Biomass: This scenario reduces the development of new biomass feedstocks[2] by 50%.

Low Electrification: This scenario assesses the impact of a delayed adoption of electric vehicles and heat pumps.

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[1] "Decarbonization" is the process of removing sources of carbon dioxide (and other greenhouse gases) from a system – in this case, removing fossil fuel emissions from Florida's energy system.

[2] Biomass feedstocks are plant-based and animal-based sources of fuel, like trees, grasses, or animal fats, for example.

100% Renewable Primary: This scenario describes an energy system based solely on biomass, wind, solar, hydro, and geothermal sources by 2050.

No New Regional Transmission (TX): This scenario limits the development of new electricity transmission lines between regions within the U.S.

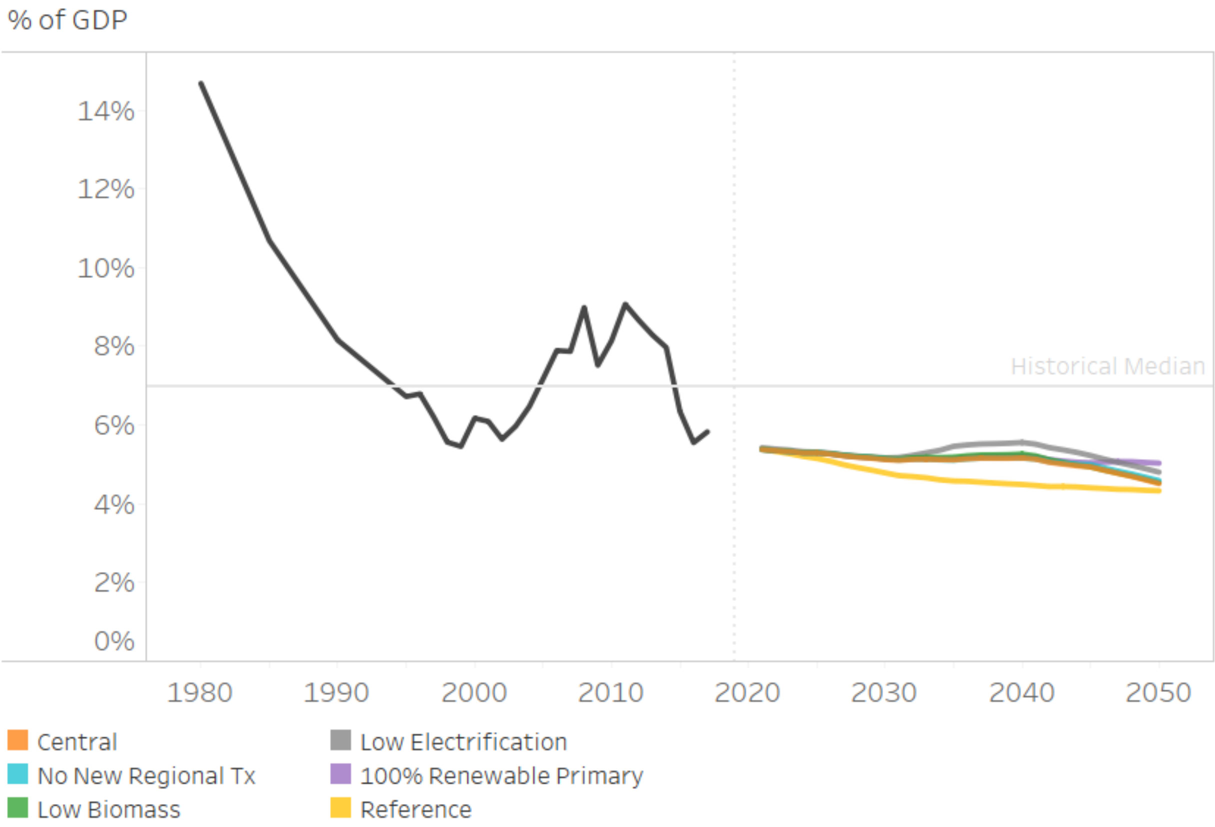
Florida Energy System Results

Energy decarbonization in Florida relies on four principal strategies: (1) **Electricity decarbonization** requires reducing the amount of fossil fuels used for electricity generation, thereby reducing the amount of greenhouse gas emissions from every unit of electricity delivered by about 95% by 2050; (2) **Energy efficiency** is the reduction in energy required to provide energy services such as heating and transportation, and energy use per unit GDP is reduced by about 50% below today's level; (3) **Electrification** involves switching energy uses including transportation and building heating off of fossils fuels and onto low-carbon electricity, and (4) **Capturing carbon** that would otherwise be emitted from power plants and industrial facilities – with the captured carbon either stored permanently (sequestered) or used to create fuels like synthetic natural gas or synthetic diesel, by combining the carbon with renewably-generated hydrogen.

Figure 1 shows historical and projected energy system costs as a share of State Gross Domestic Product (GDP). All scenarios evaluated in this study are in line with historical energy costs in Florida and, even with decarbonization, energy system costs are anticipated to decline as a share of GDP. The highest cost scenario is the 100% Renewable Primary pathway due to the emphasis on displacing *all* fossil fuels by 2050, rather than continuing to use some small amount of the lowest-cost fossil fuels and capturing and storing the associated carbon. The lowest cost scenario is the Central scenario, which allows for the most flexibility in terms of key decarbonization strategies.

Note that the costs within this chart do not reflect any of the macroeconomic benefits of transitioning off of fossil fuels, including improved air quality, avoided climate impacts (like avoided sea level rise), reduced energy price volatility, and energy independence, which could equal or exceed the net costs shown here.

Figure 1. Total energy system costs as percentage of GDP, historical and projected for Florida



Key Actions by Decade

Achieving the transition described above is not expensive but requires significant changes in public policy. Some of the **key policy challenges** that must be managed in all scenarios include: a) managing tradeoffs between using land for low carbon electricity generation (like wind farms and solar arrays) and improving natural carbon storage in forests and soils ; b) electricity market designs that maintain natural gas generation capacity for reliability while using gas generators very infrequently; c) developing electricity rates that incentivize customers to flex their energy use to better match periods of electricity surplus and shortage that come with intermittent renewables like wind and solar; d) encourage the development of carbon capture industries that can leverage periods of excess electricity generation ; e) coordination of planning and policy across sectors that previously had little interaction, such as transportation and electricity; f) coordination of planning and policy across jurisdictions; g) mobilizing investment for a rapid low carbon transition; and e) investing in ongoing modeling, analysis, and data collection that informs both public and private decision-making. These topics are discussed in more detail in *Policy Implications of Deep Decarbonization in the United States.*

Achieving this transformation in Florida by mid-century at lowest cost requires an **aggressive deployment of low-carbon technologies**, including:

2020s

- Begin large-scale transition to electric technologies in key sectors; moving to electric light duty vehicles and electric heat pumps.
- Use coal fired power plants only when absolutely necessary, prioritizing all other sources of electricity generation first. Begin retiring coal assets.
- Ramp up construction of renewable electricity generation and upgrade electricity transmission where needed.
- Allow strategic replacement of natural gas power plants to support rapid deployment of low-carbon generation. These power plants must be financed with the understanding that they will run very infrequently to provide capacity, not as they are operated today.
- Maintain existing nuclear power plants.
- Pilot new technologies that will need to be deployed at scale after 2030.
- Stop developing new infrastructure to transport and process fossil fuels.
- Begin building carbon capture for large industrial facilities.

2030s

- Maximum build-out of renewable electricity generation.
- Nearly 100% of new vehicle sales and new building heating systems using electric technologies.
- Begin large-scale production of biodiesel and bio-jet fuel.
- Large scale carbon capture on industrial facilities.
- Build out electrical energy storage.
- Deploy new natural gas power plants capable of 100% carbon capture if they exist.
- Maintain existing nuclear power plants.
- Continue to reduce generation from gas-fired power plants.

2040s

- Complete the transition to electric technologies for key sectors; virtually 100% of light duty vehicles and building heating systems run on electricity.
- Produce large volumes of hydrogen for use in freight trucks and fuel production.
- Use synthetic fuel production to balance and expand renewable generation.
- Fully deploy biofuel production with carbon capture.
- Further limit gas generation to infrequent periods when needed for system reliability.

Technical Supplement

The following technical supplement shows results for the U.S. as a whole as well as scenario figures not shown in the body of the main report for Florida.

U.S. Results

Figure 30 E&I CO2 emissions trajectories – U.S.

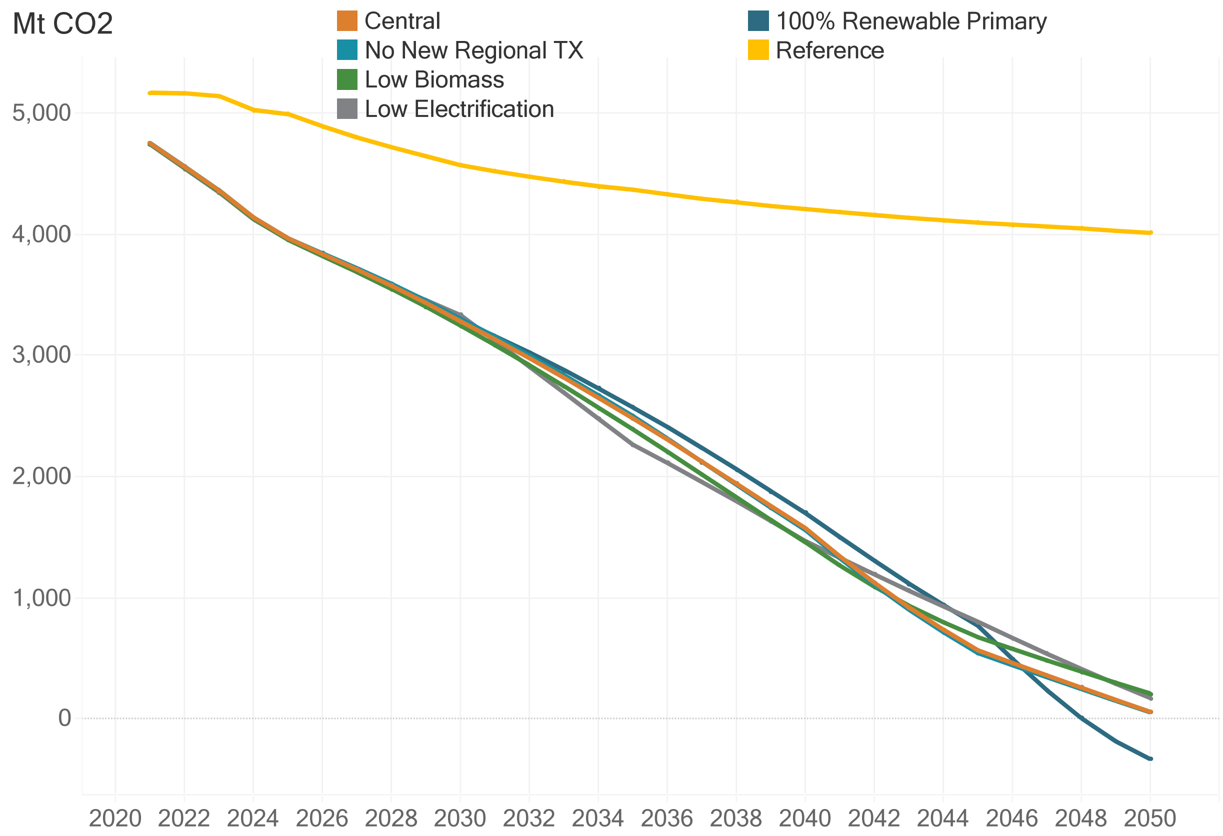


Figure 31 CO2 emissions by final energy/emissions category

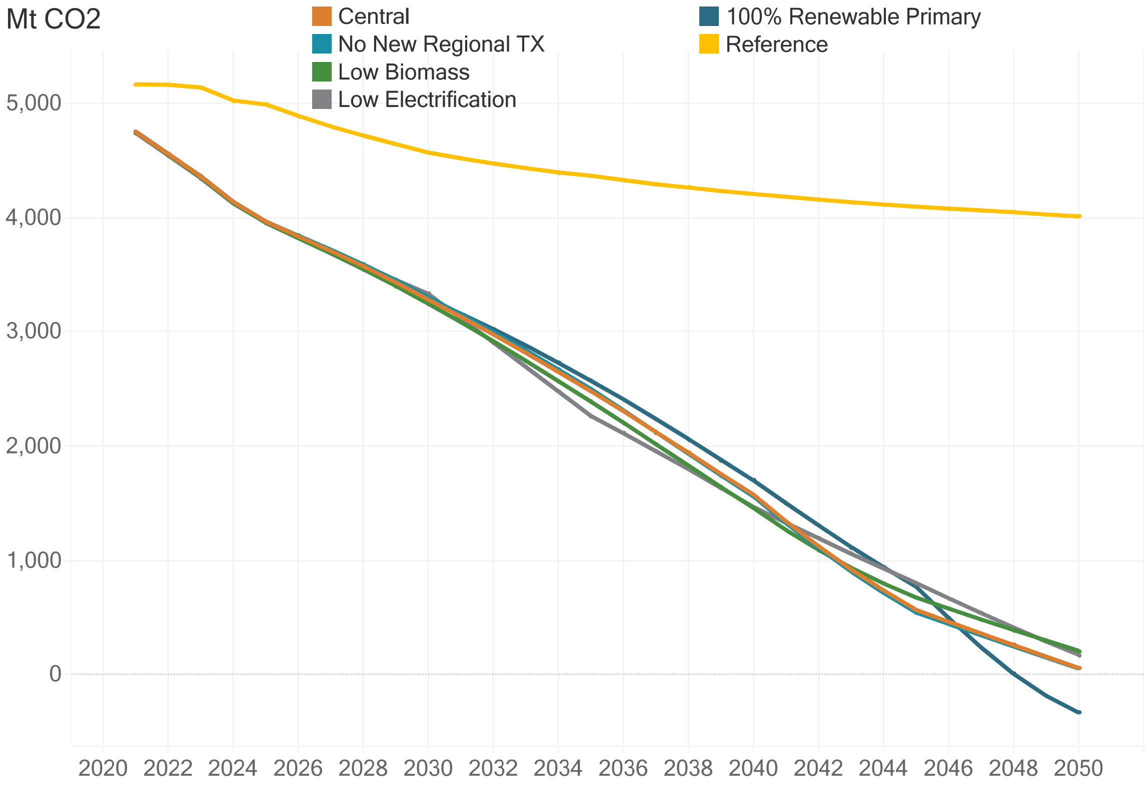


Figure 32 Cumulative E&I CO2 emissions trajectories

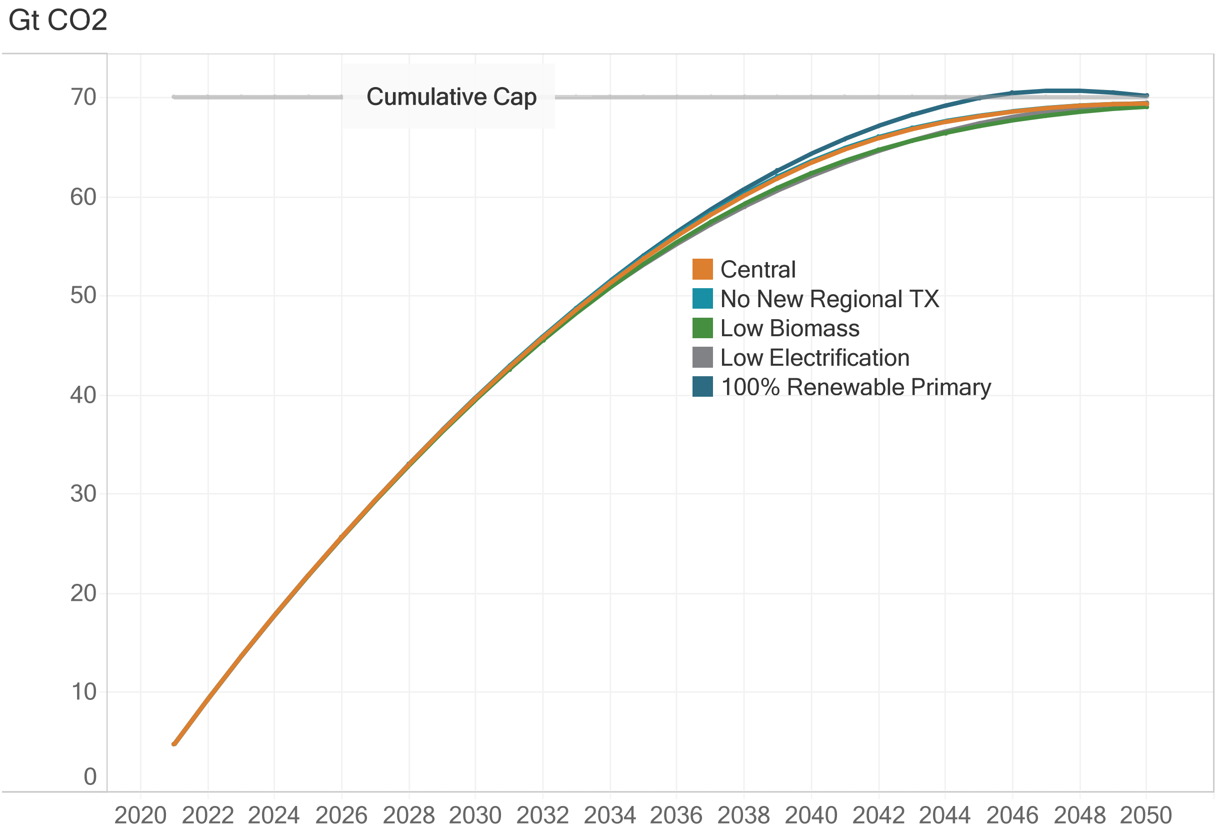


Figure 33 Four pillars of deep decarbonization – U.S.

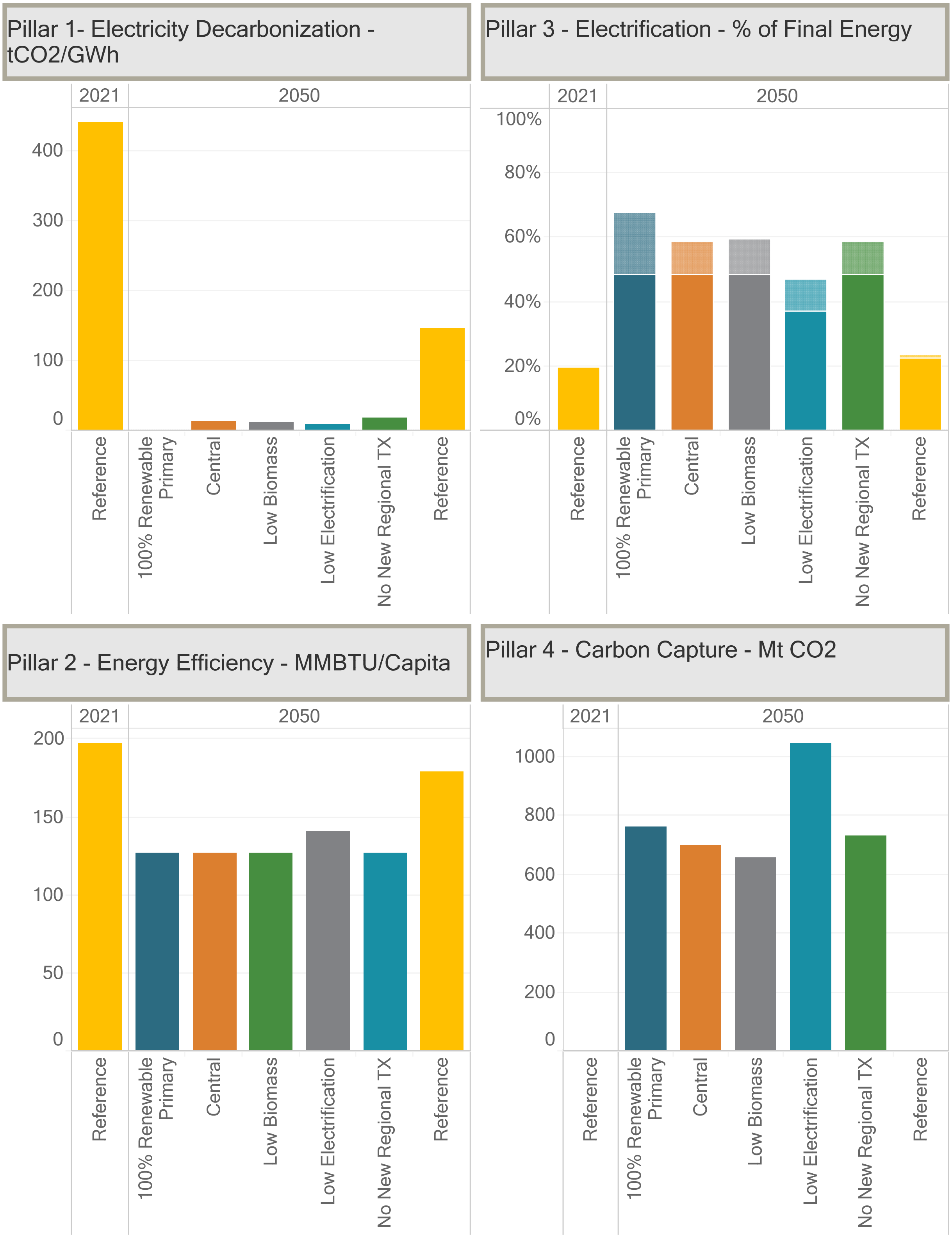


Figure 34 Final and primary energy demand for all scenarios from 2021 – 2050 – U.S.

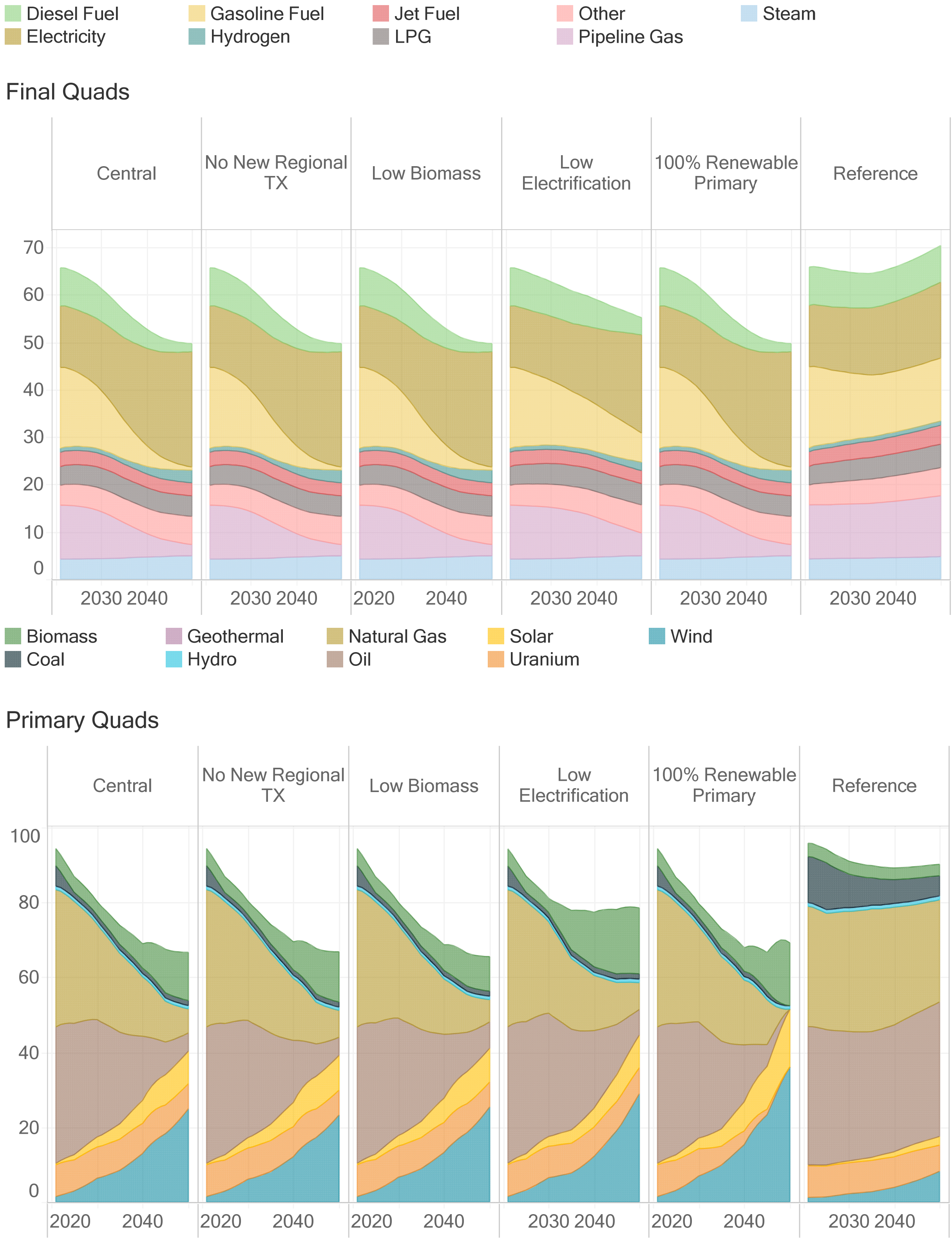


Figure 35 Components of emissions reductions in the Central scenario – U.S.

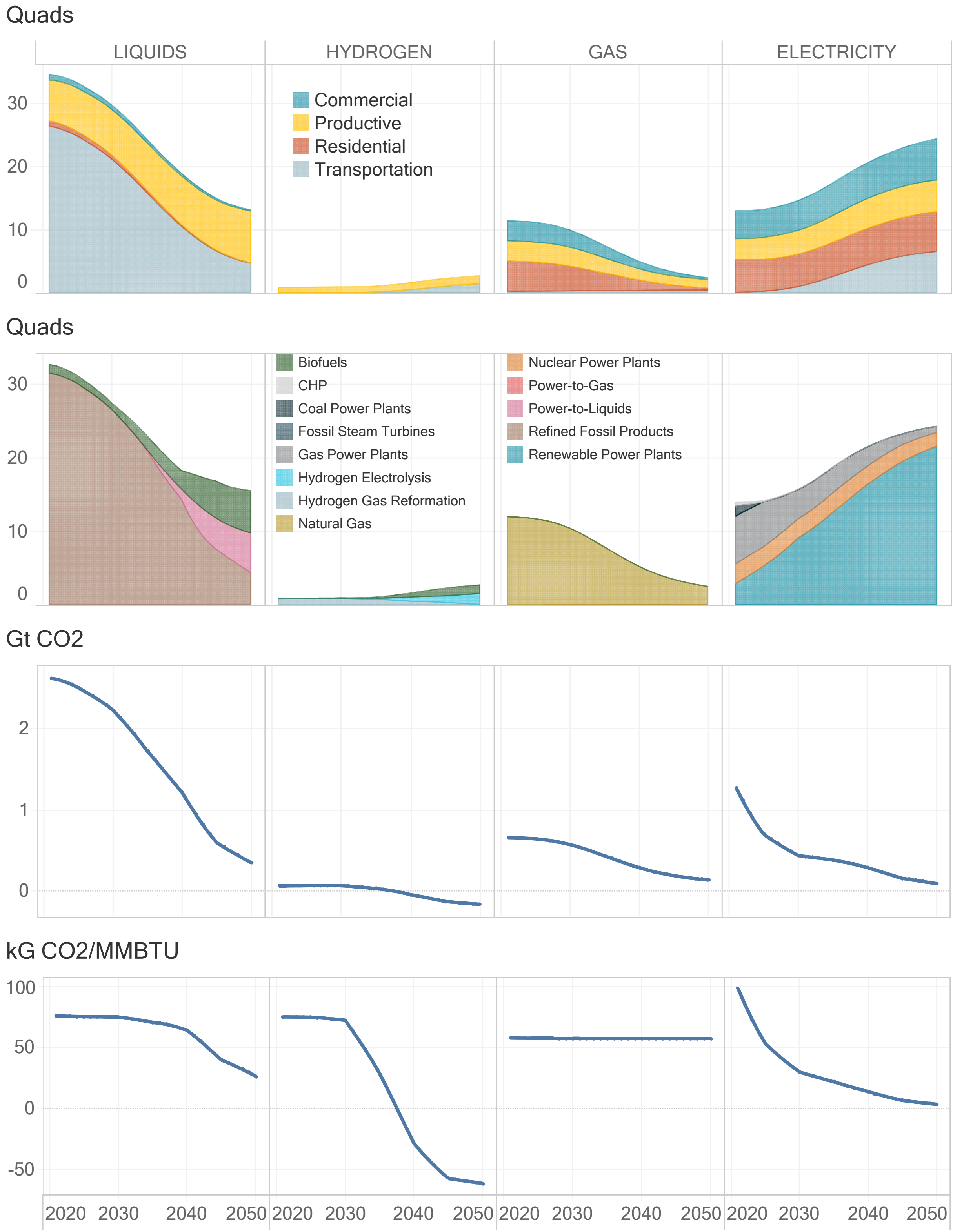


Figure 36 Components of emissions reductions in the Low Biomass scenario – U.S.

