Technical Appendix: Methods and Assumptions for ReEDS modeling

This document describes the methodology and assumptions that the Union of Concerned Scientists (UCS) used for the development of the *50 percent by 2035 National Renewable Electricity Standard (RES)* analysis:

Regional Energy Deployment System (ReEDS)

The UCS employed the National Renewable Energy Laboratory's (NREL) Regional Energy Deployment System (ReEDS)—a capacity-planning model for the deployment of electric power–generation technologies in the contiguous United States through 2050—to analyze the impacts of a 50 percent by 2035 national renewable electricity standard (RES) proposal.

ReEDS is designed to analyze in particular the impacts of state and federal energy policies, such as clean energy and renewable energy standards, for reducing carbon emissions. ReEDS provides a detailed representation of electricity generation and transmission systems. It specifically addresses issues, such as transmission, resource supply and quality, variability, and reliability, related to renewable energy technologies (NREL 2016a).

UCS used the 2016.RE.TaxExt.P1 version of ReEDS for its analysis. Based on project-specific data and estimates from recent studies, we made a few adjustments to NREL's assumptions on renewable and conventional energy technologies, as described in more detail in "Overall Model Assumptions" just below. Our assumptions for the policies being tested in our analysis are described in "Policy Assumptions for Scenarios" that appears later in this document.

Modeling limitations and uncertainties

The intent of this modeling is not to predict the future generation mix but rather to better understand key drivers and important implications for the power sector, consumers and emissions of achieving a significant increase in renewable electricity generation in the US. These modeling scenarios are not forecasts, and we make no claim that the scenarios will accurately predict the future. The goal is to illustrate the potential impacts of the scenarios to build on analyses conducted by other organizations using models and assumptions developed by credible, independent sources and informed by real-world data. The value of the analysis lies more in the difference between scenarios rather than the absolute values of the projections. Other modeling and analytic frameworks will have different emphases, strengths, and weaknesses.

Overall ReEDS Model Assumptions

Cost and performance. The cost and performance assumptions for electricity-generating technologies used in the ReEDS analysis are shown in Tables A-2 through A-5 below.

We made several changes to NREL's capital-cost assumptions. The 2016.RE.TaxExt.P1 version of ReEDS uses the EIA's AEO 2015 cost assumptions for conventional plants; our revisions are based on the Energy Information Administration's (EIA) *Annual Energy Outlook* (AEO) 2018 (EIA 2018) assumptions for capital costs, operating and maintenance (O&M) costs, and heat rates.

NREL provides a set of projections, which users can easily select, regarding cost and performance assumptions on renewable energy technologies. Our choices of these projections were consistent with the corresponding assumptions underlying the *Annual Technology Baseline 2017* report (NREL 2017), with a few exceptions noted below. The main changes we made were in the following areas:

- **Coal.** For new integrated gasification and combined cycle plants and for supercritical pulverized-coal plants, we used NREL's assumptions, which are based on the EIA's higher costs for a single-unit plant (600–650 megawatts (MW)), as opposed to dual-unit plants (1200–1300 MW). For plants with carbon capture and sequestration, we used the assumptions used by NREL and the EIA and included the tax credits from 45Q.
- **Natural gas.** For new plants, we used NREL's assumptions, which are based on the average of the EIA's assumptions for conventional and advanced plants in 2018. For plants with carbon capture and sequestration, we used the assumptions used by NREL and the EIA and included the tax credits from 45Q.
- **Nuclear.** We use the EIA's assumed costs for 2018 with no cost reductions from learning through 2050. We also assumed that all existing reactors will receive a 20-year license extension, allowing them to operate for 60-year lifetimes, and that they will then be retired because of safety and economic issues. To date, no existing reactor has received an operating license extension beyond 60 years.
- **Onshore and offshore wind.** We used NREL's cost and performance projections from its median cost-reduction case, as described in the 2017 *Annual Technology Baseline*. These cost and performance projections are based on NREL's estimate of median values from its review of literature.
- **Utility-scale solar photovoltaics (PV).** We use NREL's 2017 *Annual Technology Baseline* cost and performance projections from its mid-cost case and included the effects of the solar tariff.
- **Distributed solar PV.** ReEDS does not endogenously simulate the uptake of distributed PV systems (those installed on site by residential or commercial customers). Instead, users must select the appropriate projections for uptake of these systems as an exogenous input to the model based on projections from NREL's dGen model (NREL 2016b). For our reference case, we used NREL projections based on NREL's 2018 *Annual Technology Baseline* mid-cost case.
- **Concentrating solar power plants.** We assumed that concentrating solar power plants will include six hours of storage and exhibit the capital and O&M cost projections of NREL's 2017 *Annual Technology Baseline* mid-cost case.
- **Biomass.** We used the EIA's initial capital costs for new fluidized-bed combustion plants and for biomass cofiring with coal, but we did not include the EIA's projected cost reductions due to learning because we assumed that these were mature technologies. We also used a slightly different biomass supply curve from those of the EIA and NREL, based on a UCS analysis of data from the DOE's *Updated Billion Ton* study, which included additional sustainability criteria (ORNL 2011). We project a potential biomass supply of 680 million tons per year by 2030 (UCS 2012). Further, we limited the coal capacity that can be retrofitted for cofiring biomass to 10 percent of a plant's capacity—not the 15 percent maximum used in NREL assumptions.
- **Geothermal and landfill gas.** We didn't make any changes to NREL's assumptions for these technologies.
- **Storage technologies.** We assumed that utility-scale batteries are four-hour-duration lithium-ion systems with cost assumptions based on recent studies (Lazard 2017; Cole et al. 2016).
- **Hydro.** In order to reflect the long lead times for planning, permitting, and building large hydro dams, we restricted the construction of such facilities until after 2020. Based on the 2016

