Accelerating Clean Energy Ambition

How the United States Can Meet Its Climate Goals While Delivering Public Health and Economic Benefits

Technical Appendix

https://www.ucsusa.org/resources/accelerating-clean-energy-ambition
https://doi.org/10.47923/2023.15253

Steve Clemmer

Rachel Cleetus

Jeremy Martin

Maria Cecilia P. Moura

Paul Arbaje

Maria Chavez

Sandra Sattler

November 2023

Union of Concerned Scientists

For the analysis *in Accelerating Clean Energy Ambition: How the United States can meet Its climate goals while delivering public health and economic benefits*, UCS modified the Evolved Energy Research (EER) models that EER used to produce its "Annual Decarbonization Perspective (ADP) 2022" report (EER 2022). This technical appendix, which briefly describes our modeling framework, provides more detail on the emissions reduction targets, scenarios, and changes to key assumptions used in ADP 2022. For a more detailed description of EER's models and assumptions, see (EER 2022).

Modeling Framework

UCS used two models developed by EER to analyze changes to the US energy system that would enable the nation to meet not only science-informed goals for reducing emissions but also all US energy needs. *The EnergyPATHWAYS* model includes a detailed representation of energy use, technologies, and costs in the transportation, buildings, and industrial sectors. We paired this demand-side model with the *Regional Investment and Operations* model, which represents various supply-side options for producing, transporting, and storing electricity, fuels, and carbon dioxide (CO_2). We also used the resulting changes in the scale and method of energy production and use from the two models to estimate reductions in major air pollutants (including sulfur dioxide, nitrogen oxides, and fine particulate matter). We then ran those estimates through the *CO–Benefits Risk Assessment* (COBRA) model of the US Environmental Protection Agency to calculate public health impacts (EPA 2023a).

Emissions Reduction Targets

We modeled national targets for reducing carbon emissions that align with meeting the US commitment in the Paris Agreement to reduce net heat-trapping emissions to at least 50 percent below 2005 levels by 2030 and to reach net-zero emissions no later than 2050. This translates to a cumulative US carbon dioxide equivalent (CO_2e) budget of 74 gigatons between 2021 and 2050.

Our modeling framework captures energy-related CO_2 emissions, which represent approximately 80 percent of the nation's current overall heat-trapping emissions (EPA 2023b; EPA 2023c), along with some upstream methane emissions from the oil and gas industry. We estimated changes in non-CO_2 emissions (methane, nitrous oxide, and fluorinated gases from agriculture, forestry, industry, and land-use change) and CO_2 emissions from the land sink (soils and vegetation that absorb CO_2 naturally) outside the model. To calculate net heat-trapping emissions across the economy, we combined total CO_2 emissions from energy and industry with other heat-trapping emissions and subtracted CO_2 emissions absorbed by the US land sink.

The emissions-reduction targets are:

- **Energy and industrial CO_2 emissions**: Reductions of 47.5 percent below 2005 levels by 2030 and 100 percent by 2050.

- **Methane, nitrous oxide, and fluorinated gases**: Reductions of 32 percent below 2005 levels by 2030 and 41 percent by 2050 across the mix of gases. This assumes the United States meets the global pledge to reduce methane emissions to 30 percent below 2005 levels by 2030 and achieves an 85 percent reduction in hydrofluorocarbons emissions as required by the 2020 American Innovation and Manufacturing Act and consistent with the Kigali Amendment to the Montreal Protocol. These reductions, along with reductions in nitrous oxide emissions, are consistent with estimates from other studies (Abhyankar, Mohanty, and Phadke 2021; EDF 2021; EPA 2021; Fargione et al. 2018; Hultman et al. 2021; NASEM 2018; NRDC 2021; Larsen, Larsen, and Pitt 2020). Based on assumptions from the Princeton REPEAT project, our reference cases also capture some reductions in non-CO_2 emissions resulting from incentives and programs in the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act (IIJA) (Jenkins et al. 2023).

- **Land sink**: Holding CO_2 emissions absorbed by the US land sink constant at 2019 levels of 0.79 gigatons per year through 2050 (EPA 2021). We assume the land sink stays fixed at current levels, given the high level of uncertainty shown in recent studies around whether emissions absorbed by the US land sink will increase or decrease. Some studies show that the land sink could be enhanced with additional policies and investments in natural solutions like reforestation, afforestation, increasing soil carbon, and restoring wetlands; other studies show that increases in wildfires, drought, and other factors could result in a significant reduction in the land sink or even turn it into a source (US State Department 2022; US State Department 2021; Wu et al. 2023). Indeed, across all emissions scenarios considered, the Second State of the Carbon Cycle Report assessed that the North American land sink is likely to either “remain near current levels” or “decline significantly” (USGCRP 2018).

