# EXECUTIVE SUMMARY

# 350 PPM PATHWAYS FOR THE UNITED STATES

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EVOLVED ENERGY RESEARCH

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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/

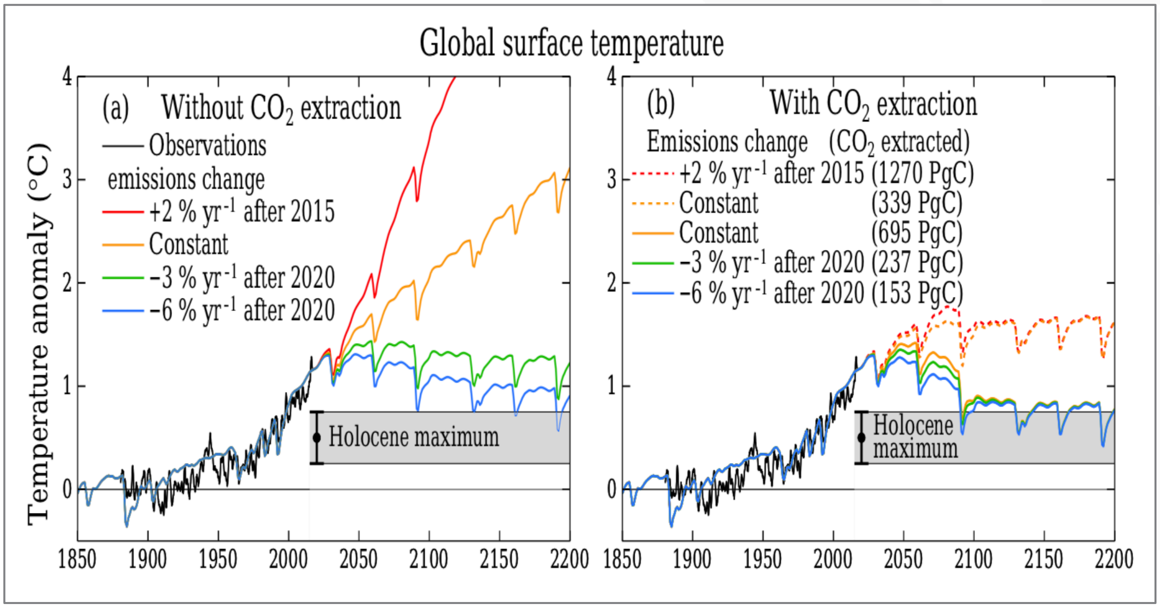
[2] Available at http://usddpp.org/.

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.

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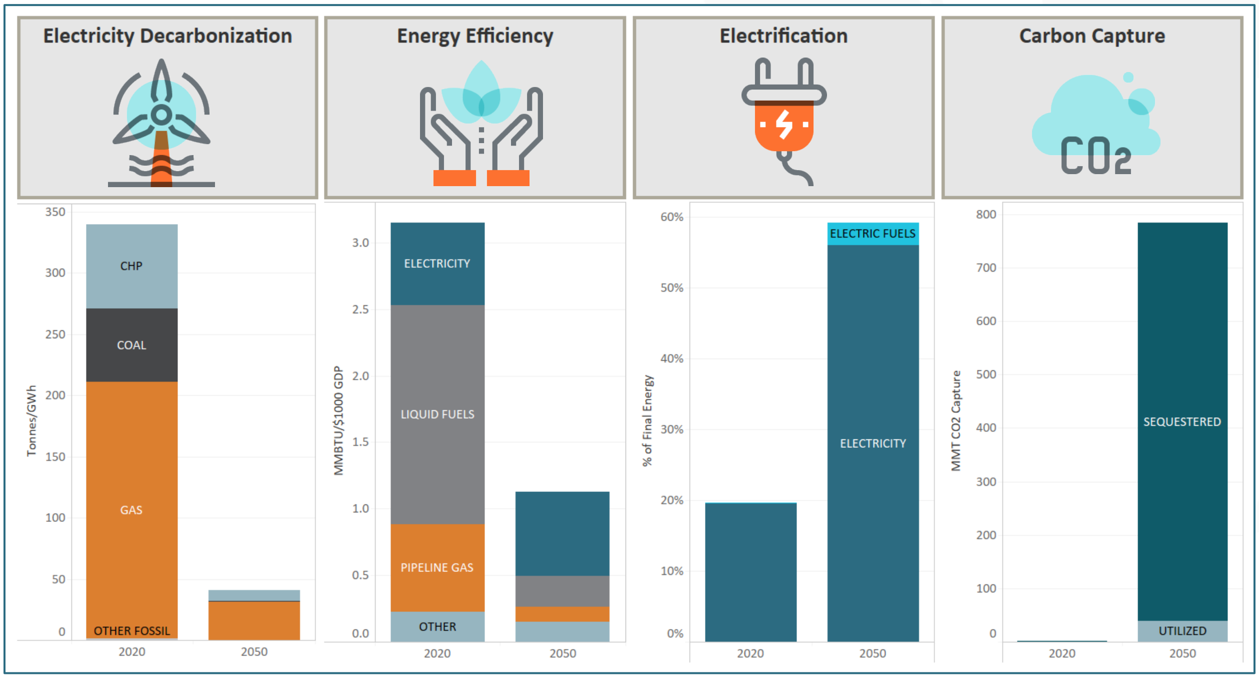
[8] U.S. EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2016,* available at https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2016