Hydropower Vision study (DOE 2016), we increased the costs of non-powered dams to be twice those assumed by NREL. We didn't make any other changes to NREL's assumptions for the hydro supply curves, which are site-specific.

Electricity sales and energy efficiency projections. ReEDS does not endogenously model electricity sales or efficiency; instead, users provide assumptions of future use. As a default, electricity sales are taken from the EIA's AEO 2018 projections. ReEDS starts with the 2010 electricity sales for each state, then projects future electricity sales using the growth rate for the appropriate census region from the AEO 2018 reference case. We adjusted these projections to account for reductions in load growth resulting from currently enacted state energy efficiency resource standards (EERS) that are not included in the AEO 2018. Our adjustments follow the approach used by the Environmental Protection Agency in its *Projected Impacts of State Energy Efficiency and Renewable Energy Policies* report (EPA 2014).

State renewable portfolio standard (RPS) programs. ReEDS uses RPS data from a 2015 Bloomberg New Energy Finance (BNEF) RPS database. We adjusted ReEDS' representation of the state programs to account for recent legislation and demand forecasts. Our adjustments are based on the Lawrence Berkeley National Laboratory's 2019 *RPS Annual Status Report* (to be released) and industry reports and projections in NREL's *Annual Technology Baseline* (NREL 2017).

Accounting for recent or planned changes to generating resource or transmission availability. We reviewed ReEDS assumptions for expected changes in power-plant capacity and transmission lines in the near term and compared that with our understanding, based on S&P Global data and industry reports and projections, of real-world conditions. Our updates to ReEDS included:

- Accounting for prescribed builds of newly constructed or under construction generating resources (including natural gas, nuclear, coal, wind, and utility-scale solar facilities) using a combination of S&P and industry association data published as of March 2018
- Accounting for recent or recently announced coal-plant retirements through 2030 based on data published as of March 2018
- Accounting for recent or recently announced nuclear-plant retirements based on data published as of April 2018
- Accounting for transmission projects under construction or in an advanced stage of development using a combination of S&P and industry association data published as of April 2018
- Including California's requirement for storage (AB 2514).

Calculation of the monetary value of carbon dioxide (CO_2) reduction benefits. To determine the monetary value of CO_2 reductions, we used the US government's estimates of the "social cost of carbon"—an estimate of the damages, expressed in dollars, resulting from the addition of one metric ton of CO_2 to the atmosphere in a given year. We multiplied the tons of CO_2 reduced in our scenarios by the social cost of carbon to derive the CO_2-reduction benefits or the avoided damages.

We used the updated values for the social cost of carbon that were reported in the Environmental Protection Agency's (EPA) *Regulatory Impact Assessment for the Clean Power Plan Final Rule* (EPA 2015, shown here in Table TA-1.

TABLE TA-1. Values for Social Cost of Carbon

Year	Social Cost of Carbon (2017$)[1]
2018	$47 per ton of CO_2
2020	$50 per ton of CO_2
2025	$54 per ton of CO_2
2030	$59 per ton of CO_2

Calculation of the monetary value of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) reduction benefits. To value SO_2 and NO_x emissions reductions, we again used estimates from the EPA *Regulatory Impact Assessment for the Clean Power Plan Final Rule* of the dollar value of the health benefits per ton of SO_2 and NO_x reduced by different industrial sectors, including the electricity sector (EPA 2015).