Figure A-1 contains more detail on these assumptions.

Scenarios

UCS modeled seven scenarios for future emissions reduction trajectories from the US energy system (Table A-1).Two reference scenarios reflect current federal and state policies and do not meet US emissions reduction goals. Five decarbonization scenarios meet the emissions reduction targets outlined above, with different assumptions about overall energy demand, biomass supply, and hydrogen supply. The assumptions used for the Net Zero Pathway scenario were used in all the other net-zero scenarios, except for the changes noted in Table A-1 for each of those scenarios. The main report only includes results for scenarios 1-4. Scenarios 5-7 are included here and in the supplemental results tables to shed light on the uncertainties related to reducing energy demand and deploying biomass and hydrogen.

Assumptions

We based projections for energy demand and fossil fuel prices for our Reference with IRA/IIJA case and Net Zero Pathway case primarily on the EIA’s Annual Energy Outlook 2022. Electricity generation technology cost and performance assumptions come primarily from the Annual Technology Baseline 2021 of the National Renewable Energy Laboratory (NREL).

FIGURE A-1. Carbon Budget for Achieving US Climate Targets (Million Metric Tons of CO_2e)

	Net GHG Emissions	CO_2 Emissions	Non-CO_2 Emissions	Land Sink
2020	5,535 =	5,025	+ 1,300	- 790
2030	3,310 =	3,220	+ 880	- 790
2050	0 =	0	+ 790	- 790
		Modeled Constraint	Exogenous Estimates	

Key changes to EER's assumptions used in the ADP 2022 include:

- **Rooftop solar**: For the Reference with IRA/IIJA case and net-zero scenarios, we increased US rooftop solar capacity to 47 gigawatts (GW) in 2025 based on projections from NREL's 2022 standard scenarios, which include the IRA and IIJA. We used projections from the model for future years.

- **Offshore wind**: For the Reference with IRA/IIJA case, we used NREL's 2022 Standard Scenarios mid-case projections that include the IRA and IIJA. For the net zero scenarios, we increased near-term values to 5 GW in 2025 and 24 GW in 2030 based on a range of projections from Bloomberg New Energy Finance, 4C, and NREL, and used longer-term projections from EER's model.

- **Wind and solar build limits**: For all scenarios, we used assumptions from the Princeton REPEAT project's mid-case IRA scenario. It assumed compound average growth rate (CAGR) limits for onshore wind and utility solar PV capacity of 20 percent per year through 2032, 15 percent per year between 2032 and 2035, and 5 percent per year thereafter.

- **Electrolyzer build limits**: For all scenarios, we used assumptions from the Princeton REPEAT project mid-case IRA scenario that assumed a 20 percent CAGR starting at 3 GW in 2024. This allows US electrolyzer deployment to reach 9 GW per year in 2030, 22 GW per year in 2035, and significantly higher levels in subsequent years.

TABLE A-1. Scenarios for Future Emissions Reduction Trajectories in the US Energy System

	Scenario	Description
1.	Reference without IRA/IIJA	Reflects laws and regulations as of November 2021 based primarily on the US Energy Information Administration's (EIA) Annual Energy Outlook 2022 reference case. Does not include the IRA or the IIJA, enabling the analysis to isolate the impact of these policies.
2.	Reference with IRA/IIJA	Includes the impacts of the IRA and IIJA, as well as other federal and state policies and regulations adopted as of September 2022. Serves as a baseline point of comparison with the decarbonization scenarios.
3.	Net Zero Pathway	Represents a least-cost mix of technologies and resources for meeting US climate targets and the EIA's projected demand for energy services under a limited set of technology and resource constraints. Serves as a point of comparison with the other decarbonization scenarios.
4.	Net Zero/Low Demand	Assumes additional reduction in demand for energy services of 10 percent in buildings and 17 percent in industry. For transportation, assumes per-capita driving decreases by 5 percent by 2050, representing a 20 percent reduction in light-, medium-, and heavy-duty vehicles compared with EIA projections ; no increase in school buses ; 50 percent increase in transit and intercity buses ; 35 percent increase in freight rail ; and 10 percent reduction in aviation, boats, shipping, military, lubricants, and motorcycles.
5.	Net Zero/ Ambitious Demand Reduction	Assumes twice the level of reductions included in the low-energy-demand case. Similar in ambition to reductions included in recent IPCC reports, sustainable development scenarios modeled by the International Energy Agency, and other studies (Grubler et al. 2018 ; Keyßer, and Lenzen 2021 ; IEA 2021 ; IEA 2022 ; IEA 2023a ; IPCC 2022c ; Nadel and Unger 2019).
6.	Net Zero/Low Biomass	Assumes a 75 percent reduction in the biomass supply in the model that comes from the DOE billion-ton study.
7.	Net Zero/ Limited Fossil Hydrogen	Caps fossil fuel-based hydrogen production, including steam methane reforming or autothermal reforming coupled with carbon capture and storage (i.e., "blue" hydrogen) at current levels of unabated fossil fuel-based hydrogen production.