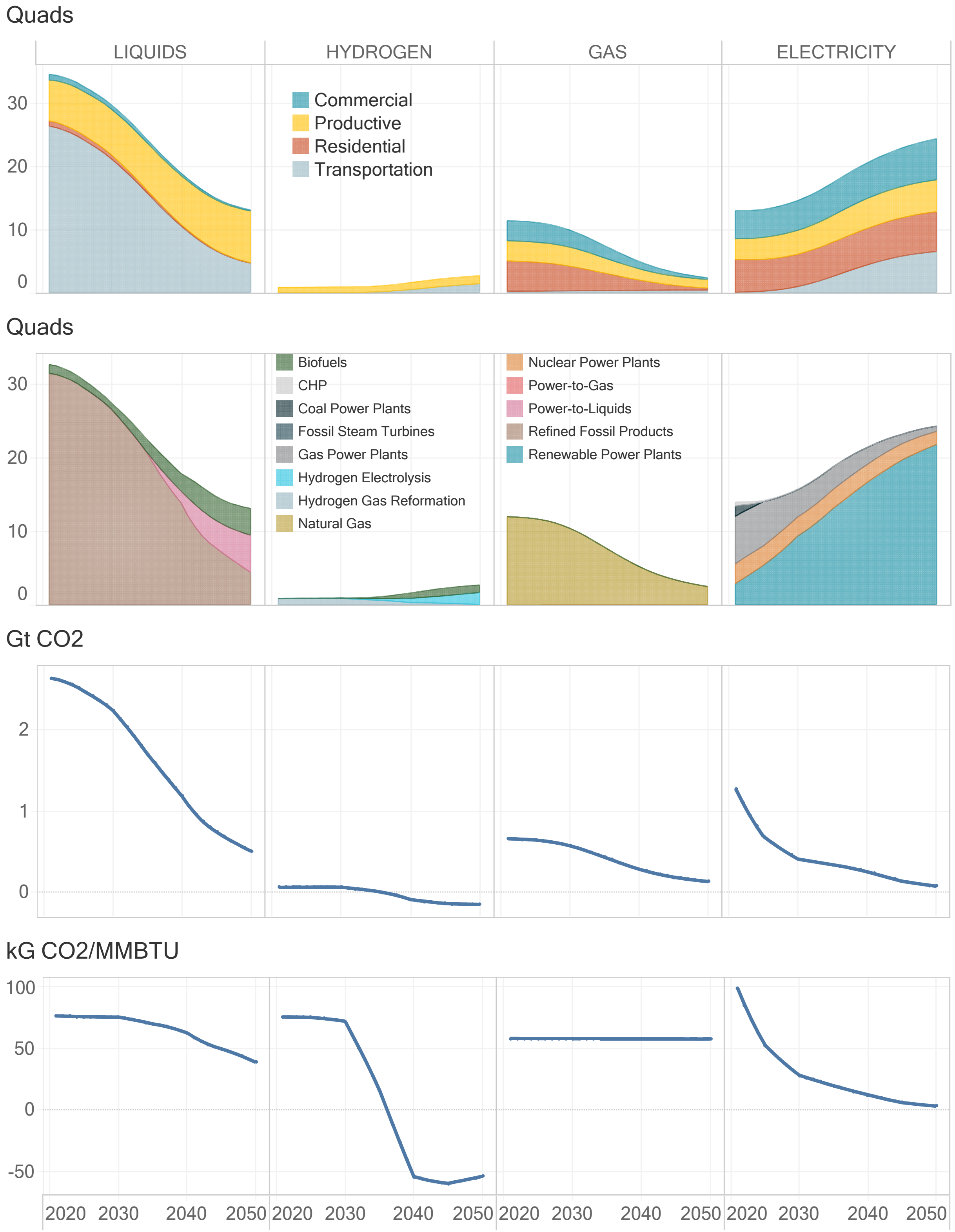


Figure 37 Components of emissions reductions in the Low Electrification scenario – U.S.

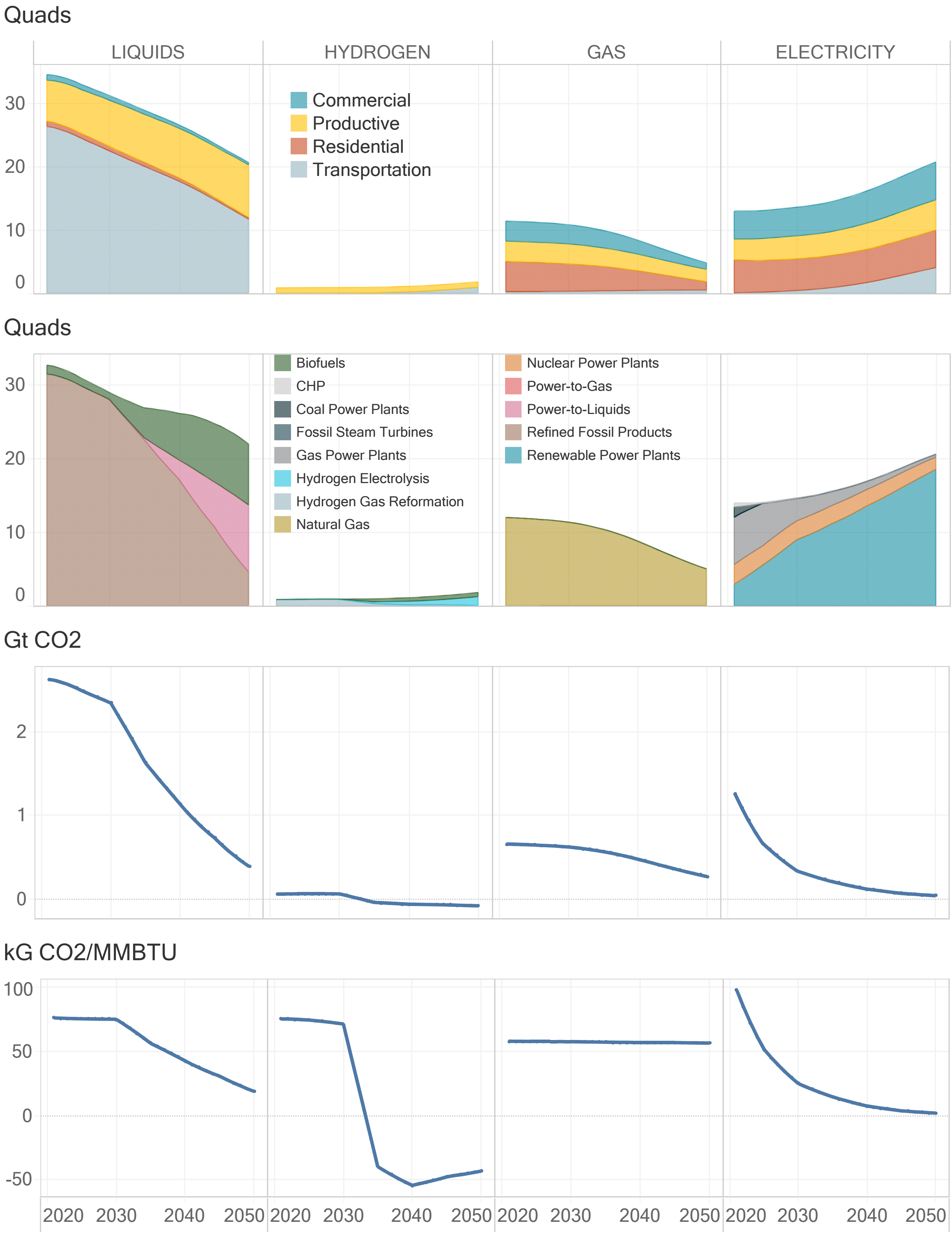


Figure 38 Components of emissions reductions in the No New Regional TX scenario – U.S.

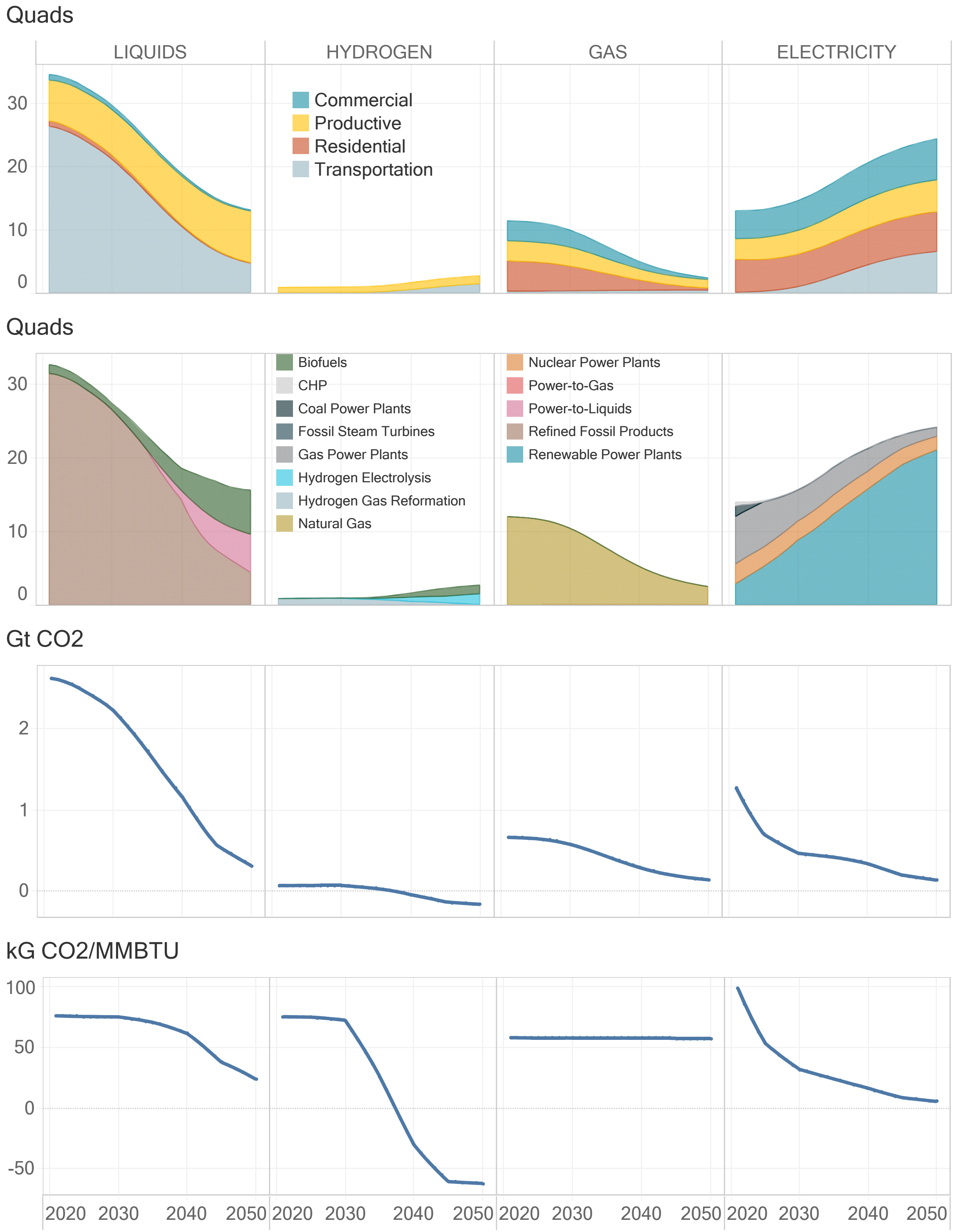


Figure 39 Components of emissions reductions in the 100% Renewable Primary scenario – U.S.

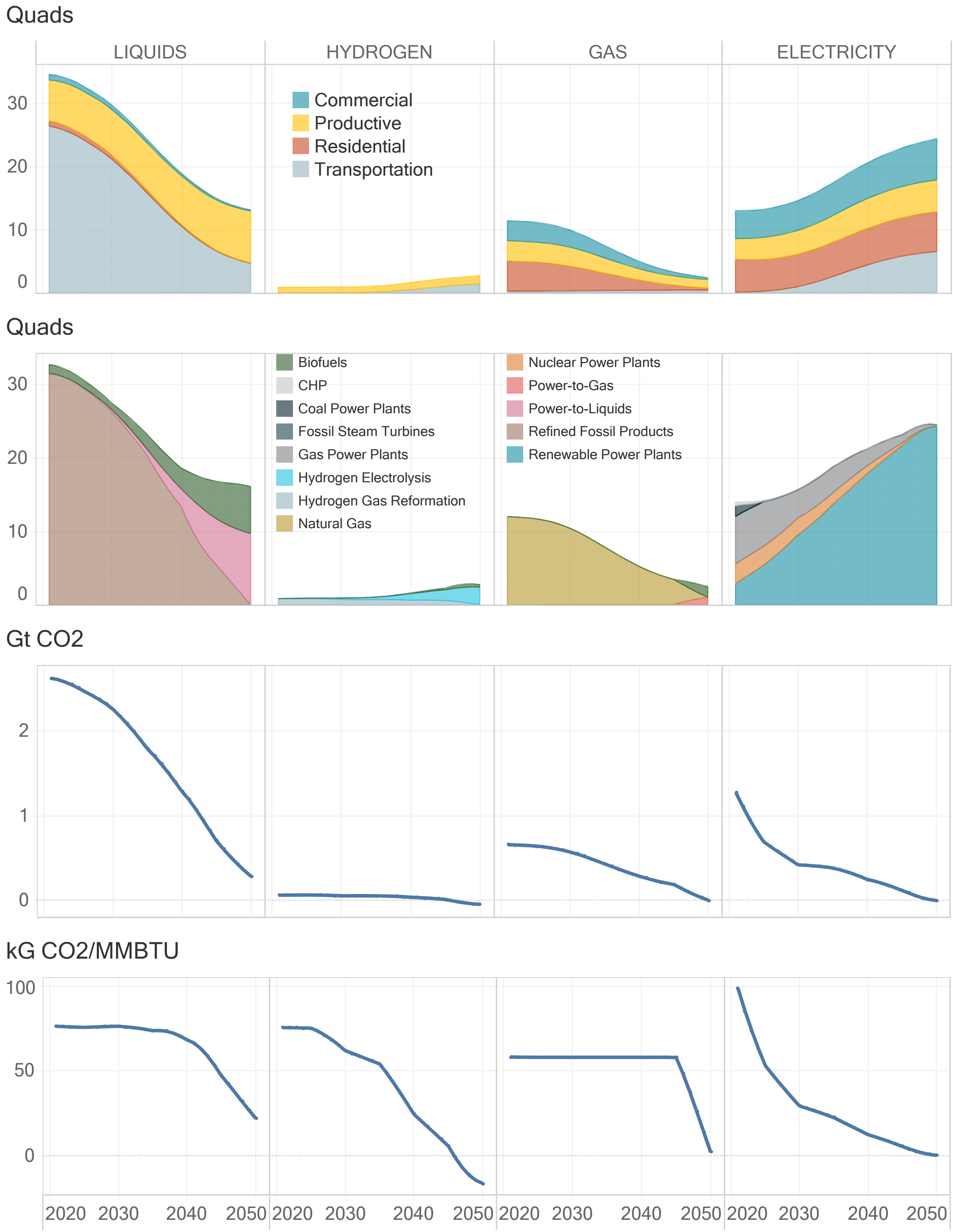


Figure 40 Annual net system cost premium above baseline in $2018 and as % of GDP – U.S.

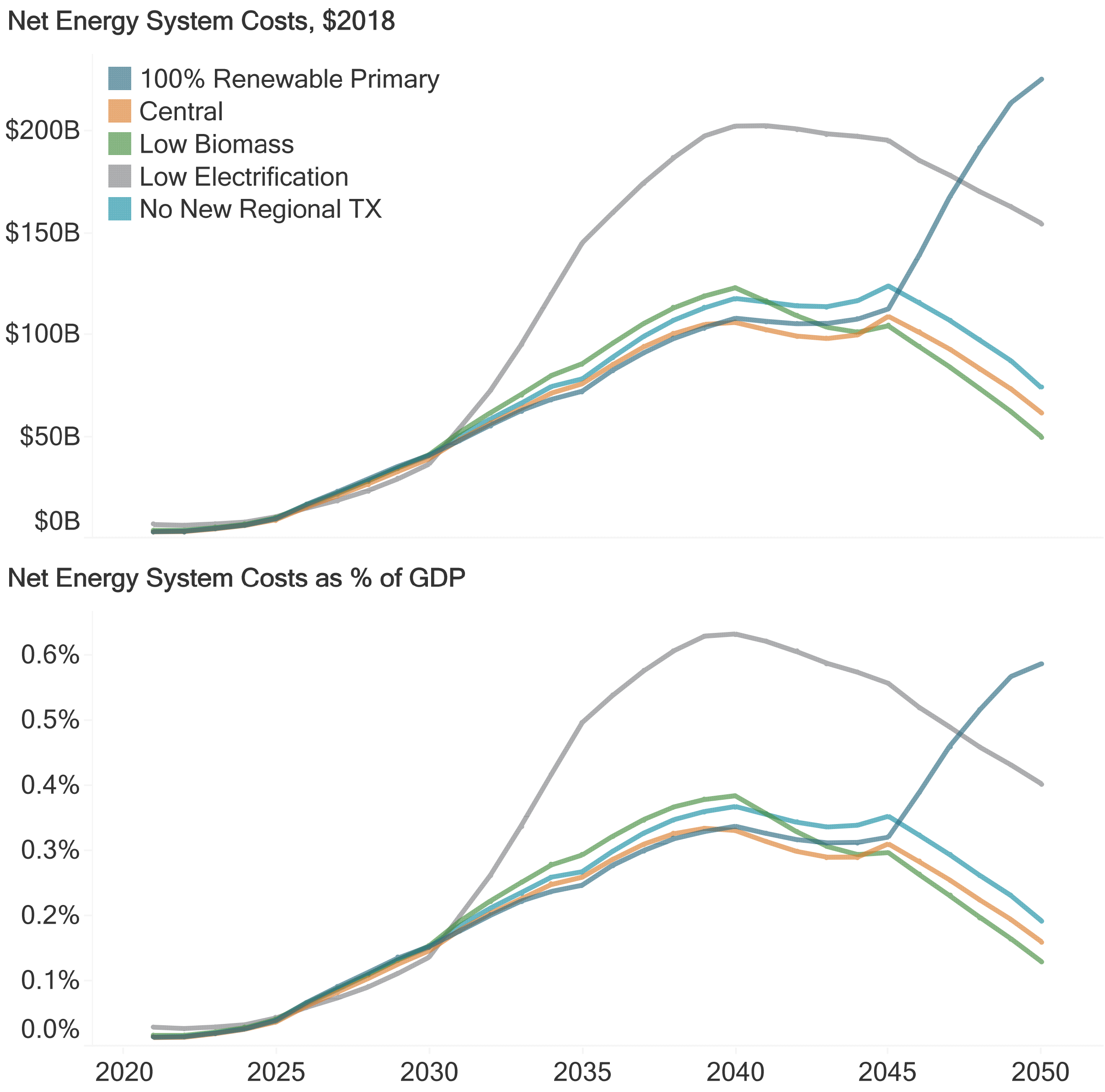


Figure 41 Net Change in E&I System Spending – U.S.

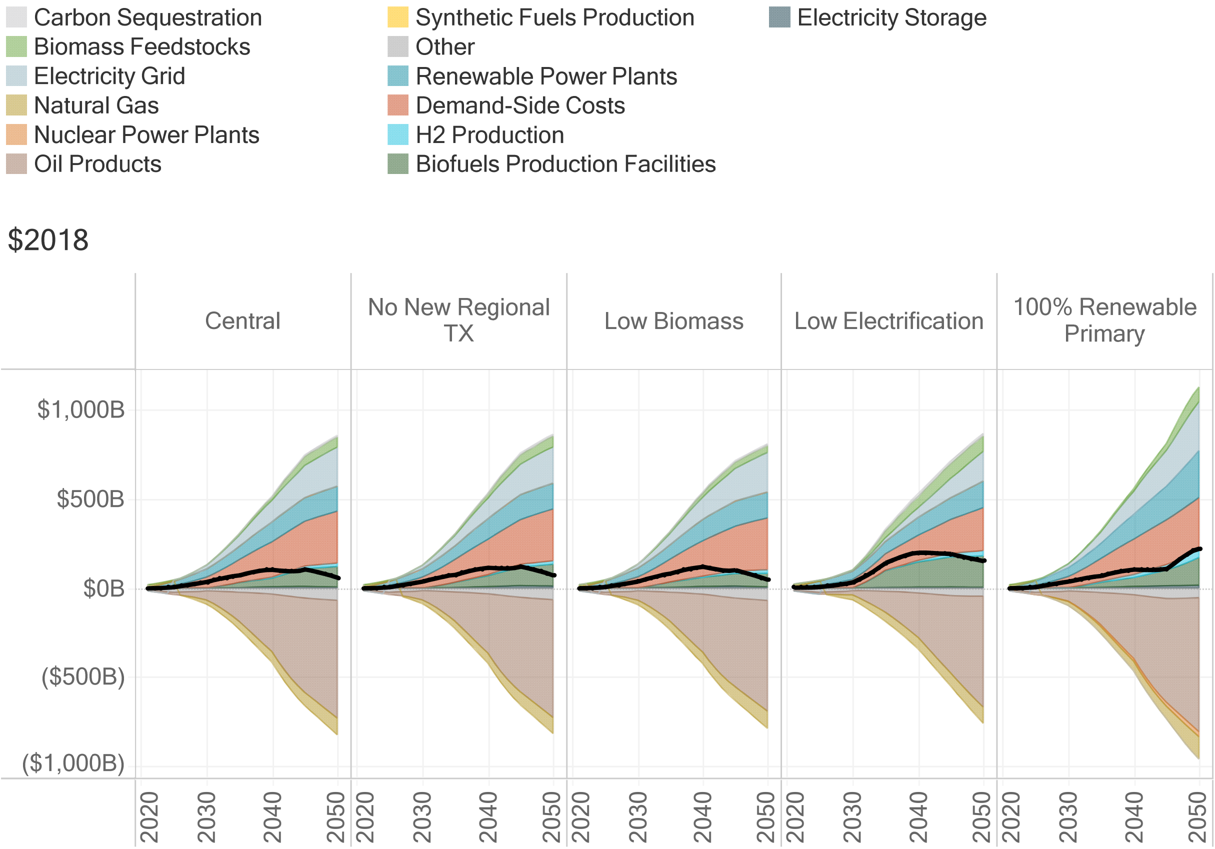


Figure 42 Total energy system costs as % of GDP –historical and projected – U.S.

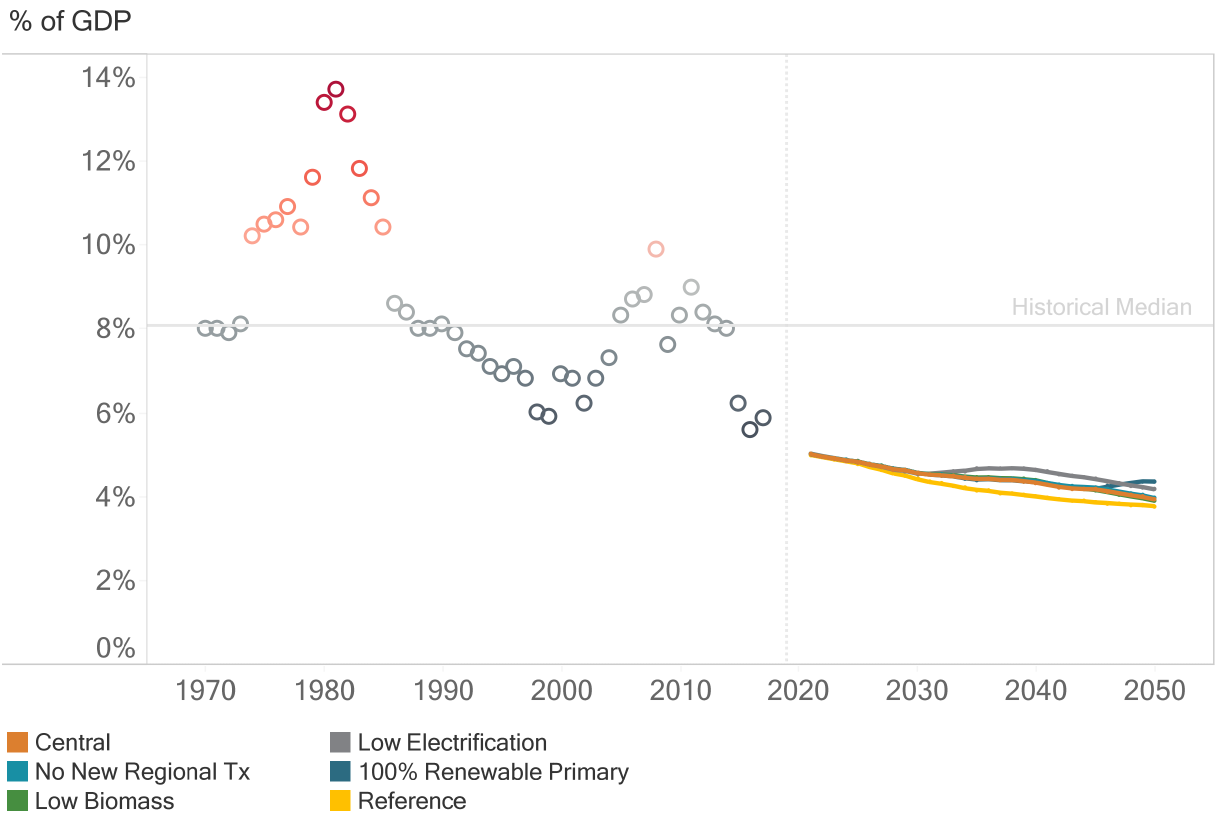


Exhibit D:

Expert Report of Dr. Jim Williams

EXPERT REPORT
OF
JAMES H. WILLIAMS, Ph.D.

Associate Professor, University of San Francisco
Director of Deep Decarbonization Pathways Project

Kelsey Cascadia Rose Juliana; Xiuhtezcatl Tonatiuh M.,
through his Guardian Tamara Roske-Martinez; et al.,
Plaintiffs,

v.

The United States of America; Donald Trump,
in his official capacity as President of the United States; et al.,
Defendants.