In particular, for the 2020 emissions reductions generated in our models, we used the values in the EPA's Table 4-7. There, these values are expressed in 2011$ using a 7 percent discount rate, so we converted them to 2017$ so as to be consistent with other dollar values in our analysis. For 2025 and 2030, we used the values in Tables 4-8 and 4-9, again converted to 2017$.

Policy assumptions. For this analysis, we compared two scenarios: a ReEDS business as usual reference case and a renewable electricity standard scenario. For each scenario we ran the ReEDS model for the contiguous United States, with a consistent set of assumptions across all states.

The ReEDS reference case includes:

- State and federal policies in place as of May 2019, and the assumption that no additional policies have been or will be implemented.
- The electricity demand and coal prices from the reference case of the AEO 2018.
- The natural gas price projection from EIA's AEO 2018 "high oil and gas resource and technology" side case, which is in the range of independent consultant projections and the reduction in natural gas prices EIA made in AEO 2019.
- The distributed PV projection from NREL's ATB 2018 mid-cost case
- We limited the amount of wind capacity the model was allowed to build from 2019-2022 based on estimates of projects under construction and in advanced stages of development from the American Wind Energy Association's 2018 Market Report and a range of projections from independent consultants from DOE's 2017 Wind Technologies Market Report.
- The federal production tax credit was assumed to be available at full value through 2020 and was gradually phased out by 2023 based on IRS guidance that allows projects that commence construction up to 4 years to be place in service.

[1] Assuming a 3 percent discount rate. Source: EPA 2015, Table 4-2.

- State energy-efficiency standards through December 2017, as calculated by UCS (based on data from state utilities and from the Database of State Incentives for Renewables and Efficiency) using a methodology developed by the EPA for state analyses
- The model's data for existing power plants updated to include recent and announced retirements and plants under construction and current state energy efficiency programs. This included seven nuclear reactors at five plants that have firm plans to retire (or have already retired) over the next eight years. We also included two reactors under construction at the Vogtle plant in Georgia.
- The model revisions described in the previous section

The National 50% by 2035 RES Case includes:

- A national RES of 22.8 percent in 2020, increasing to 42.2 percent in 2030 and 53.2 percent in 2035 layered over the reference case. The RES specifies ramp-up rates of 1.5% of retail sales in 2020, 2% per year from 2021-2029, and 2.5% per year from 2030-2035 for retail electricity providers with annual sales of 1 million MWh or more, and half the annual increase for retail providers below this threshold. We obtained state-level data on total renewables as a share of in-state generation from EIA's Electric Power Monthly (January 2019) and estimated the 2019 renewable levels from recent 5-year growth rates for non-hydro renewables. The ramp-up rates are applied to each state in proportion to sales by retail electricity providers above and below the threshold in that state, based on 2017 EIA form 861 data for electricity sales by utility and power marketer by state. The implied state-level targets based on the weighted ramp-up rates are then aggregated to calculate the national RES targets.
- These national RES targets also reflect assumptions about states that may opt-out of the policy when they reach 60% of sales from renewables. For states with a 5-year historical growth rate in non-hydro renewables greater than the federal floor, we assume these states would not opt-out and instead continue to grow at the federal floor in order to continue to sell RECs into the market. For states with 5-year historical growth rates less than the federal floor, we assume those states would continue to build renewables at that historical rate. In addition, we restrict renewables from declining after hitting the cap in a few states that have negative historical growth rates due to annual retirements or annual fluctuations in generation.
- Eligible resources: wind, solar, geothermal, ocean/tidal, incremental hydro, landfill gas, and renewable biomass
- Distributed PV projection from NREL's 80 percent by 2050 RES scenario from ATB 2018
- Due to modeling limitations, we were not able to analyze provisions in the bill that provide double credits for renewable energy projects installed on Native American lands and in impacted communities. We were also not able to analyze the potential for at-risk existing facilities that came online between 2005 and 2019 to qualify for federal renewable energy credits available to new facilities. While the model also assumes that existing renewable generation is eligible for renewable energy credit trading, the model projects that almost all

existing generation will continue to operate under the reference case so this has virtually no impact on the results of the policy case. Overall, we believe these provisions would have a modest impact on the RES targets.

TABLE TA-2. Comparison of Overnight Capital Costs for Electric Generation Technologies (2017$/kW).