- **Incremental hydro and closed loop pumped storage deployment**: For the Reference with IRA/IIJA case and net-zero scenarios, we used NREL 2022 Standard Scenarios mid-case with IRA projections.

- **Coal retirements**: We assumed all coal generation is retired by 2030 in the net zero scenarios. Without this constraint, the model retires the vast majority of US coal generation by 2030 in the net-zero scenarios.

- **Advanced nuclear costs**: For all scenarios, we assumed a higher initial levelized cost of electricity for small modular reactors of $89 per megawatt-hour (MWh) with IRA tax credits and $119/MWh without the tax credits based on a recent announcement by NuScale (NuScale 2023; Walton 2022). We applied a similar initial percentage cost increase to high-temperature gas-cooled reactors and assumed modest cost reductions over time based on EIA projections used in NREL's 2022 ATB.

- **Vehicle electrification**: For the net-zero scenarios, we assumed 100 percent zero emissions vehicle (ZEV) sales for all vehicles by 2035. By 2050, battery electricity vehicles sales represent 95 percent of total ZEV sales for cars, 90 percent for light-duty trucks, 80 percent for medium-duty trucks, and 73 percent for heavy-duty trucks. Hydrogen fuel cell vehicles represent the remaining share of total ZEV sales for each of these categories.

Inflation Reduction Act and Infrastructure Investment and Jobs Act Assumptions

Our modeling of recently passed federal policies is largely focused on the IRA, signed into law in August 2022, and specifically on its federal incentives to invest in energy efficiency, electrification, renewable energy, and other low-carbon technologies and fuels across all sectors of the US economy. The modeling also includes incentives from the IIJA. However, these had minimal impact on the results, so we do not describe them in detail here.

We based the incentives in our modeling on assumptions developed for recent IRA and IIJA analyses by NREL and the Rapid Energy Policy Evaluation & Analysis Toolkit (REPEAT) Project at Princeton University (Steinberg et al. 2023; Jenkins et al. 2023). Because of modeling limitations and tax credit guidance still undergoing finalization by the US Treasury at the time of our analysis, certain simplifying assumptions were required. Some of the more important provisions from those studies are:

- **Production Tax Credit (PTC)** for renewable and other zero-carbon generation: $26 per megawatt-hour (MWh) over 10 years of operation, plus a bonus credit that our reference policy assumes to start at an average rate of 5 percent ($1.3 per MWh) in 2023 and increases to 10 percent ($2.6 per MWh) by 2028. The representation in the model captures the modification and the extension of the existing PTC (§45) for renewable generation, as well as the creation of the new technology-neutral emissions-based PTC (§45Y), including the associated technology eligibility limitations.

- **Investment Tax Credit (ITC)** for renewable and other zero-carbon generation: 30 percent plus a bonus credit that starts at an average rate of 5 percent (35 percent for the total value) in 2023 and increases to 10 percent (40 percent total value) by 2028. As with the PTC, the representation in the model captures both the modification and extension of the existing ITC (§48), as well as the new technology-neutral ITC for zero-carbon generating and storage technologies (§48E).

- **Captured CO_2 Incentive (45Q)** for CO_2 captured and stored in geologic formations: $85 per metric ton of CO_2 and for 12 years for ethanol plants with carbon capture and storage (CCS), bioenergy with CCS, hydrogen with CCS, gas and coal power plants with CCS, and cement facilities with CCS; and $180 per ton for CO_2 stored from direct air capture projects. Steam methane reforming and auto-thermal reforming hydrogen with CCS are assumed to claim the 45X hydrogen PTC (at greater value) so are assumed ineligible for 45Q.