IN THE UNITED STATES DISTRICT COURT
DISTRICT OF OREGON

(Case No.: 6:15-cv-01517-TC)

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TABLE OF ACRONYMS AND ABBREVIATIONS

80 x 50:	80% reduction in greenhouse gas emissions by 2050
BAU:	business as usual
BEV:	battery electric vehicle
C:	Celsius
CCS:	carbon capture and storage
CH_4:	methane
CO_2:	carbon dioxide
CO_2e:	carbon dioxide equivalent
DDP-LAC:	Deep Decarbonization Pathways for Latin America and the Caribbean
DDPP:	Deep Decarbonization Pathways Project
Decarbonization:	deep reductions in greenhouse gas emissions from a system
EIA:	Energy Information Agency
FCV:	hydrogen fuel cell vehicle
GDP:	gross domestic product
GHG:	greenhouse gas
ICE:	internal combustion engine
IDDRI:	Institute for Sustainable Development and International Relations
IPPC:	Intergovernmental Panel on Climate Change
NEMS:	National Energy Modeling System
ppm:	parts per million
PV:	photovoltaic – a type of solar electric generating technology
SDSN:	Sustainable Development Solutions Network

INTRODUCTION

I, James H. Williams, have been retained by the Plaintiffs to provide expert testimony regarding the feasible pathways to achieve deep decarbonization of the U.S. energy system in line with best available science for stabilizing the climate system, and the policies that could be used to achieve this outcome. In this report, I examine how the federal government, including the agencies listed as Defendants in this case, can transform the U.S. energy system from one powered by fossil fuels to one powered by renewable energy and other low carbon forms of energy, if it plans for, and implements policies to achieve, that objective.

This expert report contains my opinions, conclusions, and the reasons for them. A copy of my full CV is attached as **Exhibit A**. A current and complete copy of a list of publications I authored or co-authored within the last ten years is attached as **Exhibit B**. In preparing this expert report, I have reviewed a number of documents. My expert report contains a list of citations to the documents that I have used or considered in forming my opinions, listed in **Exhibit C**.

In preparing my expert report and testifying at trial, I am deferring my expert witness fees to be charged to the Plaintiffs given the financial circumstances of these young Plaintiffs. If a party seeks discovery under Federal Rule 26(b), I will charge my reasonable fee of $300 per hour for the time spent in addressing that party's discovery. I have not provided previous testimony within the preceding four years as an expert at trial or by deposition.

The opinions expressed in this expert report are my own and are based on the data and facts available to me at the time of writing, as well as based upon my own professional experience and expertise. All opinions expressed in it are to a reasonable degree of scientific certainty, unless otherwise specifically stated. Should additional relevant or pertinent information become available, I reserve the right to supplement the discussion and findings in this expert report in this action.

QUALIFICATIONS

I, James H. Williams, currently serve as Associate Professor in the graduate program in Energy Systems Management at the University of San Francisco. I also serve as Director of the Deep Decarbonization Pathways Project (DDPP) for the Sustainable Development Solutions Network (SDSN). The DDPP is an international consortium of research teams that was convened at the request of the United Nations Secretary General and is led by the SDSN and the Institute for Sustainable Development and International Relations (IDDRI). I also consult with Evolved Energy Research on energy planning.

I received my B.S. in Physics from Washington and Lee University, and my M.S. and Ph.D. in Energy and Resources from U.C. Berkeley. I have spent the past three decades studying various aspects of energy planning, energy technology applications, and energy policy and regulation, most recently as Chief Scientist at the San Francisco consulting firm Energy and Environmental Economics, Inc. (E3).

I was the Principal Investigator for two studies, *Pathways to Deep Decarbonization in the United States* (2014) and *Policy Implications of Deep Decarbonization in the United States* (2015), funded by the Earth Institute at Columbia University. As the Principal Investigator, I led a research team from E3, Lawrence Berkeley National Laboratory, and Pacific Northwest National Laboratory in the preparation of these studies.

In 2007, I led an analysis for the State of California on greenhouse gas (GHG) emission reduction strategies, which became a key input into implementation of Assembly Bill 32, the State's main law governing mitigation of climate change. I was lead author of a 2012 article in the journal *Science* that analyzed California's options for reducing GHGs 80% below 1990 levels by 2050, the target set by AB 32. In 2017, I was a contributing author of a study commissioned by the State of Washington Governor's office on options for reducing GHGs 80% below 1990 levels in that state by 2050.

As a scientist who also has a background in Asian studies, I previously served as Associate Professor of International Environmental Policy at the Middlebury Institute of International Studies, where my research addressed the technical and institutional challenges of reducing carbon emissions from China's power sector.

I have worked with numerous international forums and research teams. For example, I am the lead author of a 2018 technical report on expanding the coordination of deep decarbonization activities between the northeastern states of the U.S. and the Canadian province of Quebec. I am a technical advisor to the Inter-American Development Bank on their Deep Decarbonization Pathways for Latin America and the Caribbean (DDP-LAC) project, which expands on the work done by the DDPP under my leadership.

I served as the Program Director for the China-U.S. Climate Change Forum held at U.C. Berkeley in 2006, on the Steering Committee for the Asia Society's *Roadmap for California-China Collaboration on Climate Change* starting in 2013, and the U.S.-China Collaboration on Clean Air Technologies and Policies starting in 2015. I have co-authored several technical journal articles and policy analyses with colleagues at universities and research institutes in China.

Since 2004, I have served on the Board of Advisors of Palangthai, a Thailand-based NGO focused on clean and equitable energy development in southeast Asia. Since 2005, I have served on the Board of Advisors of EcoEquity, a U.S.-based NGO focused on improving international climate equity by producing analyses that highlight equity issues, and by developing practical proposals for equitable climate policies.

I have, in the past or currently, served as an advisor or invited member for numerous energy or climate change-related committees and task forces, including the California's Energy Future Policy Committee of the California Council for Science and Technology, the California Climate Policy Modeling Forum, and the American Geophysical Union Energy Engagement Task Force.

I have served as a reviewer for scholarly publications including *Nature Climate Change, Energy Policy, Environmental Science and Technology, Energy, Pacific Affairs, and China Quarterly.*

EXECUTIVE SUMMARY

Federal government policy can transform the U.S. energy system from one powered by fossil fuels to one powered by renewable and other low carbon energy sources, if the federal government takes that path. My past work has already demonstrated that it is technically feasible to develop and implement a plan to achieve an 80% greenhouse gas reduction below 1990 levels by 2050 in the United States. Multiple alternative pathways exist to achieve these reductions using existing commercial or near-commercial technologies; however, to be successful, each pathway requires the leadership of the federal government, including the agencies listed as Defendants in this case, and comprehensive systemic planning as well as periodic interim targets that must be met to achieve the long-term (such as mid-century and beyond) targets. We determined in our studies that reductions can be achieved through high levels of energy efficiency, decarbonization of electric generation, electrification of most end uses, and switching the remaining end uses to lower carbon fuels. The cost of achieving this level of reductions within this timeframe is affordable, estimated to have an incremental cost for supplying and using energy in the U.S. equivalent to 0.8% of a forecast 2050 GDP, with a range of -0.2% to +1.8% of GDP. These incremental costs do not include potential non-energy savings and benefits including, for example, avoided human and infrastructure costs of climate change and air pollution. Our 80 x 50 analysis demonstrated that the changes required to achieve this level of emissions reductions will support the same level of energy services and economic growth as a reference case based on the U.S. Department of Energy's *Annual Energy Outlook*. Starting immediately on the deep decarbonization path would allow infrastructure replacement to follow natural replacement rates, reducing costs and allowing gradual consumer adoption.

The target of 80% reductions below 1990 levels by 2050 is used by many countries. However, climate scientists have shown that this level of reductions is not sufficient to avoid dangerous anthropogenic interference with the climate system over the long term, and the negative impacts on human, ecological, and economic health that would result from that. My research team is therefore currently modeling the requirements to meet a more stringent target in which fossil fuel CO_2 emissions in 2050 are reduced by as much as 96% below current levels, consistent with achieving an atmospheric CO_2 concentration of 350 ppm by 2100. In my expert opinion, based upon our 80 x 50 work and our early modeling results, I believe that this level of reductions is technologically feasible using current and emerging technologies; that it will likely have a higher per-unit cost for the remaining reductions beyond 80% by 2050; that it will likely require some early retirements of fossil fuel infrastructure; and that it could be aided by changes in consumption of energy services and/or rates of consumption growth, but will not diminish basic quality of life and standards of living.

EXPERT OPINION

Scientific evidence makes it increasingly clear that human-caused climate change requires rapid, aggressive mitigation action if humanity is going to avoid the most catastrophic climate change outcomes. Government policy, and the environment it creates for business and individual actions and investments, drives the shape and future of the U.S. energy system. These same influences can move the U.S. energy system decisively away from fossil fuels to an economy powered by renewable and other low carbon energy sources, if the federal government, including the agencies listed as Defendants in this case, takes that path.

I coined the term "deep decarbonization" and have studied it extensively. As the Principal Investigator for the U.S. Deep Decarbonization Pathways Project modeling and scenarios research conducted from 2013 to 2015, I led a team of researchers from Energy and Environmental Economics, Inc., Lawrence Berkeley National Laboratory, and Pacific Northwest National Laboratory. This research was focused on achieving reductions in GHG emissions 80% below 1990 levels by 2050, a target that many governments around the world have adopted.

Based on the lessons from this research, we now know it is entirely possible to rapidly remove greenhouse gas emissions from the U.S. economy while maintaining a healthy economy and modern standard of living. We also know that even deeper emission cuts beyond 80%, which science indicates is necessary to avoid dangerous anthropogenic interference with the climate system, are feasible with greater costs. We also know that there are multiple pathways to achieve deep decarbonization in the U.S., but each of them requires federal government leadership and comprehensive systemic planning as well as periodic interim targets that must be met to achieve the long-term targets (such as mid-century and beyond).

United States Deep Decarbonization Research and Conclusions

The U.S. Deep Decarbonization Pathways Project modeling and scenarios research conducted from 2013 to 2015 demonstrated the feasibility and affordability of rapidly transitioning away from fossil fuels. The research focused on achieving reductions in GHG emissions 80% below 1990 levels by 2050 (referred to hereafter as "80 x 50").

Our research asked the following questions:

a) Is achieving this target technically feasible, given realistic constraints?

b) What changes in physical infrastructure and technology are required?

c) What is the expected cost of these changes?

d) What are the policy and political economy implications of these changes?

We made the following assumptions:

a) Future U.S. population, gross domestic product, and energy service demand are consistent with the U.S. Department of Energy's *Annual Energy Outlook* Reference Case, a transparent, conservative, and well-vetted long-term forecast produced using the U.S. Energy Information Agency's National Energy Modeling System (NEMS).

b) Only commercially-demonstrated or near-commercial technologies are used. Their modeled costs and performance are based on those in the *Annual Energy Outlook* and other conservative and well-vetted public sources, such as studies by the National Academies of Science and Engineering. Changes in forecast technology and fuel prices are addressed through sensitivity analyses.

c) The time required to change the emissions characteristics of the U.S. energy system – sometimes referred to as its technological inertia – is well-represented in the analysis by the rate at which energy-related infrastructure and equipment is retired and replaced by new equipment, using an annual stock-rollover model and following conventional turnover times based on well-vetted public sources. Equipment and infrastructure that is retired before the conventionally accepted end of its economic life is subject to full cost recovery and appears as a cost in the economic modeling.

d) Electricity system operability and reliability is well-represented in the analysis using a regionally-specific hourly dispatch model of the electricity system. All future scenarios contain realistic costs of balancing supply and demand, including in scenarios with high levels of inflexible generation, such as intermittent renewable energy.

e) Environmental limits are adhered to as constraints on low-carbon resources. For example, future use of biomass resources and hydroelectric resources are constrained by transparent and well-vetted analysis conducted by the U.S. Department of Energy and its associated national laboratories. The terrestrial carbon sink on managed lands is held constant at 2012 levels in the Environmental Protection Agency's U.S. GHG inventory (the most recent available at the time of analysis).

f) All emissions reductions are the result of physical measures within the U.S., not "offsets" related to emission reductions in other countries. All emissions reductions involve the replacement of one kind of infrastructure or equipment with a higher-efficiency and/or lower carbon alternative, and this change entails a net cost that includes all conventionally assumed factors such as overnight cost, operating and maintenance cost, and finance cost over the lifetimes of the equipment involved.

Below are the key conclusions of our 80 x 50 study:

a) It is technically feasible to reduce total U.S. GHG emissions (in CO_2e) to 80% below 1990 levels by 2050. This includes reducing energy CO_2 emissions below 750 Mt, which is 84% less than the 1990 level.

b) Incremental changes in energy use and policy will not be sufficient to drive this level of change (and in some cases, may prove counter-productive). Rather, a complete transformation of the energy system is required.

c) Achieving the targets relies on three principal strategies:

(1) *Highly efficient end use of energy in buildings, transportation, and industry.* Energy intensity of GDP (energy consumed per dollar of GDP) must decline by 70% from now to 2050, with final energy use reduced by 20% despite

forecast increases of 40% in population and 166% in GDP. Relative to the reference case, 2050 energy intensity and final energy use are 33% lower.

(2) *Nearly complete decarbonization of electricity, and reduced carbon in other kinds of fuels.* The carbon intensity of electricity must be reduced by at least 97%, from more than 500 g CO_2/kWh today to 15 g CO_2/kWh or less in 2050.

(3) *Electrification where possible and switching to lower-carbon fuels otherwise.* The share of end-use energy coming directly from electricity or fuels produced from electricity, such as hydrogen, must increase from less than 20% in 2010 to over 50% in 2050. Deeply decarbonized electricity and other fuels must displace most direct fossil fuel combustion in the absence of carbon capture and storage.

d) We examined four different scenarios with different technology mixes – referred to as "High Renewable," "High Nuclear," "High Carbon Capture and Storage (CCS)," and "Mixed" –scenarios - that met the 80 x 50 target. This demonstrates that multiple pathways exist to achieve these reductions using existing commercial or near-commercial technologies, and that the results are robust in the absence of any given technology or technologies. Many more scenarios that meet the target are possible.

e) Deep decarbonization requires ongoing replacement of conventional fossil fuel-based energy supply and end use infrastructure and equipment with efficient, low emissions technologies. In all four scenarios, the 80 x 50 target could be achieved through natural replacement at the end of the existing infrastructure's economic life, and early retirement was not required. However, making any new investments in fossil fuel infrastructure *today* risks the creation of stranded assets.

f) The 80 x 50 target was demonstrated to be affordable. In the year 2050, the net energy system cost—the net change in capital, fuel, and operating costs of supplying and using energy — across the four deep decarbonization scenarios has an average median value of $300 billion, equivalent to 0.8% of a forecast 2050 GDP of $40 trillion. Uncertainty analysis shows a range across scenarios of -0.2% to +1.8% of GDP (negative $90 billion to $730 billion).[1]

g) The 80 x 50 reduction targets could be met without requiring changes in people's behaviors or consumption patterns. That means that the physical energy system will need to change but the use of "energy services" in the U.S. economy would not have to in order to meet an 80 x 50 target. Deep decarbonization will profoundly transform the physical energy system of the U.S. On average across the four scenarios, fossil fuel use decreases by two-thirds from today while decarbonized energy supplies expand by a

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[1] This represents the interquartile range of a Monte Carlo simulation of key cost parameters, primarily technology costs and fossil fuel prices.

factor of five.[2] However, this can be achieved while supporting all anticipated demand for energy services – for example, current or higher levels of driving, home heating and cooling, and use of appliances.

h) Deep decarbonization would profoundly transform the U.S. energy economy, in terms of what money is spent on and where investment will flow. In contrast to today's system in which more than 80% of energy costs go to fossil fuel purchases, in a deeply decarbonized system more than 80% of energy costs will go to fixed investments in low-carbon infrastructure such as wind generation and electric vehicles. However, the net change in consumer costs for energy services is shown to be relatively small because of savings from avoiding conventional energy costs.

i) Deep decarbonization would have a small net cost relative to U.S. GDP, as increased spending on low-carbon infrastructure and equipment is offset by reduced spending on fossil fuels. In all deep decarbonization scenarios, U.S. energy costs actually decrease as a share of GDP over time, from about 7% in 2015 to about 6% in 2050.

j) While the overall impact on energy costs is modest, the transition to deep decarbonization nonetheless offers significant benefits for the U.S. macro-economy, such as insulation from oil price shocks, even without counting the potential economic benefits of avoiding severe climate change and avoiding the public health costs of fossil fuel-related air pollution.

k) Though not a part of our initial research, a third party conducted an analysis of impacts of the deep decarbonization scenarios we modeled on the U.S. macro-economy in terms of jobs, household income, and GDP (ICF International, 2015). The study found that, compared to business as usual, deep decarbonization scenarios would result in net gains in U.S.-wide employment (1 million more jobs by 2030, up to 2 million more jobs by 2050), gains in GDP (0.6% by 2030, up to 0.9% by 2050), and increased disposable household income ($300 by 2030, up to $600 by 2050).

l) As part of our research, we discovered a number of important policy implications of deep decarbonization in the U.S. Some of the key policy challenges indicated by our analysis include:

  - *Sustained transformation*. Deep decarbonization requires the economic intensity of GHG emissions to decrease 8% per year, and per capita emissions to decrease 5.5% per year.[3] These rates of change can be achieved technically and at an

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[2] Fossil fuel use is reduced by approximately 80% from today in the high renewables scenario, 70% in the mixed and high nuclear scenarios, and 40% in the high CCS scenario.

[3] For comparison, from 2014 to 2015, economic intensity of energy-related CO_2 emissions fell by 5.2% per year and per capita emissions fell by 3.3% per year. Over the prior decade, the average rate of economic intensity decline was 2.4% per year, and per capita decline was 1.9%

affordable cost, but *require a sustained commitment to infrastructure transformation over decades*. Incremental improvements that do not facilitate complete transformation are likely to result in technology lock-in and emissions dead ends (**Figure 1**). Pathway A, the dotted black line, represents a linear trajectory from 2010 emissions of energy-related CO_2 to the 80 x 50 target level. Pathway B, the dotted red line, represents policies that reduce emissions in the short-term but do not lead to deep decarbonization in the long-term. Some examples of potential dead-ends include a pathway focused solely on energy efficiency in buildings that does not also include end-use electrification; a transition from coal to natural gas power generation without a further transition to zero carbon generation; or improvement in the fuel economy of gasoline internal combustion engine vehicles without widespread deployment of electric or fuel cell light duty vehicles.

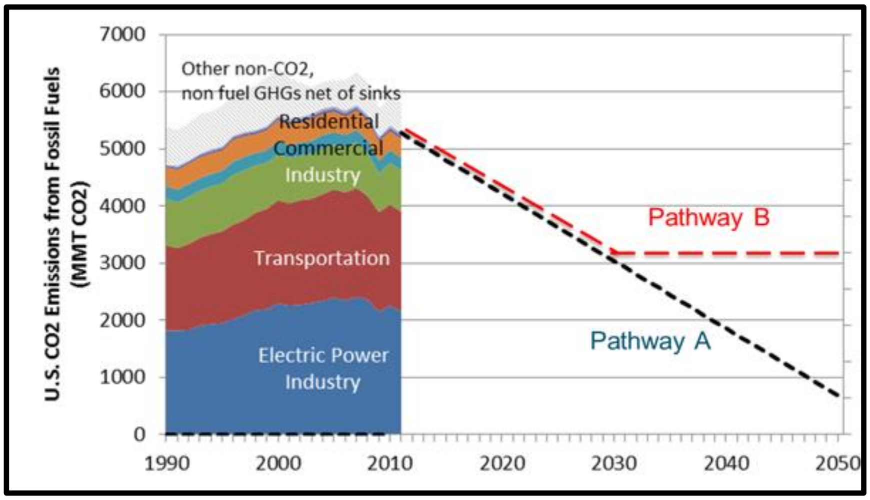

Figure 1*: Illustrative Deep Decarbonization 80 x 50 Trajectory (Pathway A) and "Dead End" Trajectory (Pathway B).*

A sustained transformation requires stable policy and a predictable investment environment, and it also requires *planning*. Deferring responsibility to a carbon market, *ad hoc* decisions, and inconsistent incentives are not likely to produce a sustained or sufficiently rapid transition to full decarbonization.

- *Timely replacement*. 80 x 50 could be achieved in the U.S. without retiring existing equipment before the end of its economic lifetime, defined as the time required to recoup initial capital investment including financing costs.[4] However,

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per year. See EIA, *US Energy-Related Carbon Dioxide Emissions 2015*, available at https://www.eia.gov/environment/emissions/carbon/.

[4] While this indicates that it is possible to deeply decarbonize the economy without creating the problem of stranded investments, the question of what to do with fully depreciated coal plants

because these lifetimes are long, there is only one natural replacement cycle before mid-century for some of the most important infrastructure, such as electric power plants, buildings, and industrial boilers. Failure to replace retiring infrastructure with efficient and low-carbon successors would lead either to failure to meet emissions goals or to potentially costly early retirement of the replacement equipment.

- *Cross-sector coordination*. As deep decarbonization proceeds, interactions between mitigation measures in different sectors (for example, electricity and transportation) become dominant in determining overall emissions. Purely sectoral policies that do not recognize the importance of these interactions will produce sub-optimal outcomes, yet there is currently little institutional coordination across sectors. Anticipatory development of shared institutional structures, both market and regulatory, will be required for efficient coordination of operations, planning, investment, and research.

- *Integration of supply- and demand-side planning and procurement*. Related to the cross-sector coordination challenge is the supply-demand side challenge within the electricity sector. Maintaining reliability in an electricity system with high levels of wind and solar, or baseload nuclear, will require corresponding levels of flexible demand, such as EV charging and hydrogen production. Currently these are seen as outside the purview of electricity planning. To build a low-carbon system that matches supply and demand resources at the required spatial and time scales, however, will require integrated planning and procurement well beyond the scope of what is currently thought of as "integrated resource planning."

- *Suitable investment environment*. The annual investment requirement for low carbon and efficient technologies rises from under $100 billion today to over $1 trillion in a span of about 20 years. This is a large increase from the standpoint of energy sector capital investment, *but not from the standpoint of the share of investment in U.S. GDP as a whole*. Financial markets can supply this level of capital *if investment needs are anticipated and a policy framework is constructed that limits risk and ensures adequate returns*.

- *The right kinds of competition*. Competition is potentially an important tool for driving innovation and reducing costs, but poorly informed policies can lead to unproductive competition. An example of this is current policies that have biofuels competing with gasoline; in the long run, this will be a poor use of scarce biomass resources, because gasoline ICE vehicles have preferred substitutes such as BEVs and FCVs, while the biomass will be needed for production of low

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and other highly emitting equipment continuing to operate after their financial lifetimes are complete is a separate policy challenge.

carbon fuels used in applications that are difficult to electrify. Long-term pathways analysis will help policy makers and investors understand what types of competition have value. Federal policy will play an important role in driving market response.

- *High rates of consumer adoption*. Achieving necessary rates of consumer adoption of equipment ranging from heat pumps to alternative vehicles will require a combination of incentives, financing, market strategies, and supporting infrastructure. This requires a high level of public-private cooperation among, for example, government agencies, auto manufacturers, and utilities in rapidly expanding alternative vehicle markets in tandem with the expansion of fueling or charging infrastructure, not unlike the public-private cooperation that originally created the fossil-fuel based energy system and infrastructure supporting ICEs.

- *Cost reductions in key technologies*. Policy makers can drive cost reductions in key technologies by helping to create large markets. High production volumes drive technological learning, efficient manufacturing, and lower prices. This effect is already visible in battery storage and wind and solar PV generation. Large markets can be built through government procurement, technology standards, consumer incentives, coordinated research and demonstration, trade, and long-term policy certainty.

- *Cost increases faced by consumers*. Businesses, utilities, and policy makers have a mutual interest in limiting the level and rate of consumer cost increases during a low-carbon transition. Coordinating energy efficiency improvements with decarbonization of energy supplies limits increases in total consumer bills even if per unit energy prices increase.

- *Distributional effects*. A low-carbon transition policy can also minimize regressive cost impacts. Distributional effects across regions, sectors, and industries are largely a function of technology strategies, which can be tailored to mitigate these effects.

Going Beyond 80% Reductions by 2050

While most analyses of deep decarbonization, including our own, have focused on 80% reductions in greenhouse gas emissions by 2050, recent studies in climate science indicate that even this level of reductions will not be steep enough to prevent dangerous climate impacts. Hansen (2008, 2013, 2017) shows that returning atmospheric CO_2 concentrations to 350 parts per million (ppm) by 2100 will be required to restore the energy balance of the planet and lower the risk of dangerous anthropogenic interference with the climate system. This objective implies reductions in fossil fuel combustion CO_2 emissions as deep as 96% below present by 2050, in addition to enhanced negative emissions. Many other researchers have also proposed steeper reduction trajectories (e.g. Rogelj, 2017) to avoid the worst impacts of climate change. This is the subject of a forthcoming IPCC special report on limiting global warming above preindustrial temperatures to 1.5 degrees Celsius or less.

For these reasons, I, along with my deep decarbonization team and in collaboration with colleagues at Evolved Energy Research, have set out to describe the pathways needed to reach an emissions target consistent with these scientific analyses.

In my expert opinion, deep decarbonization beyond 80% by 2050 is feasible, and we are now undertaking the research and analysis to illustrate the possible technical and policy pathways. Based on my extensive experience with these and other decarbonization analyses, in my expert opinion, meeting a target as deep as 96% below 2018 levels by 2050 for fossil fuel CO_2 emissions:

- Is technologically feasible given current and emerging technologies
- Will require immediate and decisive action to develop and implement a plan to cut emissions in the near term in order to meet the target and not overspend a 350 ppm carbon budget
- Will have a higher unit cost for the remaining reductions beyond 80% by 2050
- Will likely require some early retirements of fossil fuel-based infrastructure and equipment
- Will require an unprecedentedly rapid build out of renewable generation capacity – potentially building out more renewable generation capacity on an annual basis for several years than the U.S. has in operation right now.
- Will require overproduction of renewable electricity generation in many hours due to the variable nature of their output – excess power that can be stored or used in other applications that reduce CO_2
- Will require rapidly minimizing coal-fired power generation in the near term
- May require a temporary expansion of natural gas generation as coal-fired generators are phased out, at the same time that rapid electrification of the transportation and building sectors cause demand for electricity to increase more rapidly than renewables can be deployed
- Will likely require an increasing share of new appliances, heaters, and other electricity-consuming devices to be more flexible in order to be responsive to changes in electricity generation from variable renewable sources
- May require extensive use of autonomous vehicle technology in combination with electric vehicle technology to facilitate the rapid electrification of the transportation sector
- May require the use of technology to capture carbon and store it geologically or biologically, or reuse it in the synthesis of fuels
- Could be aided by changes in consumption of energy services and/or rates of consumption growth, but will not diminish basic quality of life and standards of living

CONCLUSION

My previous work demonstrates that it is technically feasible to achieve an 80% reduction in greenhouse gas emissions below 1990 levels by 2050 in the United States, while maintaining current levels of energy services without requiring any conservation measures, consistent with on the U.S. Department of Energy's *Annual Energy Outlook*. Multiple alternative pathways exist to achieve these reductions using existing commercial or near-commercial technologies. The net cost of changing the way energy is supplied and used to achieve this target is small compared to GDP and to what is currently spent on energy, even without including such benefits as avoided human and infrastructure costs of climate change and air pollution. Starting immediately on the deep decarbonization path would allow infrastructure replacement to follow natural replacement rates, reducing costs and allowing gradual consumer adoption. That is why it is important for the federal government, including the agencies listed as Defendants in this case, to promptly develop and implement a plan to reduce U.S. greenhouse gas emissions.

The target of 80% reductions below 1990 levels by 2050 is used by many countries. However, recent work by climate scientists indicates that this level of reductions is not sufficient to avoid dangerous anthropogenic interference with the climate system over the long term, and the negative impacts on human, ecological, and economic health that would result from that. My research team is therefore currently modeling the requirements to meet a more stringent target in which fossil fuel CO_2 emissions in 2050 are reduced as much as 96% below current levels, consistent with achieving an atmospheric CO_2 concentration of 350 ppm by 2100.

In my expert opinion, I believe that a reduction in national emissions as deep as 96% below present levels is technologically feasible given current and emerging technologies; that it will likely have a higher unit cost for the remaining reductions beyond 80% by 2050; that it will likely require some early retirements of fossil fuel infrastructure; and that it could be aided by changes in the consumption of energy services and/or rates of consumption growth, but will not diminish basic quality of life and standards of living.

Signed this 13th day of April, 2018 in Berkeley, California.

James H. Williams

James H. Williams

Exhibit E:

Expert Report of Dr. Mark Jacobson

EXPERT REPORT
OF
MARK JACOBSON, Ph.D.