[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)*

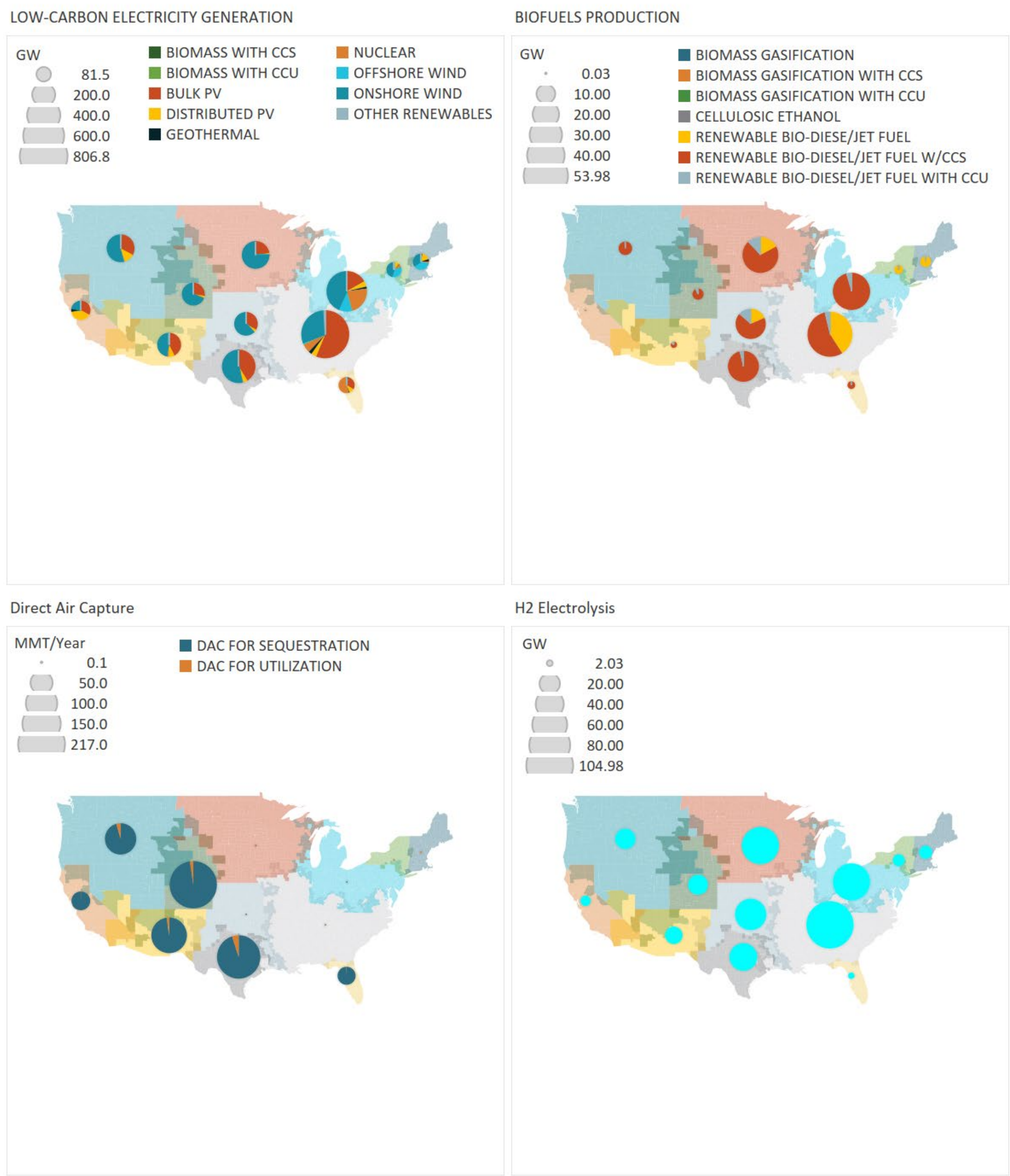


Figure ES4 shows that all scenarios achieve the steep reductions in net fossil fuel $CO_2$ emissions to reach net negative emissions by the 2040s, given a 50% increase in the land sink, including five that are limited in one key area. This indicates that the feasibility of reaching the emissions goals 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*