- **Existing Nuclear Production Tax Credit (45U)** for generation from existing nuclear facilities: $15 per MWh but reduced if the market value of the electricity generated exceeds $25 per MWh. As a simplification, the market-adjusted value of 45U was not directly represented in the model. Instead, we assumed that 45U, in combination with the Civil Nuclear Credit program under the IIJA, is sufficient to maintain cost-recovery of existing nuclear plants; thus, nuclear plants are not subject to economic-based retirement in the model until 2033.

- **Wage and apprenticeship requirements**: To qualify for the above levels of the PTC, ITC, and 45Q, new projects must demonstrate that wages for the labor force used to construct facilities equal or exceed prevailing wages and that a minimum share of work is executed by individuals from registered apprentice programs. We assumed all projects meet these requirements, which makes them eligible for the full value of the incentives.

- **Bonus credits for domestic manufacturing and energy communities**: Projects eligible for the PTC and ITC can claim up to two bonus credits if they meet specific domestic-content requirements, and/or are located in an "energy community" with brownfield sites or coal, oil, or gas facilities. For projects electing the PTC, each bonus credit increases the PTC value by 10 percent or $2.6 per MWh. For projects electing the ITC, each bonus credit increases the value by 10 percentage points (i.e., from 30 percent up to a maximum of 50 percent). We adopted NREL's assumptions that projects on average achieve half a credit in 2023, increasing to a full credit by 2028. We did not include incentives to increase domestic manufacturing from the 45X Advanced Manufacturing Production Credit or the 48C Qualified Advanced Energy Credit.

- **PTC-ITC optionality**: The IRA allows eligible projects to elect either the PTC or the ITC. In general, technologies with relatively high capital costs and low capacity factors are likely to choose the ITC, while technologies with relatively low capital costs and high capacity factors are likely to choose the PTC. We adopted NREL assumptions that onshore wind, utility-scale PV, and biopower projects will likely elect the PTC, while offshore wind, concentrating solar power, geothermal, hydropower, nuclear, pumped storage, battery storage, and distributed PV will likely elect the ITC.

- **Cost of monetizing tax credits**: We adopted NREL assumptions that assume monetizing the tax credits will result in a 10 percent reduction in value across most technologies, except for CCS credits, which are reduced by 7.5 percent due to the additional allowance for direct pay for 45Q tax credits under the IRA.

- **PTC and ITC phaseout**: Under the IRA, the PTC and ITC are triggered to begin a phase-out schedule in the year that electricity sector emissions fall below 25 percent of 2022 levels or in 2032, whichever is later. This occurred in our reference case with IRA/IIJA and net-zero scenarios between 2030 and 2035. However, we assumed that projects meeting US Treasury safe-harbor and commence-construction requirements prior to the expiration of credits could receive credits and be placed in service after the credits expire.

- **Credits for distributed solar PV**: We used NREL projections for distributed solar PV that capture tax credits available for projects installed in the residential, commercial, and industrial sectors, along with bonus credits available for deploying up to 1.8 GW per year of solar in low-income communities through 2032.

- **Hydrogen production:** We used REPEAT assumptions that provide a $3 per kilogram PTC for 10 years for electrolytically produced hydrogen (assuming electrolysis is using variable wind and solar or nuclear inputs). Hydrogen from methane reforming with CCS or bioenergy with CCS is assumed to claim Section 45Q tax credit for CCS, which is more valuable. Direct pay eligibility is assumed to allow monetization of the full credit value.

- **Low-carbon fuels:** We used REPEAT assumptions for tax credits and incentives that are available for biofuels, sustainable aviation fuels, and other low-carbon fuels.

- **Demand-side incentives:** We used REPEAT assumptions for several tax credits and incentives available in the buildings, industrial, and transportation sectors. In the buildings sector, this includes incentives to weatherize and insulate new and existing homes and multifamily buildings, increase the efficiency of commercial buildings, purchase more-efficient equipment and appliances, and install efficient electric heat pumps that can also provide cooling in the summer. In the industrial sector, it includes incentives for energy-efficiency retrofits, implementing advanced industrial technology at energy-intensive facilities, and installing carbon capture, utilization, and storage. In the transportation sector, it includes incentives for purchasing new and used battery electric, plug-in hybrid, and fuel cell vehicles for light-duty, medium-duty, and heavy-duty applications.

- **Other incentives,** such as those to reduce methane and other non-CO_2 gases and invest in agriculture and forestry projects to enhance the land sink, were not modeled explicitly, but assumptions outside the model partially capture them. Several other IRA incentives were also not included as described in more detail in the NREL and Princeton REPEAT project materials.

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https://doi.org/10.47923/2023.15253