Professor, Dept. of Civil and Environmental Engineering
Director, Atmosphere/Energy Program
Senior Fellow, Woods Institute for the Environment
Senior Fellow, Precourt Institute for Energy
Stanford University

Kelsey Cascadia Rose Juliana; Xiuhtezcatl Tonatiuh M.,
through his Guardian Tamara Roske-Martinez; et al.,
Plaintiffs,

v.

The United States of America; Donald Trump,
in his official capacity as President of the United States; et al.,
Defendants.

IN THE UNITED STATES DISTRICT COURT
DISTRICT OF OREGON

(Case No.: 6:15-cv-01517-TC)

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TABLE OF ACRONYMS AND ABBREVIATIONS

BAU:	business as usual
CCS:	carbon capture and sequestration
coal-CCS:	coal with carbon capture and sequestration
CO_2:	carbon dioxide
CSP:	concentrated solar power
DOE:	United States Department of Energy
EIA:	United States Energy Information Administration
EPA:	United States Environmental Protection Agency
HVAC:	heating, ventilation and air conditioning
HVDC:	high-voltage direct-current
IPCC:	United Nations Intergovernmental Panel on Climate Change
kW:	kilowatt (measure of electric power)
kWh:	kilowatt hour
MW:	megawatt (measure of electric power)
OTA:	United States Congress, Office of Technology Assessment
ppm:	parts per million
ppmv:	parts per million by volume
PV:	photovoltaic
R&D:	research and development
RE:	renewable energy
UNFCCC:	United Nations Framework Convention on Climate Change
WWS:	wind, water, and sunlight

INTRODUCTION

I, Mark Jacobson, have been retained by Plaintiffs in the above-captioned matter to provide expert testimony about the feasibility of transitioning the United States of America to 100% clean and renewable energy in all energy sectors by mid-century, including whether this transition would remedy the constitutional violations alleged in the First Amended Complaint in this case. All energy sectors include electricity, transportation, heating/cooling, and industry.

QUALIFICATIONS

Since 1989, I have been researching academically and professionally, the impacts of human emissions of gases (including carbon dioxide and other greenhouse gases) and particles (including black carbon) on air pollution, human health, weather, and climate. Starting in 1999, I began examining in detail clean, renewable energy solutions to these problems. In 2015, this research culminated in the development of roadmaps to transition the all-sector energy infrastructures of each of the 50 United States to 100% clean, renewable energy by 2050 (Jacobson et al., 2015a, which includes a link to the spreadsheets used to derive all numbers in the paper). The research has also resulted in the development of 100% clean, renewable energy roadmaps for 139 countries of the world (Jacobson et al., 2017a, which also includes a link to spreadsheets) and electric power grid stability analyses for the 48 contiguous United States (Jacobson et al., 2015b) and for 20 world regions containing the 139 countries examined (Jacobson et al., 2018) after those states and countries have converted to 100% clean, renewable energy. I carried out this research, analysis, and clean, renewable energy roadmap development primarily with Dr. Mark Delucchi at U.C. Berkeley, but also along with several other experts. The purpose of this report is to summarize the portion of this research related to the United States and its major conclusions and implications on the feasibility of transitioning the country swiftly off of fossil fuels to clean and renewable energy in all sectors by mid-century.

The opinions expressed in this report are my own and are based on the data and facts available to me at the time of writing. All opinions expressed herein are to a reasonable degree of scientific certainty, unless otherwise specifically stated. Should additional relevant or pertinent information become available, I reserve the right to supplement the discussion and findings in this expert report in this action.

My full CV, including a list of publications I authored within the last ten years, is attached as **Exhibit A** to my report. My report contains a list of citations to the principal documents that I have used or considered in forming my opinions, listed in **Exhibit B**. **Exhibit C** contains a summary of my previous expert testimony. **Exhibit D** is a chart summarizing other decarbonization studies of which I am aware. I also attach, as **Exhibits E-H**, my central papers discussed herein.

In preparing my expert report and testifying at trial, I am deferring my expert witness fees to the charged plaintiffs given the financial circumstances of these young plaintiffs. If a party seeks discovery under Federal Rule 26(b), I will charge my reasonable fee of $200 per hour for the time spent in addressing that party’s discovery.

EXECUTIVE SUMMARY

In this report, I summarize research, conclusions, and implications of studies that I and my colleagues previously performed to develop 100% clean, renewable all-sector (electricity, transportation, heating/cooling, industry) roadmaps (plans) for the 50 United States (Jacobson et al., 2015a) and to analyze resulting electric grid stability for the 48 contiguous United States (Jacobson et al., 2015b). I also rely on our updated peer-reviewed research on an energy roadmap for the United States as a whole (Jacobson et al., 2017a) and a grid stability study for the United States plus Canada combined (Jacobson et al., 2018). I set forth a substantive discussion of numbers from the 50-state roadmaps in Jacobson et al. (2015a) where the numbers are set forth both on a state specific basis and for the U.S. as a whole. However, the U.S.–as-a-whole numbers were updated in Jacobson et al. (2017a) based on updated cost, efficiencies, and other data. Jacobson et al. (2017a) does not have an in-depth discussion of those data simply because the 2015a study provides state-by-state breakdowns as well. Nevertheless, both studies provide a consistent conclusion. Namely, I conclude in both studies that it is both technically and economically feasible to transition from a predominantly fossil fuel-based energy system to a 100% clean, renewable energy system for all energy sectors by 2050, with about 80% conversion by 2030, even after taking into account the U.S. Department of Energy's (DOE's) Energy Information Administration's (EIA's) energy demand forecasting and taking into account efficiencies resulting from the transition from fossil fuels to clean, renewable energy.

Presently, fossil fuels supply more than 80% of our all-purpose energy in the United States, not out of necessity, but because of political preference and historic government support that led to the development and maintenance of a widespread fossil-fuel infrastructure. Our plans provide state-by-state roadmaps to replace 80% of existing fossil fuel energy by 2030 and 100% by 2050. The main concept is to electrify all energy sectors with existing or near-existing technologies, and then to generate the electricity for all sectors with 100% wind, water, and sunlight (WWS), namely onshore wind, offshore wind, utility-scale photovoltaics (PV), rooftop PV, concentrated solar power (CSP) with storage, geothermal power, wave power, tidal power, and hydroelectric power. A 100% WWS system would also require electricity storage, heat storage, cold storage, and some hydrogen storage along with an expanded transmission and distribution system.

First, based on our 2015 study (Jacobson et al., 2015a), converting to 100% WWS would reduce the U.S.-average end-use power demand by a mean of ~39.3%. Approximately 82.4% of the reduced power demand is due to a) the higher work output to energy input of electricity compared with fossil-fuels (burning fossil fuels to move vehicles results in much more waste heat than using electricity), and b) eliminating the energy needed to mine, transport, and refine fossil fuels and uranium (because wind and solar energy, for example, come right to the wind turbine or solar panel, respectively). The rest of the reduction in power demand is due to end-use energy efficiency and conservation improvements beyond those expected in a business-as-usual (BAU) case.

Second, averaged over the United States, our roadmaps propose that all-purpose U.S. energy in 2050 could be met with ~30.9% onshore wind, ~19.1% offshore wind, ~30.7% utility-scale photovoltaics (PV), ~7.2% rooftop PV, ~7.3% concentrated solar power (CSP) with storage, ~1.25% geothermal power, ~0.37% wave power, ~0.14% tidal power, and ~3.01% hydroelectric power (where virtually all hydroelectric dams exist already). This is only one of many possible mixes. We have run our model with other mixes as well to demonstrate that a 100% WWS system by 2050 is feasible (e.g., Jacobson et al., 2017a).

Third, over all 50 states, converting from fossil fuel energy to WWS would provide an estimated 3.9 million 40-year full-time construction jobs and about 2.0 million 40-year full-time operation jobs for the energy facilities alone.

Fourth, converting from fossil fuel energy to WWS would also eliminate ~62,000 (19,000-115,000) U.S. air pollution premature mortalities per year today and ~46,000 (12,000-104,000) per year in 2050, avoiding ~$600 ($85-$2,400) billion per year (2013 dollars) in 2050, based on statistical cost of life as defined by the U.S. government, equivalent to ~3.6 (0.5-14.3) percent of the 2014 U.S. gross domestic product.

Fifth, converting from fossil fuel energy to 100% WWS would further eliminate ~$3.3 (1.9-7.1) trillion per year in 2050 global warming costs to the world due to U.S. emissions.

Sixth, these plans will result in each person in the U.S. in 2050 saving ~$260 (190-320) per year in energy costs ($2013 dollars) and U.S. health and global climate costs per person decreasing by ~$1,500 (210-6,000) per year and ~$8,300 (4,700-17,600) per year, respectively.

Seventh, the new footprint over land required to implement our plan would be ~0.42% of U.S. land. The spacing area between wind turbines, which can be used for multiple purposes, will be ~1.6% of U.S. land area. 0.42% of U.S. land is equivalent to ~14,800 square miles. For comparison, an upper bound of ~75,000 square miles of land (2.1% of U.S. land area) may have been used to date for roads, well pads, and storage facilities for the 2.5 million inactive and 1.7 million active oil and gas wells alone in the United States to date (Fracktracker Alliance, 2015). Pennsylvania alone has ~560,000 abandoned oil and gas wells (Pennsylvania Department of Environmental Protection, 2016). 20,000 new oil and gas wells are drilled in the United States every year. Allred et al. (2015) estimate that the area taken up by well pads, roads, and storage facilities for natural gas wells sum to 0.0178 square mile per well. Extrapolating this estimate to oil wells and to all abandoned plus active oil and gas wells in the U.S. gives the 75,000 mi^2 estimate. While this is an upper bound for oil and gas wells, coal and oil extraction has required additional land as have oil and gas pipelines, oil refineries, gas stations, power plants, and other oil, gas, and coal infrastructure, which will become obsolete upon the transition to 100% clean and renewable energy.

Eighth, the state-by-state roadmaps have been calculated to keep the 48 contiguous state U.S. grid stable at low cost in two separate peer-reviewed studies under multiple storage scenarios (Jacobson et al., 2015b; Jacobson et al., 2018). In the latter study, grid stability over the U.S. and Canada combined were found under three different scenarios, including two with no added hydropower turbines and one with added hydropower turbines.

In other words, the roadmaps will keep the lights on. Power supply will continue to match demand as it currently does, every minute of every day. Although the wind doesn't always blow and the sun doesn't always shine, it is possible to match power demand during those periods at a given location by using stored energy, shifting the time of peak demand for energy with financial incentives (demand response), and by adding some long-distance transmission to connect wind and solar in remote locations to cities. In our studies, storage is in the form of heat (in water, rocks, and thermal mass); cold (in ice and water); electricity (in concentrated solar power (CSP) with storage, batteries, pumped hydropower systems, and existing hydropower dams); and hydrogen (for use in transportation). In our studies, we have found that the grid can stay stable with no coal, natural gas, oil, biofuels, or nuclear power. The resulting 2050-2055 U.S. electricity social cost (energy cost plus health cost plus climate cost) for a full system is much less than for current energy sources, and the energy cost alone is similar or less.

In sum, conversions of the energy infrastructure of the United States to 100% wind, water, and sunlight for all purposes is technically and economically feasible at low cost and high benefit. Based upon my review of the available information and pertinent literature identified herein, as well as my many years of experience as described herein, I conclude that a transition to 100% clean, renewable energy by mid-century would stop the affirmative government infringement of the youths' constitutional rights as described in the First Amended Complaint, and even though not all of the harm caused by historic emissions would be remediated, it would put the nation on the correct path toward climate stabilization.

EXPERT OPINION

1. Technological and Economic Feasibility of Converting 100% of Our Energy From Fossil Fuels to Clean, Renewable Energy For All Sectors by 2050 and 80% by 2030.

Our research suggests that it is technologically and economically possible to electrify fully the energy infrastructures of all 50 United States and provide that electricity with 100% clean, renewable wind, water, and sunlight (WWS) at low cost, if the transition is commenced immediately (Jacobson et al., 2015a; 2017a). Whereas, a 100% transformation is technically and economically possible by 2030, we believe that, for social and political reasons, a more practical expectation to transition all sectors (electricity, transportation, heating/cooling, industry) is 80% by 2030 and 100% by 2050. These conclusions are based upon the assumption that the transition commences immediately. Our research further finds that the U.S. electric power grid with 100% WWS can stay stable at low cost (similar or less than today's direct energy cost and much less than today's social cost, which includes energy, health, and climate costs) because electrifying transportation and heating creates more flexible loads, allowing grid operators to shift times of peak demand more readily (Jacobson et al., 2015b; 2018). Further, flexible loads allow low-cost storage options for heat and cold to be used to displace electricity demand and store excess electricity rather than wasting it.

The methodology for this research, outlined in detail in Jacobson et al. (2015a,b) and updated in Jacobson et al. (2017a; 2018), is as follows:

1) For each of the 50 states, we start with contemporary business-as-usual (BAU) end-use power demand by fuel type in the residential, commercial, transportation, and industrial sectors.

2) We use U.S. Department of Energy (DOE) Energy Information Administration (EIA) data and other data to project BAU end-use power demand by fuel type to 2050.
3) We electrify end-use demand in 2050 by fuel type in each sector, for each state. For some sectors, electricity is used to produce hydrogen.
4) We specify a mix of WWS electric power generators to meet the end-use electric demand in each state. The mix is limited and optimized by the technical potentials of each WWS resource in each state.
5) We calculate the required footprint and spacing area required for the WWS technologies.
6) We calculate the cost of constructing the WWS infrastructure for each state, including necessary upgrades to national electricity transmission infrastructure.
7) We calculate the number of long-term, full-time construction and operation jobs required for the generators and the corresponding number of jobs lost in the BAU energy sectors, primarily in the fossil fuel industry.
8) We calculate the air pollution mortality and morbidity reduction and corresponding health cost reduction due to transitioning from BAU to WWS.
9) We calculate the greenhouse gas emission reduction and corresponding climate cost reduction due to transitioning from BAU to WWS.
10) We use a weather prediction model to predict the time-dependent wind and solar fields in 2050 in each of the 48 contiguous U.S. states under the 100% WWS case in each state.
11) We project time-dependent power demand to 2050 from contemporary data.
12) We simulate the time dependent matching of power demand with WWS supply over the U.S. every 30 seconds for 6 years, with zero loss of load, accounting for low-cost heat storage (in water and rocks), cold storage (in water and ice), electricity storage (in concentrated solar power with storage, pumped hydroelectric storage, batteries, and hydroelectric power), demand response, and long-distance transmission.
13) We calculate the resulting cost of energy matching supply with demand.

The research concludes that converting from fossil fuel combustion to a completely electrified system for all purposes could reduce U.S.-averaged end-use power demand (load) ~39.3%. Approximately 82.4% of the reduced electricity use results from the higher work output to energy input of electricity over fossil fuels and the elimination of energy needed to mine, transport, and refine fossil fuels and uranium. The rest of the reduced electricity use is due to end-use energy efficiency and conservation improvements beyond those expected in a business-as-usual (BAU) case. The conversion to WWS should also stabilize energy prices since fuel input costs will be zero, avoiding much of the market fluctuations in the price of oil, coal, and gas.

Remaining all-purpose annually-averaged end-use U.S. load, based on the Jacobson et al. (2015a) study, is proposed to be met (based on 2050 energy estimates) with ~328,000 new onshore 5-MW wind turbines (providing 30.9% of U.S. energy for all purposes), ~156,000 off-shore 5-MW wind turbines (19.1%), ~46,500 50-MW new utility-scale solar-PV power plants (30.7%), ~2,270 100-MW utility-scale CSP power plants (7.3%), ~75.2 million 5-kW residential rooftop PV systems (3.98%), ~2.75 million 100-kW commercial/government rooftop systems (3.2%), ~208 100-MW geothermal plants (1.23%), ~36,000 0.75-MW wave devices (0.37%),

~8,800 1-MW tidal turbines (0.14%), and no new hydroelectric plants in the 48 contiguous states but 3 new hydroelectric plants in Alaska. The output of existing hydroelectric plants would be increased slightly so that hydropower supplies 3.01% of U.S. all-purpose power.

The Jacobson et al. (2015b) grid integration study based on the 50-state plans suggests that an additional ~1,360 CSP plants (providing an additional ~4.38% of annually-averaged load) and 9,380 50-MW solar-thermal collection systems for heat storage in soil (providing an additional 7.21% of annually-averaged load) would be needed as a first estimate to ensure a reliable grid. That study also assumed an increase in the peak hydropower discharge rate while holding the annual-average hydropower output constant. It also assumed a significant amount of underground thermal energy storage. This was just one possible mix of energy generators and storage. While that study faced criticism from authors, the criticisms were not only responded to point-by-point (Jacobson et al., 2016; 2017b) but the most significant ones were also shown to be moot in a follow-up peer-reviewed published study (Jacobson et al., 2018).

The subsequent study (Jacobson et al., 2018) performed a similar calculation as in Jacobson et al. (2015b) but with more storage options, including two with zero added hydropower turbines and one with zero underground or other thermal energy storage. More specifically, the additional simulations included (1) zero increase in the hydropower discharge rate but increasing the discharge rate of concentrated solar power (CSP) and adding battery storage while keeping thermal energy storage; and (2) zero increase in the hydropower discharge rate and zero thermal energy storage but using CSP with storage, batteries, and heat pumps instead.

Simulations for Jacobson et al. (2018) were performed for 20 world regions, including the United States plus Canada, island countries, medium-sized countries, and large countries and continents, rather than just one world region in Jacobson et al. (2015b). All simulations for all world regions resulted in stable grids at low cost over a 5-year simulation period, including with no added hydropower turbines and, in one case, with no thermal energy storage at all. These results for extreme conditions suggest there are multiple intermediate solutions with a variety of combinations of WWS storage technologies and resources. All methods resulted in low-cost solutions and 100% WWS by 2050. The fact that the system works with either increased hydropower discharge or increased CSP and batteries or CSP, batteries, and heat pumps is illustrative of the feasibility of transitioning the nation's energy system to 100% WWS. There is not just one way of achieving the transition, but many pathways. In fact, even critics of our methodology do not disagree with the conclusions we reach.[1]

Practical implementation considerations will determine the actual design and operation of the U.S. energy system and may result in technology mixes different than proposed here (e.g., more rooftop PV, less power plant PV).

Other studies in the U.S. and abroad provide parallel support for the ability to swiftly move away from fossil fuels. These studies are briefly summarized in **Exhibit D**. While I do not endorse

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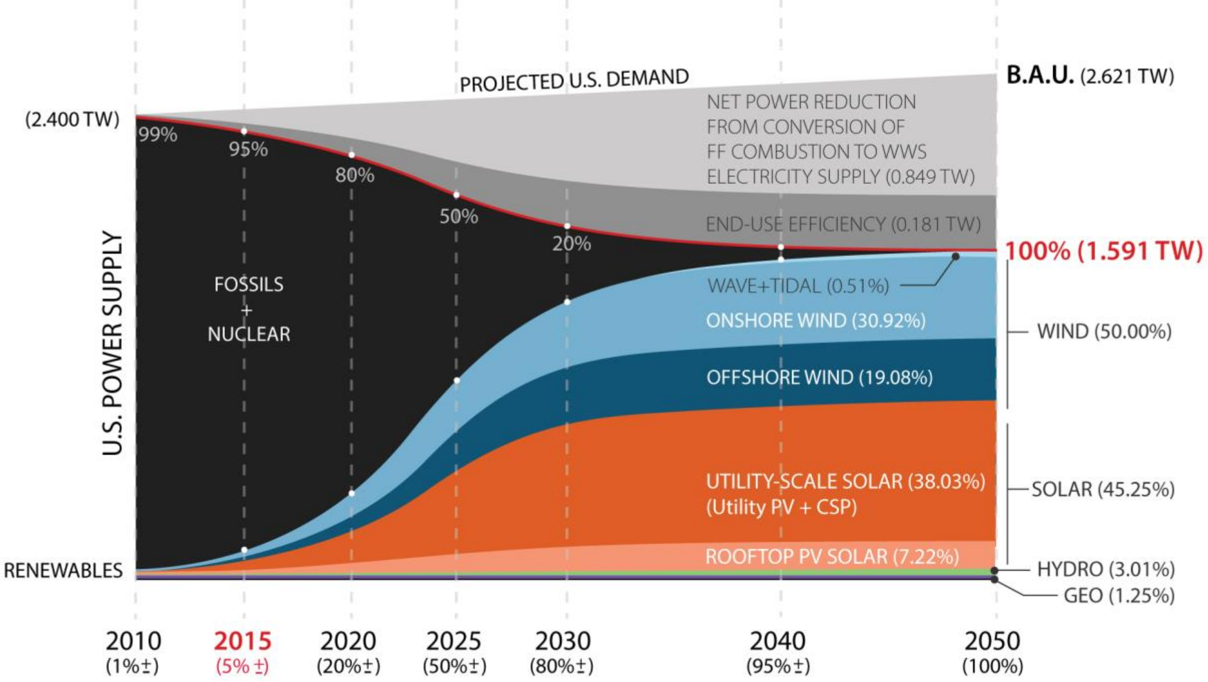
[1] June 20, 2017 Daniel Kammen Twitter: "A significant misunderstanding here: yes the 100% target is needed AND is feasible, but one must do the analytics correctly to be useful."

each of these studies and not all of the studies consider all energy sectors or 100% clean energy by 2050 as we do, collectively they illustrate the vast potential and feasibility of swift decarbonization and transition to clean, renewable energy. Specifically, several of these published studies conclude that 100% renewable energy for all sectors by 2050 for France, the European Union, and globally is feasible.

The timeline for conversion under either modeled scenario is proposed as follows: 80% of all energy to be WWS by 2030 and 100% by 2050 (**Figure 1**). If this timeline is followed, implementation of these plans and similar ones for other countries worldwide provides the pathway to eliminate energy-related global warming; air, soil, and water pollution; and energy insecurity. Transitioning at this pace should avoid global temperatures from rising more than 1.5ºC as a peak temperature increase since 1870 and reduce CO_2 back to 350 ppm by 2100 (Section 2). Transitioning to 100% WWS by 2050 also provides the best opportunity for the federal government to further reduce global surface and ocean temperatures to levels that will over the long term stabilize the planet's ice sheets.

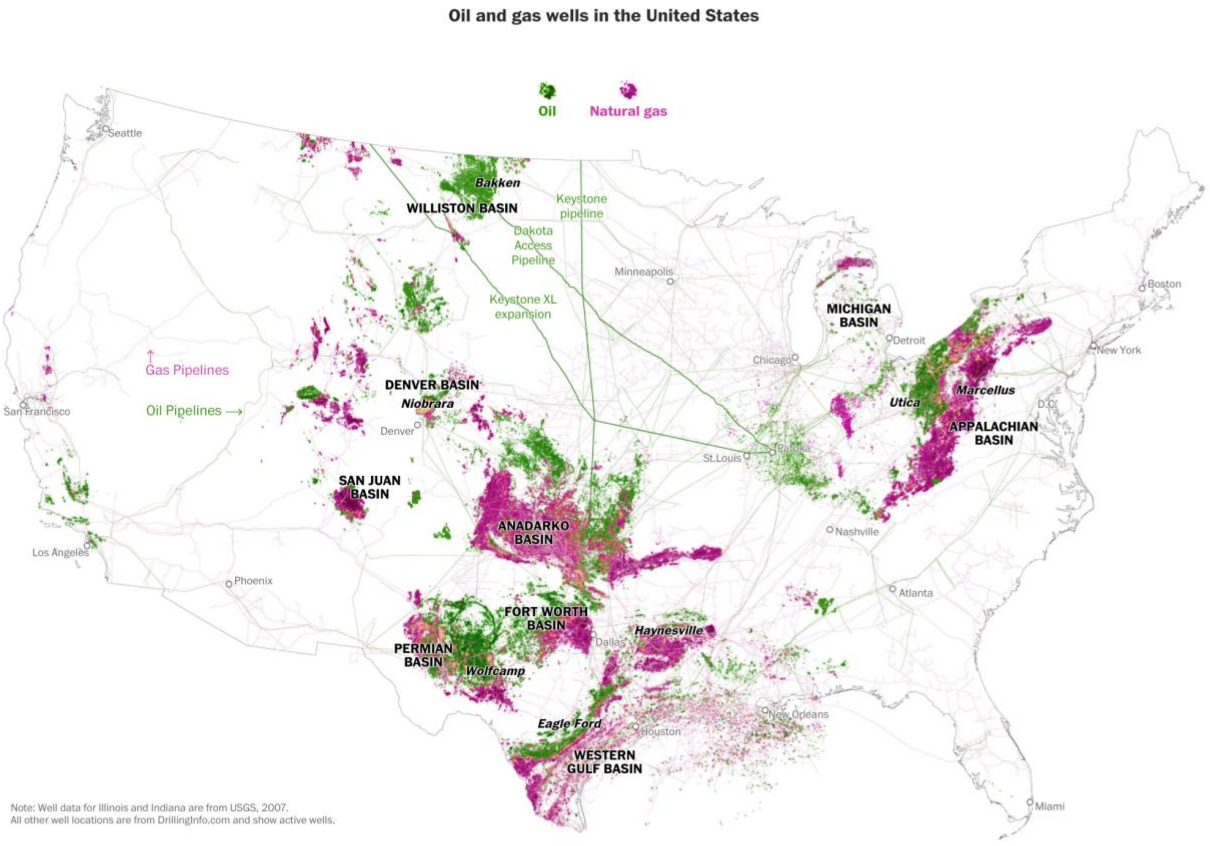
Figure 1. Time-dependent change in U.S. end-use power demand for all purposes (electricity, transportation, heating/cooling, and industry) and its supply by conventional fuels and WWS generators based on the state roadmaps proposed. Total power demand decreases upon conversion to WWS due to the higher work output per unit energy input of electricity over combustion, the elimination of energy used to mine, transport, and refine fossil fuels, and additional end-use energy efficiency measures in the WWS case. The percentages on the horizontal date axis are the percent conversion to WWS that has occurred by that year. The percentages next to each WWS source are the final estimated penetration of the source. The 100% demarcation in 2050 indicates that 100% of all-purpose power is provided by WWS technologies by 2050, and the power demand by that time has decreased. In 2010 nuclear power represented ~4% of the total end-use fossil plus nuclear power (from Jacobson et al., 2015a).



The additional footprint on land for WWS devices is equivalent to about 0.42% of the U.S. land area, mostly for utility scale PV. An additional on-land spacing area of about 1.6% is required for onshore wind, but this area can be used for multiple purposes, such as open space, agricultural land, or grazing land. The land footprint and spacing areas (open space between devices) in the proposed scenario can be reduced by shifting more land based WWS generators to the ocean, lakes, and rooftops.

As described previously, 0.42% of U.S. land is equivalent to ~14,800 square miles. For comparison, an upper bound of ~75,000 square miles of land (2.1% of U.S. land area) may have been used to date for roads, well pads, and storage facilities for the 4.2 active plus inactive oil and gas wells in the United States (Fracktracker Alliance, 2015). Additional land is required for coal and oil extraction, oil and gas pipelines, oil refineries, gas stations, power plants, and other oil, gas, and coal infrastructure (see **Figure 2**). Thus, the roadmaps here will take much less footprint than oil and gas alone in the United States.

Figure 2. Oil and Gas Wells in the United States (Meko and Karklis, Wash. Post, 2017).



Note: Well data for Illinois and Indiana are from USGS, 2007.
All other well locations are from DrillingInfo.com and show active wells.

Offshore oil and gas infrastructure is similarly extensive for the Gulf of Mexico, as depicted in **Figure 3**.

Figure 3. Gulf Coast Oil and Gas Infrastructure (Meko and Karklis, Wash. Post, 2017).

The 2017 unsubsidized business costs of new onshore wind and utility-scale solar plants is already less than that of new natural gas power plants (Lazard, 2017). Rooftop PV, offshore wind, tidal, and wave are more expensive, but their costs are declining rapidly. By 2030 and

2050, however, the business costs of all WWS technologies are expected to drop, whereas conventional fuel costs are expected to rise (Jacobson et al., 2015a and references therein).