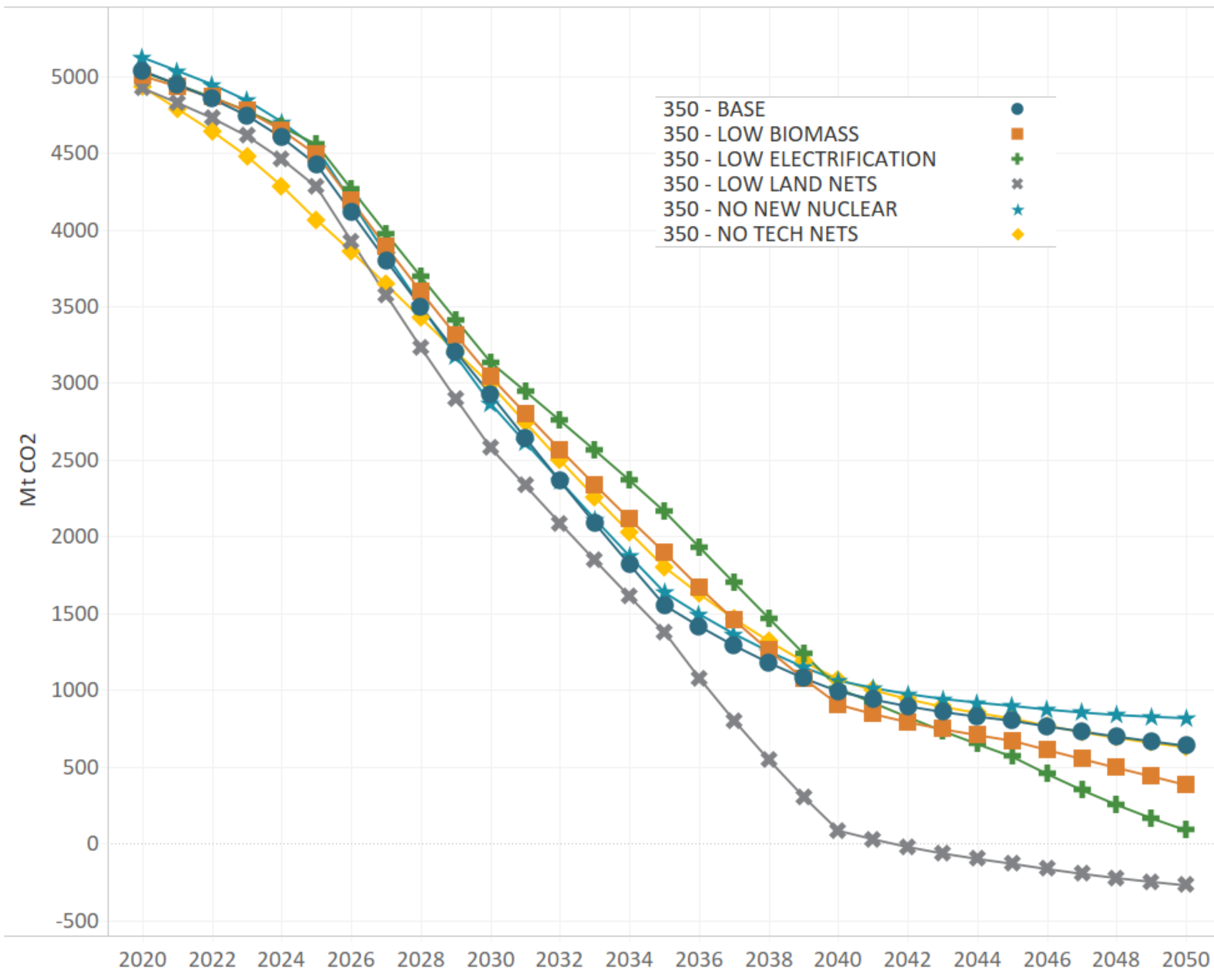
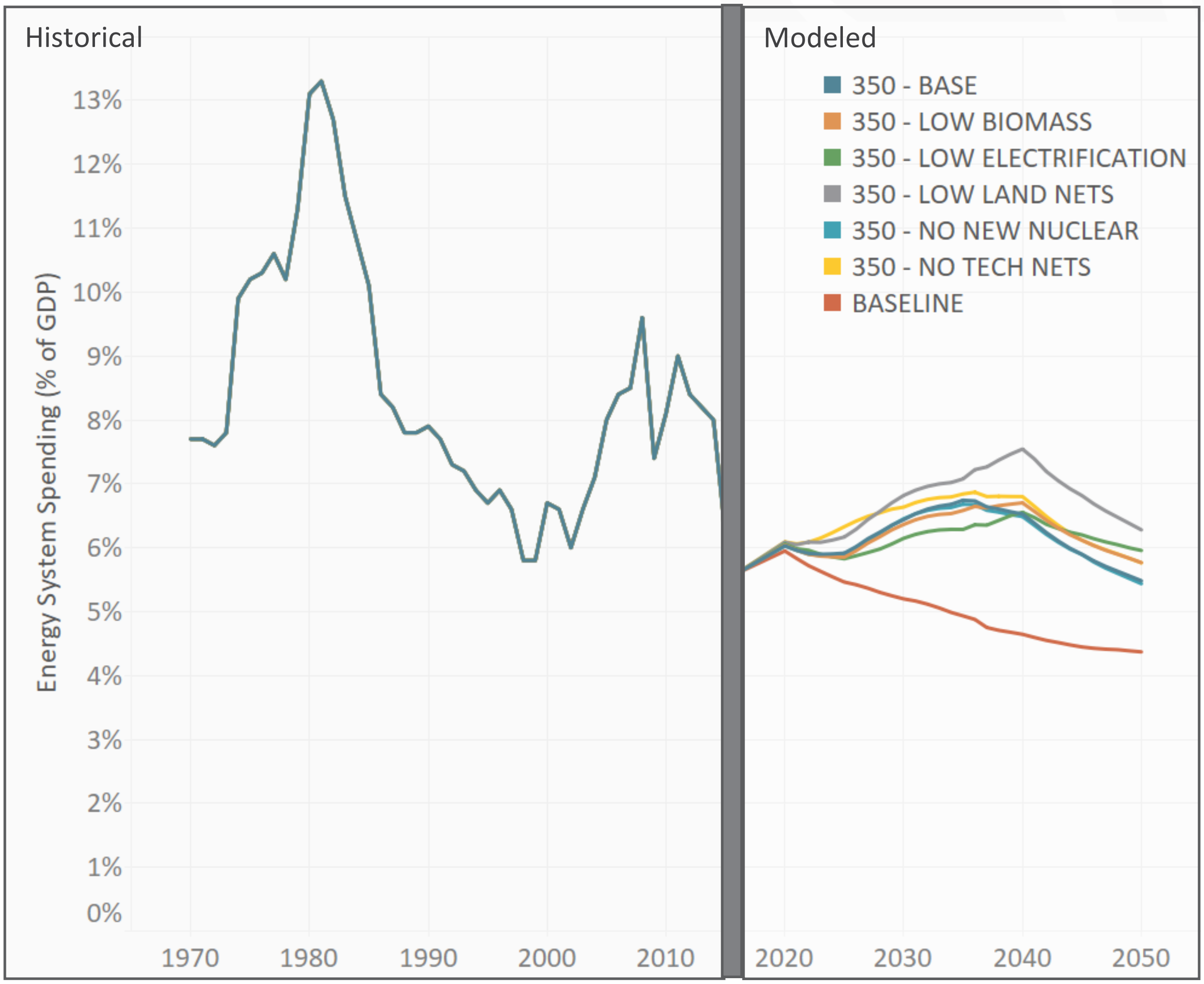



Figure ES5 shows U.S. energy system costs as a share of GDP for the baseline case and six 350 ppm scenarios in comparison to historical energy system costs. While the 350 ppm scenarios have a net cost of 2-3% of GDP more than the business as usual baseline, these costs are not out of line with historical 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