	Overnight Capital Costs				
Technology	2010	2020	2030	2040	2050
Natural gas, combined cycle	1,054	1,047	1,000	965	926
Natural gas, combined cycle / carbon capture and storage	N/A	2,146	1,864	1,570	1,335
Natural gas, combustion turbine	895	895	851	820	785
Coal, supercritical pulverized coal	3,186	3,699	3,570	3,478	3,359
Coal, integrated gasification and combined cycle	4,109	3,966	3,713	3,543	3,357
Coal, pulverized coal / carbon capture and storage	7,109	5,627	4,958	4,358	3,807
Nuclear	5,946	5,946	5,946	5,946	5,946
Hydro*					
Biomass, dedicated	4,466	3,873	3,656	3,511	3,339
Biomass, cofired with coal**	2,989	2,989	2,989	2,989	2,989
Solar, utility-scale PV	4,617	1,130	940	836	741

Solar, residential PV	6,981	2,354	1,525	1,266	1,164
Solar, commercial PV	3,488	1,624	1,119	1,014	961
Solar, concentrating solar power plant with six-hour Storage	9,767	6,945	6,174	5,643	5,352
Wind, onshore					
- class 3	1,920	1,488	1,404	1,415	1,377
- class 4	1,920	1,500	1,344	1,336	1,290
- class 5	1,488	1,323	1,404	1,311	1,262
- class 6	1,779	1,469	1,290	1,268	1,214
- class 7	1,635	1,448	1,267	1,243	1,189
Wind, shallow offshore	5,640	4,811	4,093	3,982	3,856
Wind, deep offshore	6,228	5,311	4,516	4,393	4,254
Landfill gas	9,288	8,765	8,542	8,323	8,039
Geothermal	2,575	2,575	2,575	2,575	2,575

Source: UCS 2018

**Hydro capital costs are too detailed to show in this table; ReEDs uses supply curves with capital cost variation by potential resource capacity.*

***The cost for biomass co-firing is per kW of biomass capacity.*

TABLE TA-3. Operation and Maintenance (O&M) and Heat Rate Assumptions

Technology	Fixed O&M ($2017/kW-yr)	Variable O&M ($2017/MWh)	Heat Rate (Btu/kWh)	
			2020	2050
Natural gas, combined cycle	10.6	2.8	6,624	6,275
Natural gas, combined cycle /	33.8	7.2	7,504	7,493

carbon capture and storage				
Natural gas, combustion turbine	12.3	7.2	9,756	9,075
Coal, supercritical pulverized coal	33.2	4.8	8,760	8,740
Coal, integrated gasification and combined cycle	54.1	7.6	7,867	7,450
Coal, pulverized coal / carbon capture and storage	70.0	4.7	9,105	9,316
Nuclear	101.3	2.3	10,479	10,460
Biomass	112.2	5.6	13,500	13,500
Solar PV-utility	13.4	0.0	n/a	n/a
Solar CSP-With Storage	68.3	0.0	n/a	n/a
Wind-Onshore	52.5	0.0	n/a	n/a
Wind-Shallow Offshore	136.5	0.0	n/a	n/a
Geothermal	175.6			

Source: UCS 2018

Note: Fixed and variable O&M costs are for 2020 through 2050; costs for earlier years are higher.

TABLE TA-4. Solar Capacity Factors

Technology	Solar Capacity Factor
Utility-scale solar PV	14-28%
Concentrating solar plant with six-hour storage	28-38%

Source: UCS 2018

TABLE TA-5. Comparison of Wind Capacity Factors

Technology	Wind Capacity Factor				
	2014	2020	2030	2040	2050
Wind, onshore class 3	32.0%	34.5%	37.0%	38.3%	39.6%
Wind, onshore class 4	37.7%	40.7%	43.6%	45.1%	46.7%
Wind, onshore class 5	43.9%	46.5%	49.2%	50.8%	52.5%
Wind, onshore class 6	46.6%	49.0%	51.5%	53.2%	54.9%
Wind, onshore class 7	51.1%	53.7%	56.4%	58.2%	60.1%
Wind, offshore class 4	34.6%	35.3%	37.9%	38.3%	38.8%
Wind, offshore class 5	40.3%	41.2%	44.1%	44.7%	45.2%
Wind, offshore class 6	43.2%	44.2%	47.3%	47.9%	48.4%
Wind, offshore class 7	47.3%	48.4%	51.8%	52.4%	53.0%

Source: UCS 2018

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