In 2050, the direct (business) cost of a full 100% WWS grid-integrated system (including generation, transmission, distribution, and storage) is calculated to be similar or less than that of a fossil fuel system (Jacobson et al., 2015b; 2018). The total social cost (business cost plus health and climate cost) of a 100% WWS system will be about one-third to one-fourth that of a fossil-fuel system due to the high climate and health costs of fossil fuels (Jacobson et al., 2015b; 2018).

The 50-state WWS roadmaps are anticipated to create ~3.9 million 40-year construction jobs and ~2.0 million 40-year operation jobs for the energy facilities alone, outweighing the ~3.9 million jobs lost to give a net gain of 2.0 million 40-year jobs. Earnings during the 40-year construction period for these facilities (in the form of wages, local revenue, and local supply-chain impacts) are estimated to be ~$223 billion per year in 2013 dollars and annual earnings during operation of the WWS facilities are estimated at ~$132 billion per year. Net earnings from construction plus operation minus lost earnings from lost jobs are estimated at ~$85 billion per year.

The state roadmaps will reduce U.S. air pollution mortality by ~62,000 (19,000-115,000) U.S. air pollution premature mortalities per year today and ~46,000 (12,000-104,000) per year in 2050, avoiding ~$600 (85-2,400) billion per year (2013 dollars) in 2050, equivalent to ~3.6% (0.5-14.3) of the 2014 U.S. gross domestic product.

Converting to WWS would further eliminate ~$3.3 (1.9-7.1) trillion per year in 2050 global warming costs to the world due to U.S. greenhouse gas emissions. These plans will result in the average person in the U.S. in 2050 saving ~$260 (190-320) per year in energy costs (2013 dollars), $1,500 (210-6,000) per year in health costs, and $8,300 (4,700-17,600) per year in climate costs for a total annual per capita savings of $10,060 (5,100-23,920).

Uncertainties remain in terms of the range of energy, health, and climate costs we estimate in our analysis. These ranges may miss costs impacted by unforeseen political/social events. As such, the estimates should be reviewed periodically. However, even recognizing such uncertainties, I conclude to a strong degree of scientific certainty that transitioning to 100% WWS is in the economic best interest of the United States.

Transitioning to 100% WWS will allow the United States to produce as much power as it uses in the annual average at present, thereby reducing its reliance on international competition for energy, potentially reducing international conflict and increasing energy stability within the United States. In addition, the economic benefits of transitioning to 100% WWS would flow toward the citizens of the United States, as we would not be required to purchase fossil fuels from other countries.

Transitioning to 100% WWS will increase access to distributed energy, providing easier and more access to energy for those living in remote areas.

Transitioning to 100% WWS will reduce the risk of large-scale system disruption due to large power plant outages and physical terrorism (but not necessarily due to cyberattack) because much of the world power supply will be decentralized into more, smaller power sources.

Based on the scientific results presented, current barriers to implementing the WWS roadmaps are neither technical nor economic. They are social and political. Such barriers are due partly to the fact that most people are unaware of what changes are possible, what technology is available, and how they will benefit from a transition to WWS in their own lives and partly due to the fact that many with a financial interest in the current energy industry resist change. Because the benefits of converting (reduced global warming and air pollution, new jobs and stable energy prices) far exceed the costs, converting has little downside.

2. What is Needed to Decrease Atmospheric CO_2 to 350 ppm by 2100

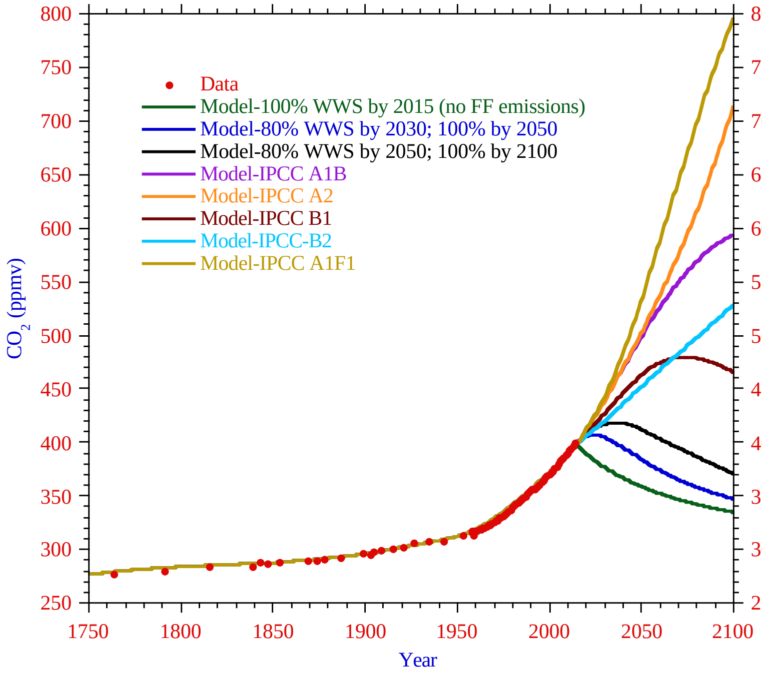
Transitioning 80% of the United States and the world's energy and land-use change emissions to WWS by 2030 and 100% by 2050 is consistent with a trajectory to allow atmospheric CO_2 levels to decrease to near 350 ppm by 2100.

Matthews (2016) estimates the global emission limits to keeping temperature increases under 1.5°C with probabilities of 67% and 50% as 2400 Gt-CO_2 and 2625 Gt-CO_2, respectively.

Between 1870 and the end of 2015, a cumulative ~2050 Gt-CO_2 was emitted globally from fossil-fuel combustion, cement manufacturing, and land use change. (Mathews, 2016). This suggests no more than 350-575 Gt-CO_2 can be emitted for a 67-50% probability of keeping post-1870 warming under 1.5°C. Given the current and projected global emission rate of CO_2, it is necessary to cut energy- and land-use change emissions yearly until emission cuts reach 80% by 2030 and 100% by 2050 to limit warming to 1.5°C with a probability of between 50% and 67%.

Figure 4 illustrates the possible impact on global atmospheric carbon dioxide levels of an 80% conversion to WWS by 2030 and 100% conversion by 2050 as well as possible impacts from less aggressive emission reductions. The 100% by 2050 scenario can reduce CO_2 to near 350 ppm by 2100, a level last measured in the atmosphere around 1988. All IPCC (2000) emission scenarios result in CO_2 levels in 2100, ranging from 460 to 800 ppm. Such scenarios are certain to drive temperatures dangerously higher. A WWS scenario for the United States is essential for stabilizing and ultimately reducing temperatures over the long-term.

Figure 4. Comparison of historic (1751-2014) observed CO_2 mixing ratios (ppmv) from the Siple ice core (Neftel et al., 1994) and the Mauna Loa Observatory (Tans and Keeling, 2015) with GATOR-GCMOM model results (Jacobson, 2005) for the same period plus model projections from 2015-2100 for five Intergovernmental Panel on Climate Change (IPCC) scenarios (IPCC, 2000) and three WWS cases: an unobtainable 100% WWS by 2015 case, an 80% WWS by 2030 and 100% by 2050 case (from Figure 1 above), and a less-aggressive 80% by 2050 and 100% by 2100 case.



The model is set up as in Jacobson (2005) with two columns (one atmospheric box over 38 ocean layers plus one atmospheric box over land). It treats full ocean chemistry in all layers, vertical ocean diffusion with canonical diffusion coefficients, ocean removal of calcium carbonate for rock formation, gas-ocean transfer, and emissions from fossil fuels. It also accounts for photosynthesis, plant and soil respiration, and removal of carbon dioxide from the air by weathering. Fossil-fuel emissions from 1751-1958 are from Boden et al. (2011), from 1959-2014 are from Le Quere et al. (2015), and for 2015 onward from the WWS scenarios scaled from 2014 emission and from the individual IPCC scenarios. Land use change emissions per year are 300 Tg-C/yr for 1751-1849, from Houghton (2012) for 1850-1958, from Le Quere et al. (2015) for 1959-2014, from the IPCC (2000) A1B scenario for the WWS cases for 2015-2100, and from the individual IPCC scenarios for the remaining cases. The net carbon sink over land from 1751-2100 is calculated from the time-dependent photosynthesis, respiration, and weathering processes mentioned.

3. List of Technology Replacements and Timelines for Their Implementation

Below is a list of electric appliances, transportation options, and WWS power generators that are needed to transition to 100% WWS. Most of these technologies are available today, and the rest (e.g., for aircraft and ships in particular) are currently being designed to transform the energy infrastructure of the United States. The list is not a complete list, but demonstrates that 95% of the technological solutions for a complete transition to WWS by 2050 already exist. Future innovations over the next 30 years and beyond will very likely provide even more technological mechanisms to facilitate the remaining transition to 100% WWS for all purposes by 2050.

A. Technology Replacements

i. Increase Energy Efficiency / Reduce Energy Demand

a. Increase efficiency in buildings through:

Lighting:

- LED lighting
- Advanced lighting controls

Appliances:

- High efficiency pumps and motors
- High efficiency commercial appliances (refrigerators, washers, dryers)
- Energy efficient residential appliances (refrigerators, water heaters, etc.)
- Variable refrigerant flow

Heating and cooling efficiency in buildings through:

- Programmable thermostats
- Improved wall, floor, ceiling, and pipe insulation
- High-efficiency double- and triple-pane windows
- Energy efficient framing practices
- Passive solar design
- Sealing doors, windows, walls, outlets, and fireplaces to reduce heat / cold loss
- Evaporative cooling systems
- Ductless heat pumps for heating and air conditioning
- Water-cooled heat exchanging
- Night ventilation cooling
- Passive ventilation design
- Combined space and water heating
- Air flow management
- Heat recovery ventilation systems
- Building energy monitors to identify opportunities to reduce wasted energy

Water efficiency:

- High efficiency residential and commercial water fixtures
- High efficiency irrigation systems
- Greywater re-use systems

b. Reduced transportation demand through:

- Telecommuting rather than commute by car
- Improved biking infrastructure
- Improved pedestrian infrastructure

  - Improved public transportation
  - Transportation Demand Management programs that support adoption of low-carbon transportation practices
  - Improved carpooling and ride-sharing programs and technologies
  - Urban land use practices to reduce transportation demand (i.e. mixed use development, increased residential densities)

c. **Improved vehicle efficiency through:**
  - Low rolling resistance tires
  - Lightweight materials (i.e. carbon fiber, aluminum, fiberglass)
  - Regenerative braking systems
  - High efficiency settings or dashboard fuel efficiency displays

ii. WWS Electric Power Generators
- Onshore/offshore wind turbines
- Solar photovoltaics (PV) for rooftops and power plants
- Concentrated Solar Power (CSP) plants
- Geothermal power plants for electricity
- Tidal turbines
- Wave devices
- Existing large hydroelectric reservoirs used more efficiently
- Small hydroelectric reservoirs
- In-stream hydroelectric turbines

iii. Low-Temperature Heat Generators
- Geothermal heat pumps
- Natural geothermal heating
- Solar thermal collection devices for heat

iv. Electricity Storage
- CSP with storage (either molten salt or phase-change material)
- Pumped hydroelectric storage
- Hydroelectric power plant reservoirs
- Batteries

v. Heat Storage Devices
- Hot water tanks
- Rocks stored underground
- Thermal walls

vi. Cold Storage Devices
- Chilled water tanks
- Ice storage

vii. **Hydrogen Storage Devices**

- Electrolyzers to produce hydrogen from electricity
- Electric compressors to compress hydrogen
- Tanks to store hydrogen for transportation primarily

viii. **Demand Response**

- Technology to enable remote start up and shut down of appliances and equipment that have flexible demand (i.e. water heaters, HVAC equipment, electric vehicles)
- Utilities provide incentives for industry, companies, and individuals to shift their electricity use for certain uses and processes to non-peak times of day or night – Time of Use electricity pricing

ix. **Electric Vehicles**

- Light-, medium-, and heavy-duty on-road automobiles
- Short-distance trucks, buses trains, ships, aircraft
- Motorcycles
- Non-road vehicles
- Construction equipment
- Agricultural equipment
- Forklifts

x. **Hydrogen Fuel Cell/Electric Hybrid Vehicles**

- Long-distance trucks
- Buses
- Long-distance trains
- Long-distance ships
- Long-distance aircraft
- Construction equipment
- Agricultural equipment

xi. **Electric Car Charging Infrastructure**

- Home car chargers
- Chargers installed in parking garages and on streets

xii. **High-Temperature Industrial Equipment**

- Electric arc furnaces
- Dielectric heaters
- Electric induction furnaces

xiii. **Electric Appliances to Replace Gas or Gasoline**

- Heat pump air and water heaters
- Electric induction cooktop stoves
- Electric dryers
- Electric leaf blowers

- Electric lawnmowers
- Electric water sprayers
- Electric fans

xiv. Long-Distance Transmission

- High-voltage direct-current (HVDC) lines

Whereas, much new WWS infrastructure can be installed upon natural retirement of BAU infrastructure, new policies are needed to force remaining existing infrastructure to retire early to allow the complete conversion to WWS by 2050. Because the air-pollution and climate-impact benefits (avoided costs) (28.5 (11.2-72) ¢/kWh-BAU-all-energy) resulting from closing BAU plants early far exceed the annualized remaining *net* asset value of such plants (the difference between the annualized capital cost and the annualized salvage or re-use value) divided by annual energy produced, and because net jobs increase upon replacing BAU plants, retiring them early results in large net health, employment, and climate benefits to society.

B. Timelines for Transitioning Individual Sectors

The overall timeline proposed for transitioning to 100% WWS is 80% by 2030 and 100% by 2050. To meet this timeline, rapid transitions are needed in each technology sector. Below is a list of proposed transformation timelines for individual sectors.

> ***Development of super grids and smart grids:*** as soon as possible, the United States should develop long-term power-transmission-and-distribution systems to provide "smart" management of energy demand and supply at all scales, from local to international, with a 100% WWS system. This allows supply and demand to be optimized.
>
> ***Power plants*****:** by 2020 at the latest, no more construction of new coal, nuclear, natural gas, or biomass fired power plants; all new power plants built should be WWS.
>
> ***Storage:*** starting immediately, heat, cold, and electric storage technologies should be deployed. Heat storage technologies include underground storage in rocks, storage in hot water tanks, and storage in thermal mass (e.g., wax, cement blocks). Cold storage includes primarily storage in ice and water. Electric storage includes storage in concentrated solar power, pumped hydroelectric power, batteries, and in existing hydroelectric reservoirs. Other types of storage are also possible.
>
> ***Heating, drying, and cooking in the residential and commercial sectors*****:** by 2020, all new devices, appliances, and machines should be electric.
>
> ***Industrial heat*****:** by 2023, all new high-temperature heating equipment for industrial applications should be electric.

***Large-scale waterborne freight transport*:** by 2020-2025, all new ships should be electrified and/or use electrolytic hydrogen, all new port operations should be electrified, and port retro-electrification should be well underway.

***Rail and bus transport*:** by 2025, all new trains and buses should be electrified. This requires changing the supporting energy-delivery infrastructure and the manufacture method of transportation equipment.

***Off-road transport, small-scale marine*:** by 2025 to 2030, all new production should be electrified.

***Long-distance heavy-duty truck transport*:** by 2025 to 2030, all new heavy-duty trucks and buses should be electric or hydrogen fuel cell-electric hybrids.

Light-duty on-road transport: by 2025-2030, all new light-duty on-road vehicles should be electric.

***Short-haul aircraft*:** by 2035, all new small, short-range aircraft should be electric.

***Long-haul aircraft*:** by 2040, all remaining new aircraft should be hydrogen fuel cell-electric hybrids.

During the transition, conventional fuels and existing WWS technologies are needed to produce the remaining WWS infrastructure. However, much of the conventional energy would be used in any case to produce conventional power plants and automobiles if the plans proposed here were not implemented. Further, as the fraction of WWS energy increases, conventional energy generation will decrease, ultimately to zero, at which point all new WWS devices will be produced with existing WWS. In sum, the creation of WWS infrastructure may result in a temporary increase in emissions before they are ultimately reduced to zero.

4. Recommended First Steps and Potential Policies

Whereas, much new WWS infrastructure can be installed upon natural retirement of BAU infrastructure, new policies are needed to encourage remaining existing infrastructure to retire early to allow the complete conversion to WWS. Because the annual air-pollution and climate-impact benefits (avoided costs), as quantified here, resulting from closing BAU plants early far exceed the annualized remaining *net* asset value of such plants (the difference between the annualized capital cost and the annualized salvage or re-use value), and because net jobs increase upon replacing BAU plants, retiring them early results in large net benefits to society.

5. Why Nuclear, Biofuels, and Coal with Carbon Capture are Not Included

While some people have suggested that energy options aside from WWS, such as nuclear power, coal with carbon capture and sequestration (coal-CCS), and biofuels, can play a role in solving these problems, all four technologies, while better in several respects than fossil fuel technologies, have some disadvantages relative to fossil fuel technologies and significant disadvantages relative to WWS technologies. These advantages/disadvantages are listed below and then explained in more detail below that.

With respect to some of the disadvantages, it is important to note that because we must reduce emissions 80% by 2030 (thus only 12 years from 2018), we do not recommend power plant technologies that cannot be installed within the next few years.

Nuclear power

Advantages

- Low carbon and air pollution relative to fossil fuels.
- Requires only modest land use.

Disadvantages

- Requires 10-19 years between planning and operation versus 2-5 years for wind/solar.
- Expensive; cannot be built without significant financial support and insurance guarantee from government.
- Carries weapons proliferation risk.
- Carries meltdown risk (1.5% of all reactors built to date have melted down).
- Nuclear waste disposal issue (where to put the waste).
- Significant water is required for cooling with current and future technology.
- Nuclear material mining risks.
- Nuclear material transportation risks.
- 6-23 times the carbon emissions of wind power per unit energy generated.
- Not a renewable resource.
- Potential terrorism target.

Coal with carbon capture

Advantages

- Less carbon dioxide emissions than coal without carbon capture.
- Keeps coal miners employed in mining.

Disadvantages

- Requires 25% more energy than regular coal → 25% more air pollution emissions than regular coal because carbon capture equipment reduces only carbon dioxide.
- Still produces 50-60 times more CO_2 per unit energy than wind because it doesn't reduce CO_2 from mining or transporting coal, which is one-third of the emissions associated with coal power generation.
- Still results in land/habitat destruction due to coal mining.
- Still results in black lung disease to coal miners.
- Much more expensive than wind or solar power.
- Requires a minimum of 6-9 years between planning and operation versus 2-5 years for wind/solar.
- Coal-CCS can only be placed near specific geological formations.
- Long-term geologic storage of CO_2 is unproven.

- CO_2 stored underground has potential to leak.
- Not a renewable resource.

Biofuels

Advantages

- Carbon produced from burning a biofuel can be recaptured during regrowth of the biofuel.
- Biofuel combustion emits less of some chemicals than gasoline or diesel combustion.
- Biofuels can sometimes be substituted directly for fossil fuels in some automobiles, for example.

Disadvantages

- Biofuels require a significant amount of energy to produce, and a lot of that energy can be from fossil fuel combustion.
- Biofuel combustion emits more of some chemicals than gasoline or diesel combustion.
- Overall ozone production and mortality from burning ethanol as a fuel exceeds that from burning gasoline in the United States.
- The land required for growing biocrops is enormous.
- Solar PV produces 20 times more electricity than a biocrop produces energy over the same amount of land.
- Using land for food instead of fuel raises the price of food and spurs deforestation in parts of the world to create more land for biocrops.

With respect to the cost of nuclear and coal-CCS, the Intergovernmental Panel on Climate Change (IPCC) (2014) states (Section 7.8.2), "*Without support from governments, investments in new nuclear power plants are currently generally not economically attractive within liberalized markets,…"*

Similarly, Freed et al. (2017), who are strong nuclear advocates, state, "*…there is virtually no history of nuclear construction under the economic and institutional circumstances that prevail throughout much of Europe and the United States*."

Further, Cooper (2016), who compared WWS with nuclear and CCS scenarios, concluded, "*Neither fossil fuels with CCS or nuclear power enters the least-cost, low-carbon portfolio*."

IPCC (2014) further states that, with high penetrations of renewable energy (RE), nuclear and CCS are not efficient (Section 7.6.1.1), "*…high shares of variable RE power…may not be ideally complemented by nuclear, CCS,…"*

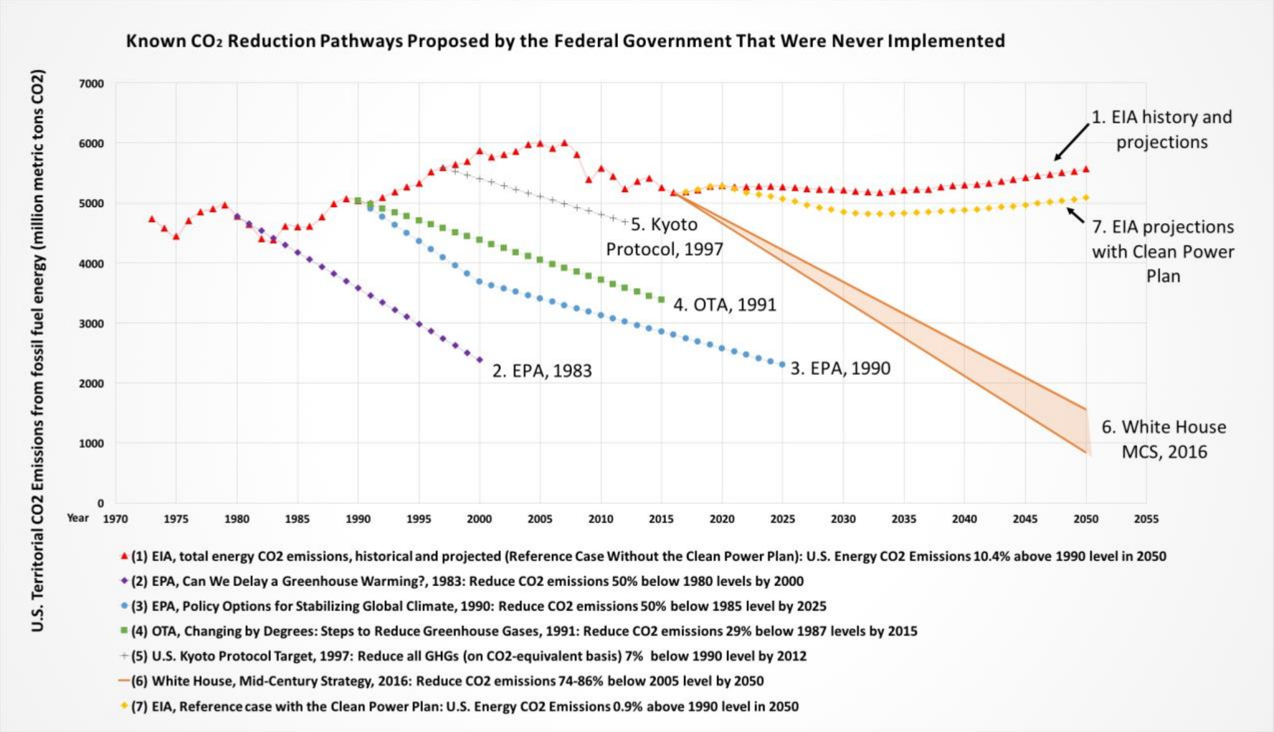
With respect to the other disadvantages of nuclear, IPCC (2014, p. 517) concludes that there is "*robust evidence"* and *"high agreement*" that "*Barriers to and risks associated with an increasing use of nuclear energy include operational risks and the associated safety concerns, uranium mining risks, financial and regulatory risks, unresolved waste management issues, nuclear weapons proliferation concerns, and adverse public opinion."* As such, expanding the use of nuclear to countries where it doesn’t exist may increase weapons proliferation and meltdown risks. Wind, water, and solar power have none of these risks. More advanced nuclear cannot be evaluated until it is commercialized, but it does not exist today.

With respect to the time lag between planning and operation of nuclear versus wind/solar, the air pollution emissions of nuclear versus coal-CCS versus biofuels versus wind/solar, please see Jacobson (2007, 2009).

6. Historical WWS Technological Feasibility

The United States could have begun the WWS transition by at least the late 1970s and early 1980s. In my expert opinion, had government promoted a climate-safe national energy policy at that time, the proportion of our nation’s energy system powered by WWS would today be much greater than it is currently in my estimation. For example, the graph in **Figure 5** below shows several historical examples of the U.S. government making recommendations, roadmaps, or plans since the early 1980s to decarbonize the national energy system, none of which was implemented. Notwithstanding their knowledge of climate change, and the alternative energy systems available to the country, the Federal Defendants chose to continue a fossil fuel energy system, which still supplies the majority of our energy today across all sectors. The red line shows actual and projected business as usual US emissions by the EIA under the Trump administration, which diverge substantially from the other recommended energy emission pathways.

Figure 5. Known CO_2 reduction pathways proposed by the Federal Government that were never implemented. ((1) EIA Reference Case, 2017 (2) EPA, 1983, (3) EPA, 1990, (4) OTA 1991, (5) Kyoto Protocol, 1997, (6) U.S. White House, 2016, (7) EIA Reference Case: with Clean Power Plan, 2017)



Other Examples:

- California developed the first three major wind farms worldwide in the late 1970s and early 1980s. These were Altamont Pass, Tehachapi, and San Gorgonio Pass. However, U.S. national policy shifted, and further growth of wind was slowed substantially for 1-2 decades. During that period, the center of wind farm development and manufacturing moved to Europe.

- Similarly, burgeoning U.S. policy in the 1970s encouraged solar energy expansion, but dominant U.S. policies that favored traditional fossil fuels squeezed out solar growth in the 1980s and 1990s. Only in the last decade has solar begun to grow substantially. In a December 5, 1978 Department of Energy Domestic Policy Review of Solar Energy Report to the White House, Defendant DOE projected that technical capacity for solar penetration by the year 2000 was 26-31% of national energy supply (Schlesinger 1978). The same report also confirmed the inefficiency of the energy system where 56% of annual energy use was consumed in conversion, transmission and end-use losses, not in actual energy use. The report confirms that widespread use of solar energy, which was technically available even in the 1970s was “hindered by Federal and state policies and market imperfections that effectively subsidize competing energy sources.” The lack of federal R&D and other support, which was largely given to fossil fuels, limited the “long-term contribution of solar energy to the nation’s energy supply.” (Schlesinger 1978).

- Electric cars have been around for over 180 years (since 1837). The first U.S. electric car was built in 1890. By 1900, 34,000 cars, or 38% of the U.S. fleet was electric. However, their popularity declined in the 1910s due to greater range of fossil fuel cars. Electric cars only began to re-emerge in the U.S. in the 1990s following a push by the California Air Resources Board to reduce emissions. But, pressure by the oil industry combined with U.S. policy that supported the internal combustion engine and fossil fuels, not electric vehicles, caused manufacturers to stop producing and even destroying electric cars. After the development of the Toyota Prius, Tesla began working on an electric car in 2004, successfully producing a long-distance Roadster in 2008. In my expert opinion, if government had given support to electric cars during any decade prior to the mid- to- late 2000s, I believe, the percent of the U.S. automobile market that is electric would be significantly higher than today.

- It is my expert opinion that if the policies of the United States had encouraged more subsidies and R&D for renewable energy, efficiency, electric appliances, and electric cars rather than subsidies and other support for fossil fuels, our country would be a lot further toward a renewable-powered energy system today than it is, the amount of carbon dioxide pollution emitted would be substantially less, and the harms from climate change would not be as severe as they are today and are projected to be in the near and long-term.

CONCLUSION AND RECOMMENDATION

In sum, I conclude that electrification and use of direct heat in all energy sectors in the United States, and providing the electricity and direct heat with 100% wind, water, and sunlight (WWS) by 2050, with 80% by 2030, is technologically and economically feasible. Use of WWS technologies may be the only way to solve the climate, air pollution, and energy security problems in a timely manner. They also involve the least risk of collateral damage and serve multiple public interests, including creating more full-time, long-term jobs than lost, reducing reliance on the international search for energy, providing energy security, and reducing substantial air pollution health and climate problems. Given that 4-7 million people currently die premature each year worldwide due to fossil fuel pollution, including 62,000 (19,000-115,000) in the United States, and climate is changing rapidly due to the increase in human-emitted gases and particles into the atmosphere, the rapid deployment of a 100% WWS solution is important and practical for solving these problems simultaneously. The bottom line is that it is technically and economically feasible to transition off of fossil fuels by 2050 and supply our energy needs with 100% WWS. The primary barrier is the lack of government direction to move energy policy in the WWS direction and government policies and actions that continue to favor a fossil-fuel based energy system.

In my expert opinion, if the U.S. defendants in this case are ordered to plan for, and implement, a 100% WWS transition by 2050, it is feasible to develop such a plan and almost all the technology is available to carry out the plan quickly in a cost-effective manner.

Signed this 6th day of April, 2018 in Palo Alto, California.

Mark Z Jacobson

Mark Jacobson, Ph.D.

Exhibit F:

Expert Report of Dr. G. Philip Robertson

EXPERT REPORT
OF
G. PHILIP ROBERTSON

University Distinguished Professor of Ecosystem Ecology
Michigan State University

Kelsey Cascadia Rose Juliana; Xiuhtezcatl Tonatiuh M.,
through his Guardian Tamara Roske-Martinez; et al.,
Plaintiffs,

v.

The United States of America; Donald Trump,
in his official capacity as President of the United States; et al.,
Defendants.

IN THE UNITED STATES DISTRICT COURT
DISTRICT OF OREGON

(Case No.: 6:15-cv-01517-TC)

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TABLE OF ACRONYMS, ABBREVIATIONS, AND DEFINITIONS

BECCS: bioenergy with carbon capture and storage
C: carbon
C_{eq}: carbon equivalent; used to quantitatively compare greenhouse gases via a common metric based on global warming potentials for individual gases
CO_2: carbon dioxide; contains 27.3% carbon
CO_{2eq}: carbon dioxide equivalent
EPA: U.S. Environmental Protection Agency
DOE: U.S. Department of Energy
GtC: gigatonne of carbon, equivalent to 1 billion tonnes of carbon, or 1 PgC; 1 GtC = 1,000 MtC
ha: hectare, equivalent to 2.47 acres
IPCC: United Nations Intergovernmental Panel on Climate Change
Mha: million hectares, 1 Mha is equivalent to 2.47 million acres
MtC: million tonnes of carbon, sometimes abbreviated MMTC; 1,000 MtC = 1 GtC
N_2O: nitrous oxide
NRCS: Natural Resources Conservation Service
PgC: petagram of carbon, equivalent to 10^{15} gC
ppm: parts per million
tC: tonne of carbon, equivalent to 1,000 kgC or 10^6 gC
USDA: U.S. Department of Agriculture

Avoided Emissions: Greenhouse gas emissions not yet released that could be avoided if practices were altered from conventional practices. This includes fossil fuel emissions that are avoided by substituting biofuel combustion for fossil fuel combustion.

Carbon Sequestration: Any process that removes carbon dioxide from the atmosphere and stores the carbon portion in natural sinks like soils.

Negative Emissions: Greenhouse gas (CO_{2eq}) removed from the atmosphere with the carbon portion sequestered for long periods of time – sometimes indefinitely – within natural carbon sinks like soils and forests. In this report, negative emissions are those above and beyond the existing rate of natural sinks.

Federal Land: All U.S. federally-owned or federally-managed lands including forest lands, range lands, other agricultural lands, wetlands, and waterways.

Lands of the United States: All lands, both publicly owned and privately owned, within the boundaries of the United States.

Conterminous lands of the United States: All lands, both publicly and privately owned, within the 48 adjoining states plus the District of Columbia; also known as the contiguous U.S.

US Forests: All forestlands within the United States

Federal Forestland: All U.S. federally-owned or federally-managed forestlands.

INTRODUCTION

I, G. Philip Robertson, have been retained by the Plaintiffs in the above-captioned matter to provide expert testimony about the potential capacity for improved management of United States forest, range and agricultural lands to achieve net negative carbon emissions and avoid future greenhouse gas emissions. In this report I provide background on the global carbon cycle, describe how different land management practices can contribute to negative and avoided emissions, and provide a quantitative assessment of the potential for changes in management practices to provide meaningful greenhouse gas mitigation.

I have worked in the field of carbon and nitrogen biogeochemistry for 40 years since beginning my PhD studies in 1976. I am currently University Distinguished Professor of Ecosystem Ecology in the Department of Plant, Soil and Microbial Sciences at Michigan State University, where I have held a regular faculty position since 1987. I have been a University Distinguished Professor for the last seven years. Since 2017 I have also held the title of Scientific Director for the Department of Energy's Great Lakes Bioenergy Research Center at the University of Wisconsin and Michigan State University. For my entire career the main focus of my research has been studying the processes that regulate biogeochemical cycles of carbon and nitrogen at multiple scales, including plant, soil, and microbial interactions that affect the delivery of important ecosystem services such as climate stability, water quality, and plant productivity. I work primarily in agricultural ecosystems, and more broadly on the issue of agricultural sustainability, which includes the responses of cropping systems to climate change and the potential for land management to contribute to greenhouse gas mitigation. My CV, which includes a statement of my qualifications, is contained in **Exhibit A** to this expert report. A list of publications I authored within the last ten years is attached as **Exhibit B** to this expert report.

In preparing my expert report and testifying at trial, I am not receiving any compensation and am providing my expertise pro bono to the Plaintiffs given the financial circumstances of these young Plaintiffs. I have not provided previous testimony within the preceding four years as an expert at trial or by deposition. My report contains citations to all documents that I have used or considered in forming my opinions, listed in **Exhibit C** to this report.

The opinions expressed in this report are my own, not necessarily the opinions of any of the institutions for which I work or donate my time. The opinions expressed herein are based on the data and facts available to me at the time of writing, as well as based upon my own professional experience and expertise. All opinions expressed herein are to a reasonable degree of scientific certainty, unless otherwise specifically stated. Should additional relevant or pertinent information become available, I reserve the right to supplement the discussion and findings in this expert report in this action.

EXECUTIVE SUMMARY

Earth's carbon is found in six reservoirs: rocks, oceans, atmosphere, plants, soil, and fossil deposits. In the carbon cycle, carbon moves from one reservoir to another. The human-induced transfer of carbon from fossil deposits to the atmosphere is causing Earth to warm. Even when that transfer ceases, in order to return the atmospheric reservoir to a point conducive to human well-being, we will need to remove carbon from the atmosphere and store it in other reservoirs. This is known as carbon sequestration or negative emissions. The potential for increased carbon sequestration from U.S. forest, range, and agricultural land management is, at peak, around 0.414 GtCeq per year (414 MtCeq per year). This could result in negative emissions within the US totaling about 21 GtCeq by 2100. Changes to land management practices could avoid the emissions of another 0.12 GtCeq per year, totaling 9.7 GtCeq by 2100. All told, over the period 2020 to 2100, changes to land management practices in the U.S. could mitigate more than 30 GtCeq between 2020 and 2100, which is over 30% of the negative and avoided emissions needed, after phasedown of fossil fuel emissions, to return Earth's atmosphere to a more stable state.

Three types of CO_2 removal are most widely discussed today: 1) Improved land management, 2) Bioenergy with CO_2 capture and storage (referred to as BECCS), and 3) Direct air capture. BECCS and direct air capture are both theoretically possible but currently unproven at any meaningful scale, and thus are not analyzed in this report. Of these three, improved land management represents the most mature, technically feasible, widely deployable, and lowest cost option currently available. Thus, this report focuses on improving land management to remove and store CO_2 and to reduce future emissions of three key greenhouse gases – CO_2, nitrous oxide, and methane.

Soil represents one of the largest actively cycling reservoirs of carbon on earth, most of which is stored in the form of soil organic matter, largely comprised of decomposing plant residue. Almost everywhere, conversion of native forest and grasslands to agriculture has resulted in a 30–50% loss of this carbon to the atmosphere as further decomposition to CO_2 is accelerated. Almost all soils actively managed for agriculture, as well those that have been abandoned from agriculture due to degraded fertility, have soil carbon levels well below their original levels, providing significant opportunities to sequester additional carbon.

There are a number of well-tested methods to increase soil carbon through agricultural practices on land used to grow annual crops. Avoiding tillage with no-till technology is one well-recognized practice to rebuild soil carbon. Other practices can be just as effective: adding winter cover crops to avoid bare soil for most of the year can increase soil carbon, as can diversifying crop rotations – growing more than one or two crops in sequence – and applying compost or manure. Growing perennial grasses or trees on degraded or low value agricultural soils can also result in significant carbon gains. On pastures and rangeland, soil carbon storage can be improved by increasing plant productivity via improved plant species and by avoiding over grazing via careful attention to the number of livestock per acre. About 43% of all pasture and rangeland in the U.S. is managed by federal agencies.

Forests can also be managed to enhance carbon sequestration in trees and soil. Faster growing species accumulate more carbon over their lifetimes and therefore planting more of these species will store more carbon in wood, as will growing trees in longer rotations (the number of years between harvests). A number of management factors can increase forest soil carbon. About 42% of all forestland in the conterminous U.S. is managed by federal agencies.

In addition to increasing carbon sequestration, changes in land management practices on federal and private lands can also reduce the amount of greenhouse gas emissions stemming from land use. Nitrous oxide is a greenhouse gas 250-300 times more potent than CO_2. Agriculture is responsible for 84% of global anthropogenic nitrous oxide emissions, and most agricultural emissions (62%) come from soils amended with nitrogen from fertilizers, manures, or legumes. Reducing nitrogen fertilizer rates to those needed for optimum yields is the most reliable means to reduce nitrous oxide emissions from fertilized cropping systems.

Methane is 28-36 times more potent than CO_2. Agricultural methane emissions come from digestive fermentation by livestock (52%), rice cultivation (22%), biomass burning (19%), and livestock manure handling (8%). Rice cultivation practices and livestock management offer important land-use related methane mitigation opportunities. Methane from rice production can be minimized through periodic drainage of flooded rice fields.

Finally, there is an opportunity to reduce greenhouse gas emissions and increase carbon sequestration by growing cellulosic bioenergy crops such as switchgrass on marginal lands that were formerly in agriculture and on lands now used to grow corn for grain ethanol.

All told, technology is available today to store carbon or avoid future greenhouse gas emissions from agriculture in the U.S. equivalent to more than 30 GtCeq by 2100. Farmers, ranchers, and landowners have shown a willingness to accept payments for implementing such practices. Financial incentives and federal policies will need to be aligned with the sequestration practices described below in order to achieve this scale of increased sequestration.

EXPERT OPINION

1.0 Introduction

Carbon is one of the most abundant elements on Earth. Most of the carbon on Earth is stored in rocks. The rest of Earth's carbon is in our oceans, atmosphere, plants, soil, and fossil fuels. Earth's carbon cycle involves the flow of carbon between each of these carbon reservoirs (or sinks). Some of the flow is very slow and some is fast. When carbon moves out of one reservoir it enters another, as depicted in **Figure 1**.

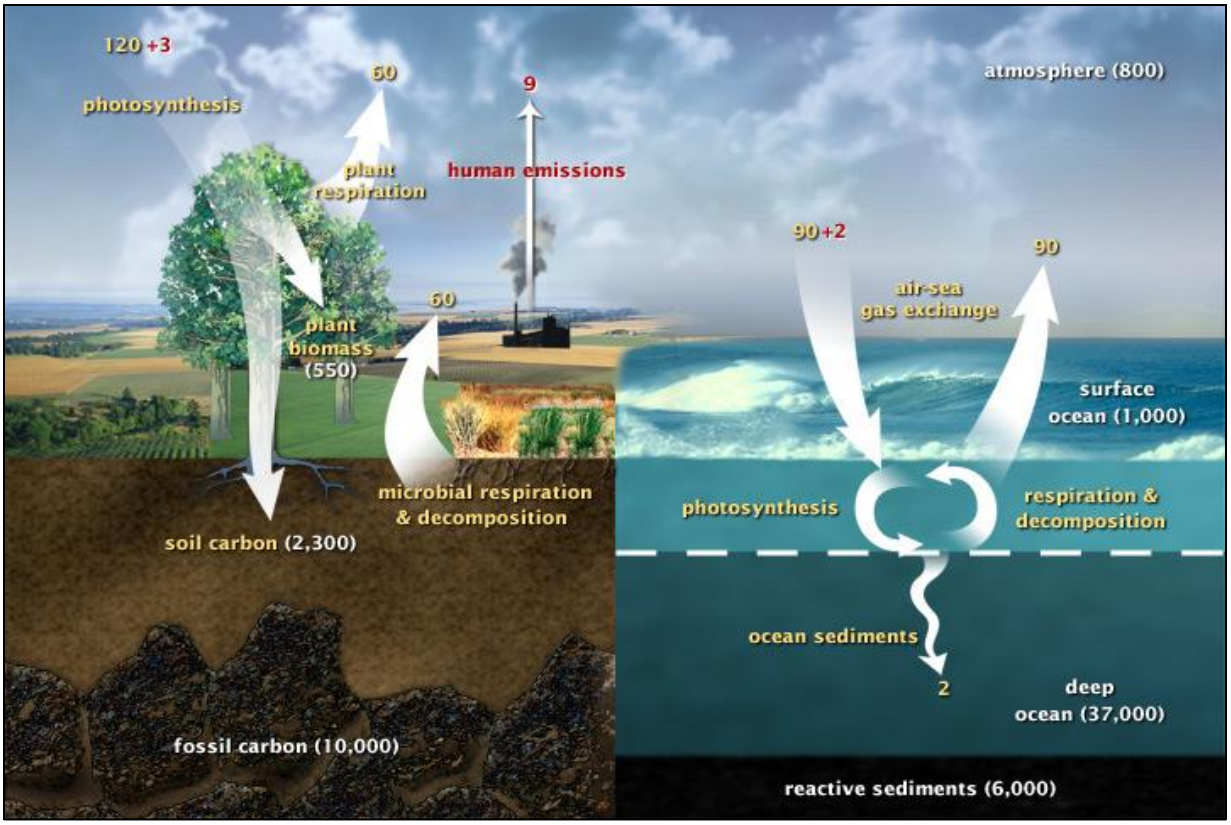

Figure 1. This diagram of the fast carbon cycle shows the movement of carbon between land, atmosphere, and oceans. Yellow numbers are natural fluxes, and red are human contributions in gigatonnes of carbon (GtC) per year. White numbers indicate stored carbon (carbon locked in deep geological reservoirs is not included except for fossil fuel reserves that could be mined). The human contribution, though seemingly small, adds up to a large imbalance and consequent increase in atmospheric CO_2. (https://earthobservatory.nasa.gov/Features/CarbonCycle/)

The atmosphere's CO_2 content is largely determined by the balance between processes that remove CO_2 from the atmosphere, such as photosynthesis and CO_2 absorption by seawater, and processes that return CO_2 to the atmosphere, such as respiration and fossil fuel burning. About 50% of the CO_2 that humans add to the atmosphere each year by burning fossil fuels is removed annually by natural removal and storage processes; the remainder accumulates in the atmosphere.

CO_2 transferred from the fossil deposits reservoir to the atmosphere through the burning of fossil fuels results in rising temperatures on Earth, as predicted by theory in the 19th century. In order to restore the Earth's energy balance so that temperatures can stabilize at safe levels for humanity and our natural systems, the carbon content of the atmosphere must be reduced. Such reductions will happen naturally over millennia if carbon emissions from the fossil reservoir cease. However, to avoid unsafe temperature increases, CO_2 must be removed more quickly. Managing plant and soil reservoirs for greater carbon storage represents a way to reduce – or mitigate – atmospheric CO_2. Increasing the amount of carbon stored in these reservoirs is commonly referred to as carbon sequestration, carbon storage and removal, or negative emissions.

Decreasing the amount of carbon stored in the atmosphere is widely acknowledged to require removing and storing CO_2 in other carbon reservoirs (negative emissions) as well as curtailing CO_2 sources such as fossil fuel burning (decarbonization) and deforestation. Of almost 900 mitigation scenarios evaluated by the Intergovernmental Panel on Climate Change (IPCC) with integrated assessment models,[1] all of the 116 deemed effective involved curtailing sources of CO_2 and more than 100 also involved CO_2 removal.[2, 3] Both CO_2 source reduction *and* CO_2 removal are thus central to future climate mitigation efforts. Indeed, under any climate recovery scenario, negative CO_2 emissions (removal and storage) will be required starting immediately to bring atmospheric CO_2 concentrations back within safe limits for our biological and human systems.[4, 5]

Three types of CO_2 removal are most widely discussed today: 1) Improved land management, 2) Bioenergy with CO_2 capture and storage (referred to as BECCS), and 3) Direct air capture.[3, 6, 7] Improved land management entails managing ecosystems to sequester more carbon in living biomass such as long-lived trees and in dead biomass such as organic matter in soils and ocean sediments. Bioenergy with CO_2 capture and storage refers to extracting energy by burning biomass and storing the resulting CO_2 in geologic reservoirs. Direct carbon capture involves extracting CO_2 directly from the air via enhanced weathering of rocks and minerals or direct air capture, with subsequent geologic storage. BECCS and direct air capture are both theoretically possible but currently unproven at any meaningful scale, and thus are not further analyzed in this report. Enhanced rock weathering and ocean fertilization have also been proposed but are less widely discussed or tested.[7, 8] Of this group, improved land management represents the most mature, technically feasible, widely deployable, and lowest cost option currently available.[3, 7] We have known about this option and its environmental co-benefits for decades.

In addition to managing land for negative emissions, land management can also contribute to climate mitigation by avoiding further greenhouse gas emissions.[4, 9] This can be done, for example, by reducing deforestation, a practice responsible for ~10% of total global carbon emissions today,[10] almost all outside the U.S. But greenhouse gases are also emitted by other land management and agricultural practices. For example, nitrogen fertilizer emits CO_2 when manufactured and emits nitrous oxide when applied to soils. Methane is emitted by soils under rice cultivation. Land management practices that avoid or reduce greenhouse gas emissions thus represent an additional climate mitigation opportunity. Some management changes have the potential to both curtail CO_2 emissions and remove CO_2 from the atmosphere. For example, producing ethanol from perennial grasses instead of corn grain both consumes less fossil fuel (curtailing CO_2 emissions) and stores more soil carbon (enhancing CO_2 removal and storage).

In the pages that follow are current opportunities for improved land management practices in the U.S. that are feasible and currently available to mitigate climate change. I emphasize those land management practices most likely to produce significant negative emissions—those that remove and store CO_2 from the atmosphere—and as well those practices capable of reducing emissions of CO_2 and the other biogenic greenhouse gases nitrous oxide and methane, respectively responsible for 82%, 10% and 5% of total U.S. greenhouse gas emissions.[11]

2.0 Scale of the Problem

From pre-industrial times fossil fuels have added 327 GtC to the atmosphere (half of that just since the 1980s),[12] with another 156 GtC added by deforestation. In 2014 fossil fuel burning added 8.8 GtC to the atmosphere,[13] with the U.S. responsible for 1.5 GtC[11] or about 17% of the global total that year. In recent years global deforestation has added annually another 0.9 GtC,[10] none from the U.S.[11]

To avoid or deflect the most disruptive effects of climate change now underway – sea level rise, shifting climate zones, species extinctions, coral reef decline, climate extremes, expanded forest burning, and human health impacts – requires returning atmospheric CO_2 concentrations, currently above 400 parts per mission, to 350 parts per million or below.[5, 14] This CO_2 level would largely restore Earth's energy balance, keeping temperatures within the Holocene range to which human societies, agriculture, and other species are adapted. This could be achieved by limiting total cumulative fossil fuel emissions to 500 GtC coupled with cumulative negative emissions equivalent to 100 GtC by 2100.[4] Hansen et al.[4] identify two major ways that land management can achieve a 100 GtC drawdown this century: 1) negative emissions from forest and soil carbon storage including reforestation and improved agricultural practices, and 2) avoided emissions from ending deforestation and deriving bioenergy from dedicated energy crops that do not compete with food crops. I agree these strategies have the potential to produce that quantity of negative emissions and both are discussed in more detail, below.

Ocean and land sinks today remove from the atmosphere about half of the CO_2 emitted by anthropogenic activities, or ~4.9 GtC annually for the 1990-2000 period.[10] About a third of the emitted CO_2, 2.6 GtC for this period, is removed by land sinks.[10] In the U.S., land sinks remove annually 0.2 GtC.[11] Negative emissions as discussed here are in addition to these existing natural sinks.

3.0 Soil Carbon Cycling and Storage

Carbon accumulates naturally during soil development as plants colonize new substrates such as sand and rock surfaces, transform atmospheric CO_2 to new biomass via photosynthesis, and then leave behind carbon-rich leaves, wood, roots, and other biomass that then decompose. Some plant parts decompose quickly, others more slowly. Wood, for example, is very resistant to microbial attack, and some of the natural carbon products that are highly resistant to microbes can persist for thousands of years. Soil organic carbon can also be trapped within soil aggregates, which are hardened clusters of soil particles (grains of sand, silt, and clay) wherein very low oxygen levels inhibit microbial activity. And some decomposition products, usually in the form of complex organic molecules, can be highly resistant to decay especially when bound to soil mineral surfaces.

Over time, most soils accumulate organic carbon to some equilibrium value that represents a few percent of total soil mass; in most soils this value is less than 5%. In waterlogged or cold soils such as those under bogs and tundra, decomposition occurs very slowly—microbial activity is suppressed by low oxygen or low temperatures or both—and in these locations, carbon can accumulate to very high proportions of soil mass.

Soil thus contains organic carbon of different ages and different susceptibilities to microbial decomposition. Soil disturbance—both natural and anthropogenic—can stimulate decomposition by altering the soil physiochemical environment. Clearing land for agriculture does exactly this: plowing the soil breaks apart aggregates and exposes protected carbon to microbial attack, and allowing soil to remain bare for much of the year causes it to be wetter and warmer—perfect conditions for microbes to convert soil organic carbon back to CO_2 in their quest for energy. Almost everywhere, conversion of native forest and grassland soils to agriculture results in a 30–50% loss of carbon from the top soil layers within just a decade or two (**Figure 2**),[15] a general pattern well-recognized since the 19th century.[16] Global estimates of this loss total 133 GtC, split nearly evenly between crop and grazing lands.[17]

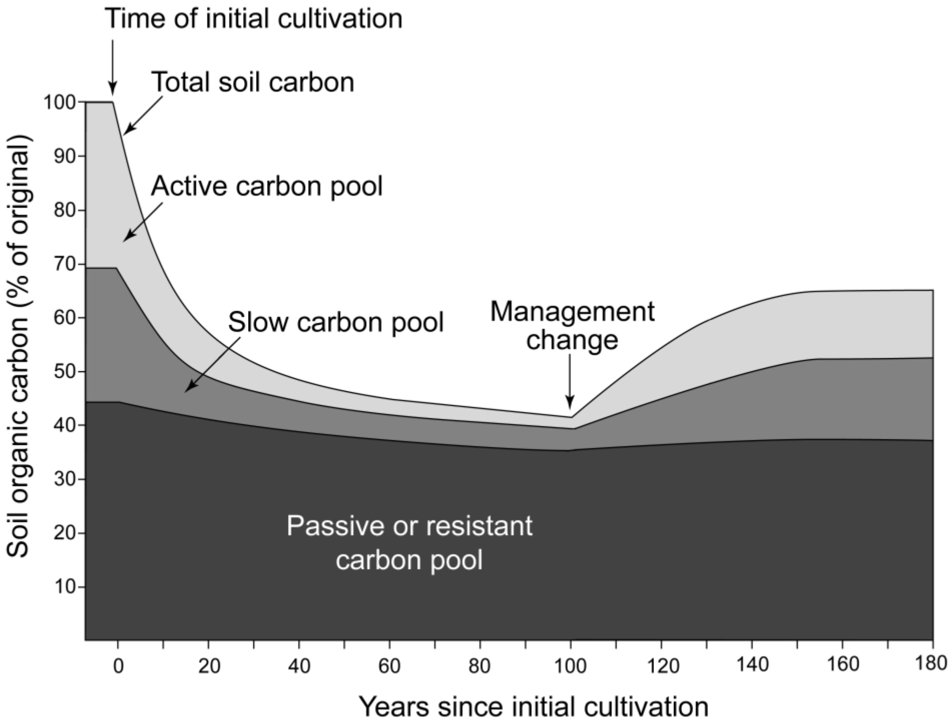

Figure 2. Changes in soil organic matter fractions following cultivation of a soil profile under native vegetation. Redrawn from Grandy and Robertson (2006).[26]

The basis for soil carbon gain is thus the net balance between photosynthesis, which fixes CO_2

into biomass carbon, and decomposition, which transforms biomass carbon back to CO_2. Thus the organic carbon content of soils is regulated by the balance between the rate of carbon added to soils from plant residues (both aboveground biomass and roots), plus, in agricultural soils, organic amendments such as compost and manure, and the rate of carbon lost from soil, mainly via decomposition, though soil erosion can be locally important.

3.1 Measuring Soil Carbon Storage

The total amount of organic carbon in a soil sample can be measured by a variety of techniques, most reliably by thermal oxidation.[18] Historically, carbon has been assessed by combusting a small soil sample at temperatures sufficient to convert organic carbon to CO_2. This generally entails placing a soil sample of known weight into a high-temperature furnace for several hours; the difference in mass on re-weighing represents oxidized carbon and by difference, the carbon content of the soil prior to combustion. A variation on this technique uses a chemical oxidizing agent rather than direct heat to combust the carbon. Today soil carbon is most commonly analyzed by gas chromatography: an automated sampler drops a tiny amount of ground, well-mixed soil into an oxygen-infused chamber that is subsequently ignited; the CO_2 liberated is then measured by gas chromatography or infrared gas absorption analysis.[19] Data from samples so analyzed can be used with high confidence; identical samples typically vary no more than 5-10%.

Due to the natural variability of soil at even small scales, most field experiments to document the effects of a management practice on soil carbon typically compare practices for similar slope positions, and often in replicated small plots, in order to detect differences with statistical confidence. Even so, to dependably detect soil carbon change typically requires a decade or more[20] because change occurs slowly such that it is much easier to detect with confidence a 10% carbon change over ten years that a 1% change over one year. Thus, both long-term sampling and experiments are important for assessing changes in soil carbon.

Soil carbon also varies with depth in the soil profile, so it is also necessary to design sampling programs to directly compare similar depths. Typically, the upper few cm of soil contain the most carbon, with concentrations falling rapidly in lower layers. Lower subsoil carbon concentrations plus its greater natural variability make it especially difficult to detect soil carbon change in lower horizons.[21] Thus, most of what we know about the effects of land management practices on soil carbon stores comes from changes in surface horizons,[22] typically the upper 25-30 cm where most root growth and biological activity occurs.

3.2 Soil Carbon Gain by Improved Land Management

Soils globally contain ~1,800 GtC to 1 m depth, comprising the largest terrestrial organic carbon pool and representing about twice the amount of carbon that is in the atmosphere (830 GtC). Soils of the conterminous U.S.[†] contain ~81 GtC to 1 m depth.[23] Thus a relatively small percentage increase in soil carbon represents a potentially strong climate change mitigation opportunity.[24]

[†] This includes soils on both federal and private lands in the lower 48 United States.

Soil carbon stocks can be increased by increasing the rate of carbon additions to soil or by decreasing the rate of decomposition, or both. Croplands and grazing lands can be managed for enhanced carbon gain, but for each there are limits to the extent of gains possible. First, with changes to soil management that lead to carbon gain, soil carbon stocks tend towards a new equilibrium asymptotically, such that gains diminish as the new equilibrium level is approached, usually over a few decades (**Figure 2**).[25] Second, this equilibrium level is finite for a given soil at a given location: soils tend to have a saturation level above which no further soil carbon increase is likely possible.[26] Furthermore, if this equilibrium is reached because of high exogenous inputs such as compost or manure, cessation of these inputs will lead to a new, lower equilibrium.[27]

Nevertheless, almost all soils in the U.S. actively managed for agriculture, as well as those that have been abandoned from agriculture due to degraded fertility, have soil carbon levels well below saturation, providing significant opportunities to manage for additional carbon. Cropland surface soils of the central U.S. are believed to have lost ~50% of their pre-cultivation carbon stocks by 1950.[28]

A number of agricultural practices have the potential to increase soil carbon. In most cases these practices differ by management system: practices for croplands are different from practices for grazing lands and both are different from practices for managed forests. Nevertheless, the principles in all cases are the same, and some practices can be applied across systems. Practices below are grouped into three categories: those relevant to cropland and grazing lands management, wetlands restoration, and forest management.

In Section 5, below, the total potential impact for the U.S. (GtC) is estimated based on the average likely carbon gain (GtC ha^{-1} yr^{-1}) for a given practice multiplied by the areal extent (acreage) on which the practice could be implemented, and then again by the number of years between 2020 and 2100 that the average gain might persist. In some cases, multiple practices could be implemented on the same lands – many cropland management practices, for example, such as no till adoption and diversified crop rotations. In other cases, practices are mutually exclusive – cropland management practices, for example, cannot be applied to set-aside cropland converted to perennial grasses. And some practices are already implemented to limited degrees.

Areal extents of potential practices are thus additional to any existing implementation, and are intentionally conservative in order to avoid the likelihood of double counting. The maximum extents possible are, of course, constrained by available land area; all private and public lands within the conterminous U.S. (the lower 48 states), on which Section 5 estimates are based, contains 159 Mha of cropland, 265 Mha of rangeland and pasture, and 256 Mha of forest lands.[29]

About 43% of total rangeland and pasture[30] and 42% of total forest land[31] in the conterminous U.S. are owned by the Federal Government and thus practices could be implemented directly. On privately held lands practices can be encouraged through financial incentives such as tax abatements or direct payments, used since the 1930s to advance national conservation goals. In 2017, for example,[32] the USDA spent $2.0 billion for the Conservation Reserve program, which kept 9.4 Mha of environmentally sensitive land set aside from production, including 0.8 Mha of restored wetlands; $2.8 billion for the Environmental Quality Incentives Program and the

Conservation Stewardship Program, which provide landowners conservation assistance to reduce soil erosion and enhance water, air, and wildlife resources on crop and grazing lands; and $0.5 billion for the Agricultural Conservation Easement Program, which helps to conserve grazing and wetlands in particular. Other than fire suppression, minor assistance was provided to private forest landowners, chiefly through the $0.02 billion Forest Stewardship program.

The duration of a given practice's carbon gain is likewise constrained by the average amount of time it takes the sink, whether soil or trees, to reach local equilibrium. For soils this will vary mainly by climate, management, and initial carbon content – for example, a degraded or long-cultivated soil will take longer to equilibrate than will a soil closer to its original carbon content. For trees this will vary mainly by location, species, and soil fertility – for example, trees in the Rocky Mountains grow more slowly than trees in the Pacific Northwest, and red pine grows faster than Douglas fir. On the other hand, the duration of avoided emissions is not constrained by biology – the emissions reductions will persist for as long as the practice persists.

3.2.1 Cropland Management

Cropland Management: Tillage

Farmers plow to control weeds, manage residues, and prepare the seed bed for planting. Plowing also causes carbon loss by mixing plant residues throughout the surface soil, bringing it into contact with microbes and other soil organisms like earthworms, and with moister soil more favorable to microbial activity. Plowing also breaks apart soil aggregates, especially the larger ones, exposing trapped organic carbon to aerobic microbes that readily respire it to CO_2.[33] In fact much of the early increase in atmospheric CO_2 starting in the 19th century was the result of pioneer cultivation,[34] which stimulated microbial activity and the conversion of soil organic matter to CO_2.

Modern advances in tillage technology provide many more options than traditional moldboard plowing, which inverts the upper 20–30 cm of soil. Contemporary lower-impact options, typically termed conservation tillage, range from chisel plowing, which avoids inverting the soil profile, to no till, which leaves the soil profile completely undisturbed. With no till, weeds are usually suppressed with herbicides or, at smaller scales, with cover crops and mechanical crimping, and seeds are planted with equipment that places seeds in slits cut through the preceding crop's residue, which is left to decompose on the soil surface rather than buried. Both of these practices can significantly increase the amount of carbon stored in the soil.

The primary impetus for the development of no-till and other conservation tillage techniques was erosion control.[35] Under no-till corn, for example, erosion can be reduced as much as 90%[36-39] by reducing the exposure of soil aggregates to raindrop impacts and to freeze-thaw and wet-dry cycles, allowing more to remain intact, protecting entrapped carbon from microbial oxidation to CO_2.[40] And plant residue, by remaining on the soil surface, decomposes more slowly.[41]

Carbon accumulation due to no-till has been documented in soils worldwide, including the U.S. since the 1950s.[35] Long-term field experiments comparing no-till to conventional tillage show typical no-till increases of 0.1–0.7 tC ha^{-1} yr^{-1}.[42, 43] West and Marland[44]estimated average rates of

0.3 tC ha^{-1} yr^{-1}, a rate consistent with other syntheses[45-48] including Eagle et al.'s,[48] who included the impact of nitrous oxide emissions in their overall estimate. Where soil carbon is already high, no-till has less capacity to increase soil carbon; no till also has less capacity to increase soil carbon in cooler or wetter areas where it can sometimes reduce crop yield.[49] Other forms of conservation tillage can also build soil carbon but at lower rates and less consistently.[50]

Importantly, to achieve a long-term increase in soil carbon from no-till practices, the no-till practices must be implemented continuously. Stored soil carbon can be quickly oxidized to CO_2 when no-till soils are tilled,[15, 51] with much of the no-till carbon benefit lost after a single tillage event.[52] Thus, while no-till is practiced on as much as 36% of U.S. soils annually, because it is practiced at least three years in a row on less than 13% of U.S. cropland,[53] and almost certainly less on a permanent basis, there presently is little long-term climate benefit. Efforts to use no-till as a negative CO_2 emissions strategy must consider no-till longevity an important design component.

An exception to this continuous long-term no-till rule is the potential for burying surface soil carbon with a single inversion tillage. In humid climates with poorly drained soils, a one-time deep inversion tillage may promote soil carbon storage by moving high-carbon surface soils to >50 cm depth, where decomposition is slowed due to cooler, wetter conditions with less oxygen. At the same time, low carbon soil at depth is moved to the surface where it can accumulate more carbon. In one of the only long-term deep tillage experiments, Alcántara et al.[54] found carbon accumulation rates equivalent to ~1 tC ha^{-1} yr^{-1} in Germany.

A further consideration is the potential for soil carbon to change at depths below the top soil horizon. Almost all quantitative assessments of no-till to date have assessed changes in soil carbon in the upper 25-30 cm of the soil where roots, soil organic matter, and microbes are most concentrated. However soil carbon also occurs at lower depths,[17] and there is the potential,[22, 55] but little quantitative evidence,[21, 56] for soil carbon changes at depth to counteract surface soil gains in some locations.

Although carbon savings associated with no-till also accrue from reduced fuel use due to fuel saved by not plowing, this saving is typically small (typically <0.05 tC ha^{-1} yr^{-1}),[44, 57] though permanent in that it is not subject to re-release like stored soil carbon.

Cropland Management: Summer Fallow and Winter Cover Crops

In most annual cropping systems soils are left bare for a substantial portion of the year**.** Without plants, soils lose carbon because there are fewer carbon inputs from roots and aboveground residues and because decomposition rates are higher – soils are wetter and warmer without plant transpiration and shading.[58] For most annual crops in the U.S. (e.g., corn, soybean, cotton, sorghum, peanut, and vegetables) the fallow period occurs over winter, stretching from mid-fall to late-spring (5-7 months). For fall-planted crops like winter wheat and winter canola, the fallow period occurs over summer and lasts from the mid-summer harvest to at least late fall (~3 months), or, where followed by a summer crop, to the following spring (9-10 months). Thus for most U.S. cropland the soil is bare for much of the year. In semi-arid regions summer fallows are often used to conserve soil moisture for a following crop.

Eliminating summer fallow periods can, in the U.S., sequester up to 0.3 tC ha^{-1} yr^{-1} of soil carbon depending on climate and tillage method. Eagle et al.[48] estimated an average soil carbon gain of 0.16 tC ha^{-1} yr^{-1}. Less the CO_2 cost of the additional nitrogen fertilizer used reduces the net benefit to 0.09 tC ha^{-1} yr^{-1}. Where summer fallow is used for water conservation, summer fallow cannot likely be eliminated but could be used less frequently, such as every third or fourth year instead of every second or third year.[59, 60]

Winter cover crops include annual grasses such as rye and legumes such as clover that are typically planted in the fall following harvest of the preceding crop. Prior to winter the cover crop germinates and grows to a size that allows it to survive wintertime temperatures in a dormant state, after which it grows rapidly the following spring. Before planting the following summer crop, the cover crop is killed and then either left to decompose on the soil surface or, more commonly but not necessarily, buried with tillage. Adding winter cover crops to a rotation can add 0.03–0.55 tC ha^{-1} yr^{-1} of soil carbon,[61, 62] depending on climate, even when the cover crop is tilled under — providing in many cases a carbon gain equal to no-till.[63]

Winter cover crops provide the additional co-benefit of reducing the need for nitrogen fertilizer due to their ability to scavenge the previous crop's leftover soil nitrogen that would otherwise be leached to groundwater or emitted to the atmosphere, and, in the case of legume cover crops, the ability to capture or "fix" nitrogen from air. This captured or new nitrogen is then made available to the next crop, reducing the need to apply fossil fuel-derived nitrogen fertilizers, thereby creating additional carbon savings by avoiding one of the most significant sources of greenhouse gases in intensively managed field crops.[64]

A recent meta-analysis[65] estimates average carbon sequestration potentials for winter cover crops of 0.32 tC ha^{-1} yr^{-1} globally, with a number of studies reporting rates as high as 1 tC ha^{-1} yr^{-1}. Including fertilizer savings, Eagle et al.[48] estimate a net potential carbon benefit of 0.37 tC ha^{-1} yr^{-1} for winter cover crop use in the U.S., not including CO_2 and nitrous oxide savings from reduced nitrogen fertilizer use, which they estimate could add another 0.16 tC ha^{-1} yr^{-1} of carbon savings. Poeplau and Don's[65] analysis suggest a new soil carbon equilibrium is reached after 155 years;[9] the reduced CO_2 and nitrous oxide savings from reduced nitrogen fertilizer use, where it occurs, would last indefinitely. For a variety of reasons, including additional seed and labor expenses as well as the risk of not killing the cover crop in a timely manner, cover crops are planted today on only ~3% of U.S. cropland.[66]

Cropland Management: Diversifying Crop Rotations

Crop species vary in the amount of biomass they produce, in the proportion of biomass that goes unharvested, including roots, and in the resistance of unharvested residue to decomposition. Thus, diversifying crop rotations is a time-tested means to build and retain soil carbon. In the U.S. as early as 1933 Salter and Green[67] reported on a 31 year experiment in which more complex rotations retained more soil carbon. In central Ohio they found that continuous corn (corn planted year after year) lost three times more soil carbon than did a three-year corn-wheat-oats rotation; continuous wheat and continuous oats similarly lost twice as much carbon as did the three year rotation (**Figure 3**).

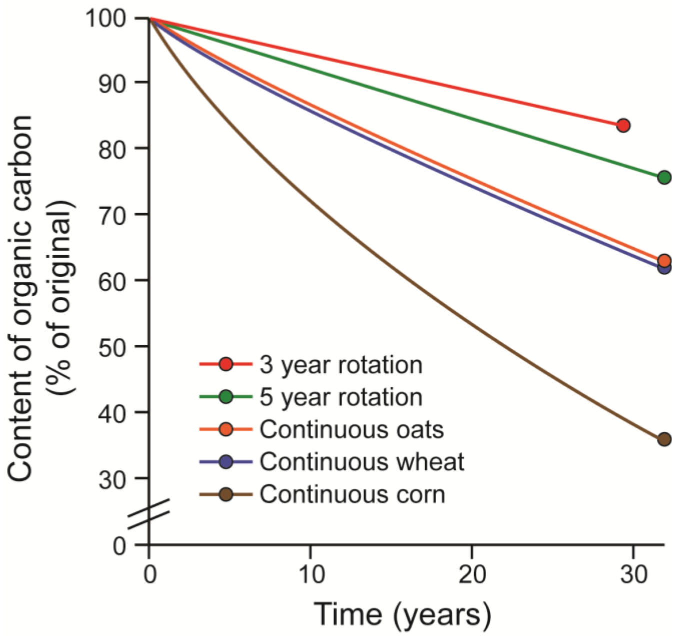

Figure 3. Rotation effects on soil carbon maintenance over a 31-year experiment. Redrawn from Salter and Green (1933).[58]

Diversifying annual crop rotations can thus significantly increase carbon stores.[50, 60, 68] The addition of perennial species such as hay and alfalfa to annual crop rotations, because of the deep and persistent roots of perennial crops and their longer growing season, can boost soil carbon still further,[42] as can the inclusion of legumes such as clover.[69] Measurements of soil carbon change under more diverse annual cropping systems range from 0.02 to 1.1 tC ha^{-1} yr^{-1},[46, 50, 70, 71] but results are highly dependent on associated full-rotation changes in crop residues, tillage, and other factors that affect soil carbon stores. In consideration of these unknowns, Eagle et al.[48] estimate an average net carbon benefit of 0.05 tC ha^{-1} yr^{-1} for diversifying crop rotations to a sequence more complex than corn – soybean, mainly achieved by lower nitrous oxide emissions.

Cropland Management: Manure and Compost Addition

Organic materials such as compost and manure, when added to productive soils, tend to increase soil carbon stocks only as long as additions are sustained.[27] Added to less productive soils, however, benefits can persist because of their additional impact on soil water holding capacity, porosity, aeration, infiltration, and nutrient holding capacity. These soil fertility co-benefits can increase crop productivity and subsequent residue inputs. Thus, while the climate benefit of moving compost or manure from one part of the landscape to another must be considered,[72] where soil fertility is sufficiently improved to increase productivity the soil carbon gain is a legitimate and persistent climate benefit.

In one recent example, Ryals et al.[73, 74] added compost to rangeland, which, exclusive of carbon in the compost addition itself, appeared to increase soil carbon storage by 25-70% or 0.51-3.3 tC ha^{-1} three years after a single compost addition.[74] Where manure is derived from crop harvest, which is the case for most dairy and feed-lot cattle in the U.S., its return to soil can be considered another form of crop residue return and thus also a climate-legitimate carbon gain when compared to business-as-usual practices. Estimates of soil carbon gain from long-term applications of livestock manure to arable soils range from 0.2 to 0.53 tC ha^{-1} yr^{-1}.[75, 76] Eagle et al.[48] estimate a range of 0.05 to 1.4 for an average of 0.71 tC ha^{-1} yr^{-1} that does not include CO_2 savings from reduced nitrogen fertilizer use. Sequestration will likely continue for the duration of manure additions, in our case >80 years – the world's longest-running manure addition experiment has found soil carbon stocks still increasing after 120 years,[77] though stocks will equilibrate to some lower level upon cessation.[77, 78]

3.2.2 Cropland Conversion to Perennial Grasses

Cropland Conversion: Set-aside Highly Erodible Cropland

Converting degraded or highly erodible cropland to perennial grasslands has the potential to sequester soil carbon insofar as perennial grasses have greater root carbon stocks than annual crops and because they are grown without tillage. Nevertheless, such conversions must be planned carefully to result in a legitimate climate benefit: Converting annual cropland to perennial grassland has no climate benefit where equivalent food production must be made up by more intensive crop production elsewhere, especially if such displaced crop production causes deforestation.[79] Indirect land use change effects, while disputed by some,[80] are undoubtedly possible and can potentially exceed local carbon savings.[81]

Nevertheless, USDA conservation programs that pay farmers to convert privately-owned annual cropland with conservation value (e.g., highly erodible land) to grasslands or trees can lead to significant soil carbon savings as a valuable co-benefit. For example, around 9 Mha are currently enrolled in the U.S. Conservation Reserve Program, down from a high of 15 Mha in 2007.[82] Sperow et al.[83] estimate that an additional 30 Mha could be added to the 9 Mha currently enrolled based on a USDA erodibility index.

Several recent reviews of soil carbon gain on conversion of annual grain to perennial grasses report average carbon sequestration potentials that range from 0.28–1.3 tC ha^{-1} yr^{-1}.[84-87] Including the upstream savings from reduced agronomic inputs and nitrous oxide emissions (but not fossil fuel carbon offsets), Eagle et al.[48] estimate an average carbon benefit of 0.97 tC ha^{-1} yr^{-1}.

Cropland Conversion: Cellulosic Bioenergy on Grain Ethanol Lands

Where annual crops are currently used for grain-based biofuel production, conversion to dedicated cellulosic feedstocks such as perennial grasses could likewise sequester soil carbon and in this case without potential indirect land use change effects. Cellulosic feedstocks would additionally provide greater life cycle carbon savings than the grain-based feedstocks they would replace.[88] In 2017 ~38% of total U.S. corn acreage, or 13 Mha, was used for grain ethanol production;[89] converting this cropland to a perennial cellulosic crop would result in carbon savings additional to those from no-till conversion (assuming conversion from no-till to avoid double counting the no-till and perennial conversion benefits).

The rate of soil carbon gain for annual cropland converted to perennial biofuel crops would be similar to that for set-aside cropland (0.97 tC ha^{-1} yr^{-1}). This assumes little of the converted annual cropland was under permanent no-till management (see Section 3.2.1, above).

Cropland Conversion: Cellulosic Bioenergy on Former Cropland

The potential for additional mitigation from planting marginal lands – former cropland now abandoned – to cellulosic biofuel crops is also significant. Additional to the fossil fuel offset benefit is the soil carbon gain, especially on soils abandoned due to low fertility. Again, placement of such crops would need to avoid land with significant standing carbon stocks such as forests and wetlands to achieve a short-term climate benefit. Robertson et al.[88] note that about 55 Mha of the 70-100 Mha of cropland abandoned since 1900 that is neither forest nor wetland would be needed to meet expected 2050 biofuel needs.[90] Planting these lands to higher productivity grass species would cause carbon accumulation additional to that already occurring in these lands.

The rate of soil carbon gain for former cropland converted to perennial biofuel crops would be similar to that for set-aside cropland but discounted by the carbon gain already occurring under existing unmanaged vegetation.[88] Assuming that the managed grasses are about twice as productive as the pre-existing vegetation, the discounted credit is likely to be ~50% of the grassland conversion credit of 0.97 tC ha^{-1} yr^{-1}, or 0.48 tC ha^{-1} yr^{-1}. This value does not include a fossil fuel offset credit.

3.2.3 Grazing Lands Management

Grazing Lands Management: Improved Animal Stocking Rates

Grazing lands, whether planted pastures as are typical in the eastern U.S., or extensive rangelands as are typical in the western U.S., are dominated by perennial grasses managed without annual tillage. Soil carbon stores can be improved significantly by increasing plant productivity via improved attention to livestock stocking rates.[86] On rangelands, estimates of soil carbon increases resulting from improved stocking rates range from 0.07 to 0.31 tC ha^{-1} yr^{-1},[91, 92] with higher rates for the Rocky Mountains and Great Plains region. In a new meta-analysis of some 50 studies, Conant et al.[86] estimate an average soil carbon sequestration potential for improved stocking management on extensive rangelands of 0.28 tC ha^{-1} yr^{-1}. Because of a relatively low sequestration rate, time to equilibration will likely exceed 80 years.

On pasturelands, Eagle et al.[48] note the potential for intensive rotational grazing to improve soil carbon storage due to increased plant productivity and careful attention to stocking rates. The average sequestration rate for the few available published studies is 0.25 tC ha^{-1} yr^{-1}.

Grazing Lands Management: Improved Plant Species Composition

Grazing lands carbon sequestration can also be increased by improving grass species composition. Interseeding legumes such as alfalfa on rangeland[93] can increase long-term carbon accrual by 3.1 tC ha^{-1} yr^{-1}, and interseeding improved grass species can improve average soil C by similar amounts.[94] Eagle et al.[48] estimate an average soil carbon gain of 0.40 tC ha^{-1} yr^{-1} for improved species composition on rangelands. Henderson et al.[95] estimate an average gain of 0.56 tC ha^{-1} yr^{-1} for planting legumes in pastures, even after decrementing rates for increased nitrous oxide emissions.

3.2.4 Frontier Technologies

There are unconventional technologies also under study for increasing carbon removal and storage through agricultural land management practices, some more mature than others. While these practices may eventually prove to increase the carbon sequestration potential within the U.S., I do not include these technologies in my quantitative assessment of negative emissions because their feasibility and benefits are yet too uncertain. The technologies include, but are not limited to:

1) Very high animal stocking rates on extensive rangeland for short periods of time, known by a number of names including intensive rotational grazing (as for pasturelands) and mob grazing, have shown promise for improving productivity and soil carbon stocks. In at least one study additional soil carbon accumulation was ~3 tC ha^{-1} yr^{-1} compared to continuous grazing.[96] These results are too early to generalize, however,[97] and recommendations await the results of further experimentation.

2) Biochar additions to soils have shown, in many cases, a propensity to increase long-term soil stocks via direct carbon stock change and improved soil fertility that, like compost, can boost productivity in degraded or infertile soils. Biochar is charcoal: a pyrolysis byproduct of the thermochemical conversion of wood to other energy products such as biogas and liquid bio-oil.[98] Most biochar is highly resistant to microbial attack, and additions to a wide variety of soils have demonstrated its general tendency to persist—indeed, many soils of fire-prone ecosystems in the U.S. contain substantial amounts of natural biochar.[99]

But biochar additions can also enhance the decomposition of native soil organic matter,[100, 101] offsetting the soil carbon benefit of biochar itself, and as well biochar may be of greater mitigation value if converted directly to energy to offset fossil fuel use.[8] A biochar recommendation awaits further research to clarify both the long-term soil carbon gain in field studies and life cycle carbon analysis in comparison to alternative uses.

3.2.5 Wetlands Restoration

Wetlands Restoration: Histosols

Histosols are soils high in organic matter due to their formation under waterlogged conditions that inhibit microbial activity. As wetland plants such as sphagnum moss produce biomass, a significant fraction accumulates as peat and high-carbon sediments. When drained for agriculture, histosols tend to be extremely productive, but once exposed to oxygen, microbial activity accelerates and histosols can lose carbon quickly at rates as high as 20 tC ha^{-1} yr^{-1}.[102] About 8% of histosol soils in the U.S. have been drained for agriculture, mostly in Florida, Michigan, Wisconsin, Minnesota, and California.

Carbon accumulation in these soils can be restored (carbon loss reversed) by taking them out of production and restoring the high water table. Although restoring wetland conditions will also restore methane production, the combination of reversed carbon loss and abated nitrous oxide emissions usually will exceed the additional methane loss, leading to a large net emissions reduction.[103] However, the area of cultivated histosols soils is relatively small in the U.S.—used mostly for vegetables and sugar cane production—so the overall mitigation potential is modest.[24] And as for cropland conversion to perennial grasslands, care must be taken to avoid indirect land use change effects. In 2017, the USDA paid farmers to maintain 0.8 Mha of restored wetlands[32] through the Farmable Wetlands Program (https://www.fsa.usda.gov/programs-and-services/conservation-programs/farmable-wetlands) within the Conservation Reserve Program (see Section 3.2); at least another 0.8 Mha is readily available.[48]

Estimates of carbon gain under restored histosols vary widely, from 0.6 to 20 tC ha^{-1} yr^{-1}.[48] An average value, considering other greenhouse gas impacts such as increased methane emissions, was estimated by Alm et al.[104] to be around 2.7 tC ha^{-1} yr^{-1} for Finnish peatlands; more recently Griscom et al.[9] suggest an average value from a global peatlands database of 3.65 tC ha^{-1} yr^{-1}.

Wetlands Restoration: Non-Histosols

A substantial fraction of non-histosol wetlands have been drained for agriculture in the U.S., and despite being below the threshold for definition as histosols, prior to agricultural conversion they generally had higher soil organic matter content than well-drained soils. About 80% of wetland drainage in the U.S. has been attributed to agriculture, or ~32 Mha since 1780. Estimates of soil carbon accumulation upon restoration are highly uncertain but in the range of 0.41 tC ha^{-1} yr^{-1},[105] much smaller than for histosol wetlands with their substantially greater soil carbon content, and in the range that could be offset by increased methane emissions. Thus it is not yet clear whether non-histosol wetland restoration is an effective carbon sequestration strategy.

3.2.6 Forest Management

Forests, like croplands and grazing lands, can be managed to enhance carbon sequestration via changes to forestry practices or by conserving standing forests. Generally forest management includes reforestation, which refers to the reestablishment of trees following forest harvest, but does not include *afforestation*, defined by IPCC[105] as the establishment of trees on lands that have been deforested for 50 years or more. In the U.S., afforestation largely comes at the expense of current crop and pasturelands[106] and thus will create indirect land use change effects elsewhere, likely resulting in little if any net climate benefit.[107, 108] About 42% of total forestland in the conterminous U.S. is publicly owned and managed by federal agencies.

Forest Management: Improved Stand Management

Improved forest management designed to enhance carbon sequestration in tree biomass includes choices of tree species (fast versus slow growing), harvest age or rotation length, and the use of practices such as fertilization, controlled burning, and thinning to increase forest productivity and carbon storage. Delaying rotation increases carbon storage because carbon continues to accumulate as the trees grow;[109, 110] even relatively old growth forests continue to accumulate carbon in soil stocks, including carbon in slow-to-decay fallen trees on the forest floor.[111, 112] But even without additional carbon sequestration, preservation of an existing forest biomass stock keeps it from the atmosphere for the period delayed.

Rotation lengths differ regionally by tree species and ownership and can be managed readily. Softwoods and mixed species in nonindustrial private forests of the southern U.S. are typically managed on rotations of 25 to 35 years or longer, although rotations in commercial forestry may be half this length.[113] In the western U.S., commercial rotations tend to be 45–60 years because of longer-lived species.

Delaying harvest and converting unmanaged forests to faster-growing species to increase forest productivity can sequester, on average, 1.4–2.1 tC ha^{-1} yr^{-1}.[113, 114] Using an economic model, the U.S. Environmental Protection Agency (EPA)[106] estimated that 7-105 MtC yr^{-1} (0.07 – 0.105 Gt C yr^{-1}) could be stored by all forests in the conterminous U.S. at carbon prices from \$1 to \$50 per tCO_2 for 100 years or more; at a conservative \$15 per tCO_2,[8] this amounts to 60 MtC yr^{-1}. Their variable price economic model yields a 55 MtC yr^{-1} average by mid-century, which is consistent with Griscom et al.'s[9] U.S. projection of 18 MtC yr^{-1}, not including planted forests nor fire management, which they consider alone could avoid 11 tC ha^{-1} yr^{-1} of carbon loss in fire-prone forests such as those in the western U.S.

Reforestation, not considered here because of overlap with marginal lands included in cellulosic biofuel estimates (Sections 3.2.2 and 4.2.4), could also provide substantial negative emissions. Griscom et al. project potential sequestration of 98 MtC yr^{-1} were all once-forested U.S. pastureland, mostly east of the Missouri River and including lands currently grazed, reforested. Such a strategy, however, would require diet shifts away from meat to avoid indirect land use effects, whereby displaced food production results in conversion of natural areas (with its carbon loss) elsewhere, such as Amazonia. On the other hand, reforestation on marginal lands not used for grazing could provide carbon benefits similar to conversion to cellulosic biofuels once biofuels were no longer used for fossil fuel displacement.[115]

Forest Management: Improved Soil Management

Soil carbon stocks in U.S. forests are, in aggregate, substantial;[116] about 50% of the carbon in U.S. forests is in the soil and another 8% in detrital material on the forest floor.[117] Various activities can affect forest soil carbon storage: rotation length, harvest intensity, and fire management are among the most important. Kimble et al.[117] estimate that in total, U.S. forests managed for timber could sequester 25 to 103 MtC yr^{-1} (0.25 – 0.103 GtC yr^{-1}), for average sequestration rates of 0.12 – 0.51 tC ha^{-1} yr^{-1}, or a mean of 0.32 tC ha^{-1} yr^{-1}, a more conservative rate than earlier IPCC[105] estimates for temperate forests of 0.53 tC ha^{-1} yr^{-1}. This sequestration would be additional to the current U.S. forest soil background sink recently estimated[118] at 13-21 MtC yr^{-1}. Kimble et al.[119] further estimate that soils under agroforestry systems – e.g. alleycrops, riparian buffers, windbreaks, and urban forests – could sequester nationally another 17-28 MtC yr^{-1}, or an average of 22.5 MtC yr^{-1}.

4.0 Agricultural Greenhouse Gas Abatement by Land Management

4.1 Measuring Nitrous Oxide and Methane Fluxes

Nitrous oxide and methane, like CO_2, are naturally occurring greenhouse gases. They are distinguished in part by their substantial global warming potentials, the degree to which they are responsible for radiative forcing of the atmosphere compared to CO_2. Over a 100-year time horizon, nitrous oxide has 265-300 times the global warming potential of CO_2, and methane 28-36. [10, 120] Another way of thinking about global warming potentials is that 1 Mt of avoided nitrous oxide emission is equivalent to 265-300 Mt of sequestered CO_2. Thus, though their atmospheric concentrations are substantially lower than those of CO_2, they pack significant punch and concentrations of each have risen by about 45% since 1970.[1] In order to directly compare the atmospheric impact of all three gases, emissions of nitrous oxide and methane are multiplied by 298 and 25, respectively,[102] and expressed as CO_2 or carbon equivalents (CO_2eq or Ceq).

Nitrous oxide is naturally emitted by bacteria in soils and other environments as a byproduct of their nitrogen metabolism. Some nitrous oxide is also emitted naturally from fires. Agriculture is responsible for 84% of anthropogenic nitrous oxide emissions,[121] and most agricultural emissions (62%) come from soils amended with nitrogen from fertilizers, manures, or legumes. Thus a major mitigation opportunity related to land management is improved nitrogen fertilizer efficiency.

Agricultural methane emissions come from enteric fermentation by livestock (52%), rice cultivation (22%), biomass burning (19%), and livestock manure handling (8%).[121] From the standpoint of land management, rice cultivation offers today a substantial cropland mitigation opportunity where rice is grown.

The non-CO_2 greenhouse gas exchanges with the atmosphere (fluxes) are not easily quantified. Most of what we know comes from thousands of gas flux measurements made from small chambers (often 25-30 cm diameter) placed on the soil surface. As gases accumulate in the chamber, over the course of an hour or two gas samples are withdrawn and analyzed for nitrous oxide or methane. The rates of gas accumulation are calculated from these samples and represent net emissions.[122]

Like soil carbon, the spatial variability of fluxes from soil is very high. Consequently, evaluations of abatement by different agricultural practices are usually made in experimental plots to isolate the effect of the practice from natural soil variability. Such comparisons provide a high degree of confidence when they are made at appropriate times: unlike soil carbon stocks, gas fluxes are also highly variable in time. It’s thus important to compare fluxes during periods of low fluxes and high fluxes, and sampling campaigns are expensive because of this need for frequent sampling. Nevertheless, nitrous oxide and methane fluxes have been measured in agricultural systems for over 40 years, and we have a reasonable understanding of the major factors that regulate fluxes and can identify a number of mitigation paths.

4.2 Avoided Emissions by Improved Land Management

4.2.1 Reduced Nitrous Oxide Emissions from Field Crops

About 50% of anthropogenic nitrous oxide emissions are from nitrogen-fertilized field crops such as corn and wheat, where natural soil bacteria that produce nitrous oxide are stimulated by more available soil nitrogen. While factors other than fertilizer can also accelerate nitrous oxide production, it has been known from field studies since the 1970s[123-125] that nitrogen fertilizers are responsible for most agricultural nitrous oxide emissions (e.g., **Figure 4**). In fact, most IPCC national greenhouse gas inventories tally agricultural nitrous oxide emissions as a fixed percentage of nitrogen fertilizer use.[126, 127] Recent evidence that N_2O emissions increase exponentially with nitrogen fertilizer additions in excess of crop need[128, 129] places even more importance on fertilizer nitrogen rate as a predictor of agricultural emissions; this exponential increase is incorporated in both commercial greenhouse gas reduction protocols[130, 131] and in USDA protocols for quantifying farm-level emissions.[132] These protocols are now being built into the COMET-Farm tool that allows farmers and ranchers to calculate the greenhouse gas impacts of current and projected practices.[133]

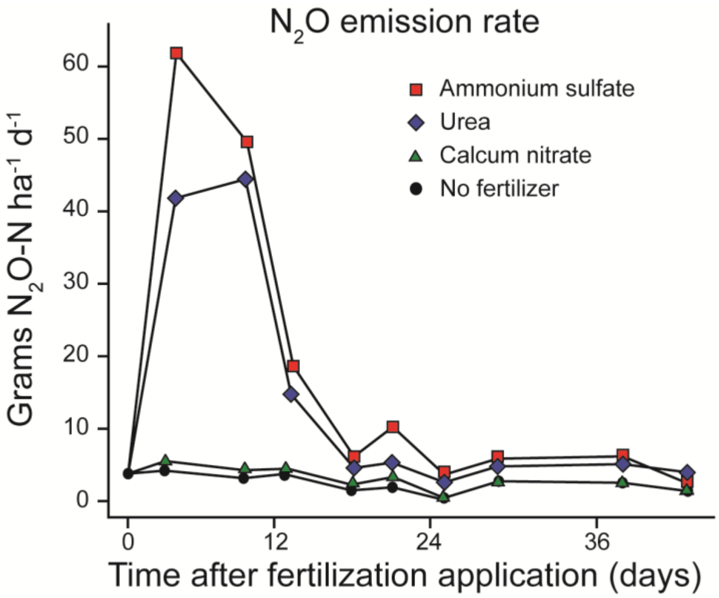

Figure 4. Nitrous oxide (N_2O) emission response to nitrogen fertilizer. Redrawn from Brietenbeck et al. (1980).[111]

While other management interventions are also known to reduce nitrous oxide emissions at specific locations,[132] reducing nitrogen fertilizer inputs to the rate needed for optimum yields (called by agronomists the economically optimum rate) is the most reliable means to reduce nitrous oxide emissions from fertilized cropping systems.[134] Carbon equivalent savings for a 15-20% increase in fertilizer use efficiency (equivalent to a 15-20% reduction in average nitrogen fertilizer use) in rainfed crops range from 0.15 to 0.29 tC_{eq} ha^{-1} yr^{-1}.[103, 134-136]

Millar et al.[134] used an optimum fertilizer rate calculator to show that nitrogen fertilizer rates on corn could be reduced for seven Midwest states by at least 15% without affecting yields. A 15% reduction represents an average avoided nitrous oxide emission of 2.2 kg N_2O ha^{-1} yr^{-1}, equivalent to 0.18 tCeq ha^{-1} yr^{-1} assuming a conservative emission factor of 0.017 kg of nitrous oxide nitrogen per kg of nitrogen fertilizer applied.[129] In 2014 the U.S. consumed 13.3 Mt of fertilizer N;[137] a 15% savings (2.0 Mt N) would additionally save 15% of the CO_2 cost of manufacture, equivalent to 2.2 MtC yr^{-1} (0.0022 GtC yr^{-1}) at a fertilizer production cost of 4 kg CO_2 per kg of nitrogen.[138]

At midcentury, others[139, 140] project a 50% increase in nitrogen fertilizer use efficiency, from 53% today to 75% in the future. If implemented immediately, this would lead to a 32% reduction in nitrogen fertilizer use,[9] for avoided nitrous oxide emissions of 0.36 tC_{eq} ha^{-1} yr^{-1} and avoided CO_2 from fertilizer production of 2.2 Mt C yr^{-1}. Cropland affected by this savings is assumed to be that planted to crops in 2012 (139 Mha) less the acreage in soybeans and peanuts,[141] major commodity crops that require no nitrogen fertilizer.

4.2.2 Rice Water Management for Methane

Rice in the U.S. grows in flooded soils that create the oxygen-depleted soil environment necessary for methane production. While rice is not a major cereal crop in the U.S., annual rice-related methane production is 3.1 GtCeq[11], about 2% of 2015 U.S. methane emissions and about 2% of total worldwide methane production from rice.[142]

Methane from flooded rice is most readily controlled by periodic drainage. Sass et al.[143] documented a 50% reduction in emissions in Texas with a single mid-harvest drainage, and almost complete cessation with a 2-day drainage every three weeks. Others have found similar responses around the world, particularly in China.[144] Eagle et al.[145] suggest a U.S. rice methane mitigation potential of 0.54 tCeq ha^{-1} yr^{-1} based on improved drainage practices. Additional mitigation can be achieved with new high-yielding rice cultivars that increase root zone porosity and consequent methane oxidation.[146]

4.2.3 Cellulosic Bioenergy Production on Grain Ethanol Lands

As noted earlier, about 44% of U.S. corn acreage is currently used for grain-based ethanol production. Were this acreage turned to biomass production for cellulose-based ethanol production, using technology that is currently in commercial use in the U.S., the climate benefit of ethanol production would be substantially improved because the production of cellulosic biomass crops like switchgrass require very few fossil fuel inputs, unlike the production of corn grain. Whereas grain-based ethanol avoids only 18% of the CO_2eq that would otherwise be emitted by gasoline, cellulosic ethanol avoids nearly 90%[147, 148]. Thus, substituting cellulosic feedstocks such as switchgrass on current corn grain ethanol cropland could provide a substantially greater fossil fuel offset than grain ethanol feedstocks, in addition to providing soil carbon sequestration as noted above in Section 3.2.

The additional climate benefit can be calculated from a standard life cycle analysis model such as GREET.[149, 150] Not including the soil carbon benefit already considered above, switchgrass with a conservative biomass yield of 8 Mg ha^{-1} yr^{-1} can provide 1.44 tC ha^{-1} yr^{-1} of fossil fuel CO_2 savings when converted to ethanol.[150, 151] The difference from corn grain (0.73 tC ha^{-1} yr^{-1} for a grain biomass yield of 11 Mg ha^{-1} yr^{-1}) represents a net avoided CO_2 emission benefit of

0.71 tC ha^{-1} yr^{-1}. The difference would be greater with a higher yielding cellulosic biomass crop.

4.2.4 Cellulosic Bioenergy Production on Marginal Lands

Cellulosic biofuels can also be grown on former agricultural lands, as noted earlier. To meet expected 2050 liquid transportation fuel demands requires ~55 Mha of the 70-100 Mha of crop and pastureland abandoned from agriculture since 1900, excluding urban, forest, and wetlands.[88] Planting this acreage to switchgrass with an avoided CO_2 emission benefit of 1.08 tC ha^{-1} yr^{-1} for an average 6 Mg ha^{-1} yr^{-1} yield[150, 151] would generate a significant avoided CO_2 emissions savings. This value does not include the soil carbon sequestration included as negative emissions. Note that this is not BECCS, insofar as the carbon in the fuel is not geologically sequestered as CO_2.

5.0 Total Mitigation Potentials

Several published studies have estimated a total biophysical potential for soil carbon sequestration globally and in the United States with land management technologies that are currently available. Before summarizing the U.S. carbon mitigation potential it is worth considering the global perspective.

5.1 Global Estimates of Potentials for Soil Carbon Gain

Recent global estimates of the biophysical potential for cropland and grazing land soils to sequester carbon range from 0.4–1.5 GtC yr^{-1} (**Table 1**).[24, 105, 152-156] Each of the estimates in Table 1 assume adoption of some combination of improved cropland and grazing land management, agroforestry, and restoration of degraded lands and histosol wetlands. Note that they do not include other sequestration practices described above, including sequestration due to improved forest management and conversion of grain ethanol lands to cellulosic biofuel crops, nor savings from avoided emissions such as those from improved nitrogen fertilizer use. That these global estimates are similar to one another arises from considering the same types of practices and using similar well-constrained field estimates that are based on long-term experiments for major mitigation practices such as no-till.

To calculate the total century-long mitigation potential requires knowing for how long these rates are sustainable. As noted earlier, soil carbon accumulation tends to behave asymptotically – after some period maximum rates slow until a new equilibrium is reached (**Figure 2**). Although very long term experiments in agricultural systems are rare, it's clear that the applicable period likely differs among management practices, climate zones, and initial soil carbon levels. Many researchers assume conservatively that average maximum rates occur for at least 20 years with the rate of sequestration after then declining to a new steady state that occurs about 40 years post management change,[28, 44] although some (e.g.[152]) assume >50 years persistence. A 30-year period at average sequestration rates seems a reasonable working value and is the value I have used for the calculations contained in this report.

Year	Estimate (GtC_{eq} yr^{-1})	Improved cropland management	Improved grazing land management	Set-aside of erodible cropland to grassland	Restoration of degraded land	Agroforestry	Restored peat soils	Reference
1998	0.4–0.9	x		x	x			Paustian et al.[152]
1999	0.5–0.6	x			x			Lal and Bruce[153]
2000	0.82	x	x	x		x	x	IPCC[105]
2004	0.4–1.2	x	x	x	x	x		Lal[154]
2008	1.4–1.5	x	x	x	x		x	Smith et al.[103]
2014	0.7–1.4	x	x	x	x	x		Sommer and Bossio[156]
2016	0.3–1.5	x	x	x	x	x	x	Paustian et al.[24]

Table 1. Published estimates of global soil carbon sequestration potentials based on biophysical processes that could be enhanced by land management actions. Not included are sequestration potentials from forest management, cellulosic biofuel crops, or carbon additions such as compost or biochar, nor savings from avoided emissions such as those from avoided nitrogen fertilizer use.

If the average global sequestration rate of 1.2 GtC yr^{-1} for the three most recent analyses[24, 155, 156] is multiplied by a conservative 30-year sequestration period, then we can calculate an end-of-century value of ~36 GtC sequestered for this set of soil carbon practices.

Expanding the scope to include forests and coastal wetlands readily boosts global negative emissions potentials well past the 100 GtC end-of-century target for restoring a 350 ppm CO_2 atmosphere.[4] In one recent analysis Griscom et al.[9] consider at the global scale 20 conservation, restoration, and land management actions that, in aggregate, could sequester or avoid as much as 6.5 GtC yr^{-1} for at least a 25 year period. They include aggressive reforestation, forest management, coastal wetland and peatland restoration, and **Table 1** practices to yield 169 GtC of negative emissions by the year 2100 if implemented soon. If reforestation were to more reasonably include reforesting only 25% of the once-forested areas, rather than 100%, their estimate reduces to 148 GtC by 2100.

Avoided emissions, including stopping deforestation and wood fuel harvest, improved nitrogen fertilizer management, and avoided coastal wetland and peatland conversion provides another 128 GtC of savings, for a global end-of-century total of 276 GtC.

It is worth emphasizing that these practices are feasible and available for implementation today, and would provide land-based CO_2 mitigation additional to the existing 2.6 GtC yr^{-1} land sink (Section 2.0).

Including frontier technologies such as biochar additions and the development of microbiome-assisted carbon accrual could further increase soil carbon sequestration potentials, perhaps by as much as 1.8 fold.[24] Worth noting too is the French government's "4 per mille" initiative announced at the time of the 2016 Paris climate accord,[157] which aims to increase global soil carbon stocks by 0.4% per year, an aspirational goal equivalent to sequestration rates of 3.4 GtCeq yr^{-1} (272 GtC if sustained through 2100) that has attracted significant attention.[158-160] Many, myself included, feel this rate is overambitious in part because we don't know the saturation potentials for most soils, but the initiative has raised awareness and will likely spur further research to identify additional soil carbon management interventions.

5.2 U.S. Potentials for Negative and Avoided Emissions by Land Management Change

Table 2 presents a summary synthesis of the management practices identified in the sections above for the U.S. Negative emissions, including Cropland management (Section 3.2.1), Cropland conversion to perennial grasses (3.2.2), Grazing land management (3.2.3), Wetland histosols restoration (3.2.4), and Forest management (3.2.6), sum to a potential total carbon storage rate of 414 MtCeq yr^{-1} (0.414 GtCeq yr^{-1}).

This rate is similar to those calculated for other recent U.S. summaries[28, 83, 159, 161] when considering individual practices. While other syntheses estimate a lower range of 75-174 MtCeq yr^{-1}, with an average rate of 85 MtCeq yr^{-1}, they do not include carbon sequestered due to improved forest management or the establishment of cellulosic bioenergy crops. These alone add 198 MtCeq yr^{-1}. A 2007 Congressional Budget Office analysis[162] that included forest management estimated a 2030 sequestration potential of 479 MtCeq yr^{-1}. Thus the present analysis (summing to 414 MtCeq yr^{-1} for negative emissions) is consistent with earlier analyses.

As noted earlier, the duration of individual sequestration rates by different practices differ. Sequestration rates for all practices could be sustained for at least 30 years, and some for 50-80 years or more as noted in Section 5.1. With these durations, total negative emissions sum to 20.9 GtCeq through 2100 (**Table 2**).

Avoided emissions are also additional in the present analysis. These include a) improved fertilizer efficiency (Section 4.2.1), b) rice water management for methane (4.2.2), and c) cellulosic bioenergy production (Sections 4.2.3 and 4.2.4). These provide additional mitigation potentials that themselves sum to an annual capacity of 122 MtCeq yr^{-1} (0.122 GtCeq yr^{-1}), totaling 9.7 GtCeq through 2100 (**Table 2**). It is worth noting that the capacity of these activities is on-going and permanent, i.e. most of their carbon benefits are not subject to saturation as are biological carbon sinks, nor subject to re-emission upon management change or natural disturbance such as forest fires. It is also worth noting that, except for cellulosic biofuels, there is likely no overlap with decarbonization pathways for energy use. Should, however, energy analyses include cellulosic biofuel production at the magnitude noted here, then the avoided emissions here (72 MtC yr^{-1} or 5.7 GtC for 80 years) would be double counted so this total should be appropriately discounted. The negative emissions due to cellulosic biofuels – soil carbon capture – does not contribute to avoided fossil fuel use so should remain part of this total.

Practice change	Local rate (tCeq ha^{-1} yr^{-1})	Areal extent (Mha)	Annual total (MtCeq yr^{-1})	Duration (yr)	Yr 2100 total (GtCeq)
Negative emissions					
Cropland management (3.2.1)					
No till adoption	0.40	94[a]	37.6	30	1.13
Reduced summer fallow	0.09	20[a]	1.8	30	0.05
Winter cover crops	0.52	66[a]	34.3	80[f]	2.75
Diversified crop rotations	0.05	46[a]	2.3	80	0.18
Manure & compost additions	0.71	8.5[a]	6.0	80	0.48
Cropland conversion to perennial grasses (3.2.2)					
Set-aside highly erodible cropland	0.97	26[b]	25.2	30	0.76
Cellulosic bioenergy on grain ethanol lands	0.97	13[c]	12.6	30	0.38
Cellulosic bioenergy on marginal lands	0.48	55[d]	26.4	30	0.79
Grazing land management (3.2.3)					
Improved stocking rates on rangeland	0.28	216[e]	60.5	80	4.84
Improved species composition	0.56	80[a]	44.8	30	1.34
Wetland histosol restoration (3.2.4)	3.65	0.8[a]	2.9	80	0.23
Forest management (3.2.6)					
Improved soil management – timberland	0.32	256[e]	81.9	50	4.10
Improved soil management – agroforestry			22.5	50	1.13
Improved stand management			55.0	50	2.75
Subtotal – Negative emissions			414.		20.9
Avoided emissions					
Improved fertilizer efficiency (4.2.1)					
Avoided nitrous oxide emissions	0.36	125[c]	45.0	80	3.60
Avoided CO_2 – fertilizer production			4.4	80	0.35
Rice water management for methane (4.2.2)	0.54	1.3[a]	0.7	80	0.06
Cellulosic bioenergy production					
Production on grain ethanol lands (4.2.3)	0.71	17[c]	12.1	80	0.97
Production on marginal lands (4.2.4)	1.08	55[d]	59.4	80	4.75
Subtotal – Avoided emissions			122.		9.7
Total potential			535.		30.6

[a] Eagle et al.[48, 145] [b] Sperow et al.[83] [c] ERS[89] [d]Robertson et al.[88] [e]Bigelow and Borchers[29] [f]Poeplau and Don[65]
[g]USDA[163]

Table 2. Potential sources and magnitude of U.S. greenhouse gas mitigation from changes in land management practices that lead to negative emissions (carbon storage) and avoided emissions for the period 2020-2100. Numbers in parentheses refer to sections in text for local sequestration values.

Assuming no overlap, and over an 80- year end-of-century lifetime, then, these avoided emissions practices sum to 9.7 GtCeq through 2100.

Altogether, then, I conclude that U.S. potentials for mitigating greenhouse gas emissions through negative emissions due to land management practices on forest, range and crop lands in the conterminous U.S. sum to 20.9 GtCeq for the period 2020-2100. This represents more than 20% of the global natural sequestration target needed to bring CO_2 concentrations to 350 ppm.[4] Including avoided emissions due to land management practices brings the sum to 30.6 GtCeq for the period 2020-2100, or >30% of the total needed.

That the federal government manages 43% of rangeland and 44% of forests in the conterminous U.S. (see Section 3.2) allows an estimate of the sequestration potential on public grazing and forest lands of 115 MtCeq yr^{-1}, or 6.2 GtCeq through 2100. About 56% of this total is sequestration on forest lands, the remainder on rangelands.

In its annual inventory of greenhouse gas emissions and sinks for the U.S., the USEPA[11] estimates for U.S. land management a background sink of 212 MtCeq yr^{-1} (0.212 GtCeq yr^{-1}) for 2015. The primary drivers of these sinks in 2015 were forest growth (181 MtCeq yr^{-1}) and forestland expansion (21 MtCeq yr^{-1}), with urban tree growth and landfills (9 MtCeq yr^{-1}) contributing most of the remaining sink. Decrementing this by concomitant changes in methane and nitrous oxide emissions brought the net land management sink to 207 MtCeq yr^{-1}. The 535 MtCeq yr^{-1} potential land management sink noted in **Table 2** (both negative and avoided emissions) is additional to this existing background sink. Were the strategies in this report fully implemented, a future USEPA inventory might tally a net U.S. sink close to 750 MtCeq yr^{-1} (0.750 GtCeq yr^{-1}).

5.3 Barriers that Prevent Optimized Biotic Greenhouse Gas Mitigation in the U.S.

The principal barriers to adopting management practice changes to mitigate greenhouse gas emissions in the U.S. are neither knowledge-based nor technical. There is ample evidence, detailed and summarized above, that land management changes can achieve real and verifiable negative and avoided emissions with high confidence. The values in **Table 2** are, in general, conservative – they include values from field observations and experiments conducted throughout the U.S. and similar ecoregions, i.e. they are empirically-based, representative estimates from farm, rangeland, and forest systems typical of the U.S. Further research will lead to their refinement, but it seems unlikely that average values will change more than 20-30%, and, importantly, the values are in any case as likely to increase in magnitude as to decrease. Further, as noted earlier, not all possible practices to drive negative or avoided emissions are included.

Research and experience show that farmers, ranchers, and forest managers who own and manage non-federal lands are willing to accept payments for providing ecosystem services such as soil organic matter accrual, nitrate leaching avoidance, wetland protection, and greenhouse gas avoidance.[164, 165] For example, in 2017, USDA and its partners worked with 680,000 land managers to fund the development of conservation plans for 27 million acres of working lands.[166] Both research[164, 165, 167-169] and over-subscribed USDA conservation programs point to farmers' and other landowners' openness to accepting conservation and other ecosystem service payments through a variety of mechanisms, including auctions. Thus, the principal barrier for engaging landowners and managers is not feasibility or lack of interest, but lack of policy support and financial incentive.

How much financial incentive is necessary? The success of USDA conservation programs show that farmers and ranchers are willing to accept relatively low payments for changing specific practices, sometimes as low as a few dollars per acre. In many cases the payments depend on co-benefits. Building soil carbon, for example, benefits soil fertility, water holding capacity, and drainage, and experimental auctions have shown lower payments would be required than, for example, reducing nitrous oxide emissions, which are considered by farmers to have fewer co-benefits.[165, 170] Practices with higher management costs – cover crops, for example – would likewise require higher payments. That said, most analyses to date that include economic costs conclude that many practices could be implemented at costs as low as \$10 per $MtCO_2$ (\$2.70 per MtC). Griscom et al.[9], for example, state that 1/3 of the potentials they consider could be provided at this cost, with the remainder requiring no more than \$100 per $MtCO_2$, which is consistent with the expected avoided cost of holding warming to below 2 °C by 2100.[171] USEPA modeling[106] concludes that some forest and agricultural management practices could be incentivized at carbon prices as low as \$1 per $MtCO_2$, with full implementation at \$50.

Various voluntary efforts such as the USDA Building Blocks for Climate Smart Agriculture and Forestry (https://www.usda.gov/oce/climate_change/buildingblocks.html)[172] provide frameworks for farmers, ranchers, and landowners to respond to climate change. For example, the Building Blocks program provides a series of measures intended to assist a wide variety of land management stakeholders to increase carbon storage and reduce greenhouse gas emissions; ten categories of activities range from soil health and nitrogen stewardship to grazing and pastureland management. The program provides case studies to inspire users and provides technical assistance through NRCS and other USDA professionals to help individual land managers meet personal greenhouse gas reduction goals. Only three years old, the effectiveness of the Building Blocks initiative is largely untested but it provides an evidence-based framework for engaging landowners and managers in the sorts of meaningful activities identified herein. The Building Blocks framework is an important start, but the quantitative goal it contains (33 MtCeq yr^{-1} by 2025) is far below the 535 MtCeq yr^{-1} identified in the present analysis, and because the initiative is strictly voluntary with no incentives, it is unlikely to meet even this goal.

More useful is the on-line COMET-Farm tool (http://cometfarm.nrel.colostate.edu)[133] that allows farmers and ranchers to calculate the greenhouse gas impacts of current and projected land management practices. Calculations are based on the USDA's methods for quantifying farm-level emissions (https://www.usda.gov/oce/climate_change/estimation.htm).[132] Calculations are specific to individual fields as identified by aerial and satellite imagery, and cover most of the crop and grazing land practices in Sections 3.2 and 4.2, including avoided emissions from improved nitrogen fertilizer management, all of which make comparisons between business-as-usual and alternative practices straightforward and directly relevant to the land being managed.

Likewise, national carbon registries offer a framework to provide landowners and carbon markets detailed evidence-based protocols for voluntarily quantifying the carbon captured or emissions avoided by specific land management practices. Both the American Carbon Registry (www.americancarbonregistry.org) and the Verified Carbon Standard (www.verra.org), for example, provide protocols for awarding carbon credits based on avoided nitrous oxide emissions by improved nitrogen fertilizer management[130, 131] as well as avoided methane emissions from improved rice management and wetland restoration.[173]

That said, scaling up sequestration nationwide on the order discussed in the present report will require revisiting the many federal policies and incentives that influence agricultural, grazing, and forestry practices on both private and public lands of the U.S. Without supportive federal policies and payments sufficient to cover costs, farmers, ranchers, and forest owners are unlikely to participate in sufficient numbers to effect meaningful change.

6.0 Concluding Opinions

Based upon a review of the literature, my own research, and in consultation with other experts in the field, it is my expert opinion that through improved land management practices, at a combined peak rate of 535 MtCeq yr^{-1} (0.535 GtCeq yr^{-1}), about 31 GtCeq of additional emissions could be sequestered and avoided by land management changes on U.S. forestland, rangelands, and farms between 2020 and 2100. Some 21 GtC could be provided by negative emissions, i.e. natural carbon removal and storage by practices such as improved cropland and rangeland management. Another 10 GtC could be provided by avoided emissions from practices such as improved nitrogen management and cellulosic bioenergy production. We have known for decades the potential for most of these practices to contribute to negative or avoided emissions. Sequestration on this scale would meet the scientific prescription for sequestration set forth by Hansen et al.[4, 174, 175]

Signed this 13th day of April, 2018 in Cambridge, UK.

G Phil Robertson

G. Philip Robertson