100% Clean Electricity by 2035?

By John Benson

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1. Introduction

Mitigating climate change is important, really important, and the sooner, the better. The first major step in this process is converting our electricity to 100% greenhouse gas (GHG) free generation. This is because many other producers of GHG plan to use clean electricity as their future energy source in lieu of their current GHG-producing methods. As an example, all types of vehicles will need to evolve to either use electricity directly or use GHG-free fuels (like hydrogen) that are produced with electric energy and/or carbon capture and storage (CCS). This is a process that will take several decades to reach near-zero-net-GHG, so it is good that we have already started and the sooner we can make electricity zero-GHG, the less GHG we will pump into the atmosphere.

My home state (California) has an official goal of reaching zero GHG electricity by 2045. I wrote about this in the post from a bit over two years ago, described and linked below.

Electric Decarbonization: *My home-state (California) has a goal to use "…renewable energy resources and zero-carbon resources…" to supply 100 percent of retail electricity sales and electricity procured to serve all state agencies by 2045.*

The statute (AB 100) calls upon the California Public Utilities Commission (CPUC), California Energy Commission (CEC), and the California Air Resources Board (CARB) to use programs under existing statutes to achieve this policy and issue a joint report on the policy to the Legislature by January 1, 2021, and every four years thereafter. This post will briefly cover the first of the above reports.

https://energycentral.com/c/cp/electric-decarbonization

The above-mentioned *"…joint report…"* concluded that this goal was achievable, but what about the more aggressive 2035 goal? California has consistently met or exceeded its climate change goals (usually the latter), so do we have a shot at 2035?

Several recent events have given us some hope that this more aggressive goal is achievable:

1. We are starting to occasionally reach net-zero electricity now.

   For the first time ever, California, the world's fifth-largest economy, was powered by 100% clean energy on Saturday, April 30, 2022. That milestone was driven largely by solar power.[1]

   Energy demand statewide reached 18,672 megawatts at 2:45 pm, with 37,172 MW available. (Excess is exported to neighboring states.) 101% of the power provided came from clean energy, according to a continuous tracker provided by California Independent System Operator (CAISO)…

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[1] Michelle Lewis, Electrek, "California runs on 100% clean energy for the first time, with solar dominating," May 2, 2022, https://electrek.co/2022/05/02/california-runs-on-100-clean-energy-for-the-first-time-with-solar-dominating/

2. The recently passed “Inflation Reduction Act (IRA) of 2022” and the Bipartisan Infrastructure Law (BIL) of 2021 contain extensive provisions to quickly evolve to 100% clean energy (see section 3 of this paper).
3. Diablo Canyon Nuclear Plant operation was extended to 2030, giving hope that this project could be upgraded to a closed cycle cooling system, and receive seismic and other retrofits to enable safe and sustainable operation for a longer period.
4. The California Legislature recently passed a $54 Billion package of bills that codified new benchmarks to get California to 90% clean electricity by 2035 and 95% by 2040.[2]
5. A recent report from the National Renewable Energy Laboratory (NREL), “*Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035*,” suggests that the 2035 goal is achievable.

This post will examine the possibility of evolving to clean electricity by 2035. The primary source for this evaluation is the NREL report cited in 5 above.

2. NREL Report

This study evaluates a variety of scenarios that achieve a 100% clean electricity system (defined as zero net greenhouse gas emissions) in 2035 that could put the United States on a path to economy-wide net-zero emissions by 2050. These scenarios focus primarily on the supply of clean electricity, including technical requirements, challenges, and benefit and cost implications. The study results highlight multiple pathways to 100% clean electricity in which benefits exceed costs. The study does not comprehensively evaluate all options to achieve 100% clean electricity, and it focuses largely on supply-side options.[3]

We evaluated four main 100% clean electricity scenarios, which were each compared to two reference scenarios: one with “current policy” electricity demand (Reference-AEO)[4] *and a second with much higher load growth through* ***accelerated demand electrification (Reference-ADE)****. The Reference-ADE case includes rapid replacement of fossil fuel use with low-carbon alternatives across all sectors, including electrified end uses and low-carbon fuels and feedstocks, resulting in annual electricity demand that is 66% higher than in the Reference-AEO case in 2035. The four core scenarios apply a carbon constraint to achieve 100% clean electricity by 2035 under accelerated demand electrification and reduce economy-wide energy-related emissions by 53% in 2030 and 62% in 2035 relative to 2005 levels.*

Table ES-1 (next page) *summarizes the four primary scenarios evaluated, which represent a range of uncertainties and themes (e.g., technology availability) and which are described below. In each scenario, assumptions common to all scenarios are called “reference,” and details are provided in the main body and Appendix C* (of reference 3).

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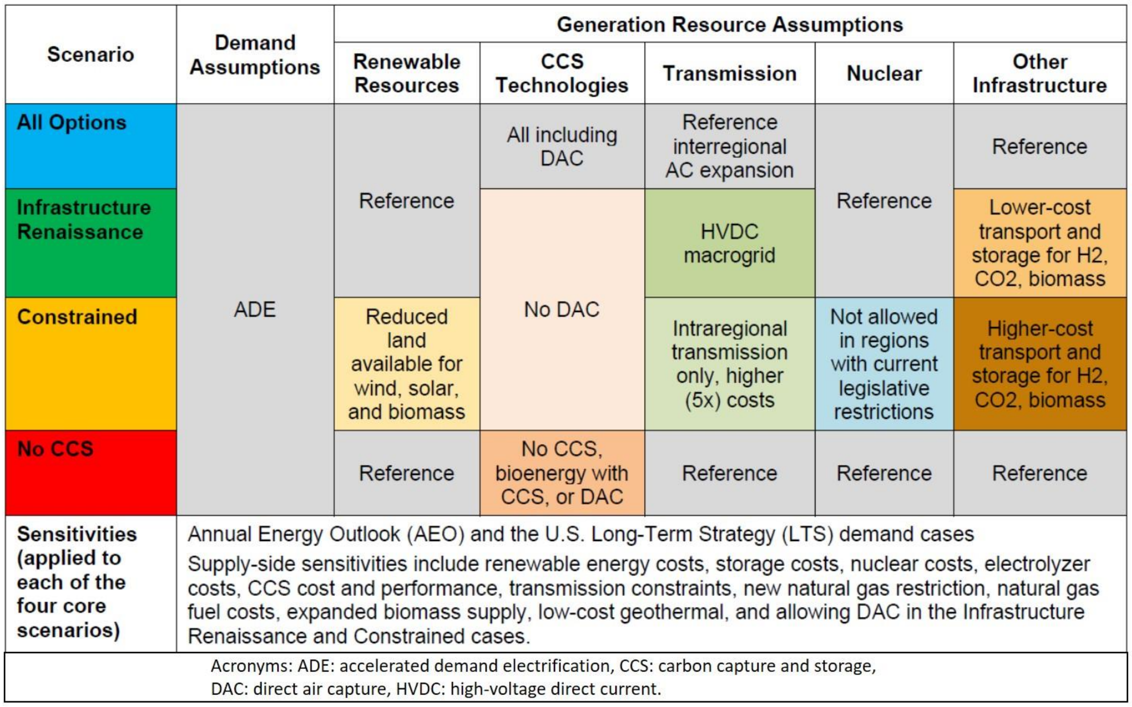
[2] See Energy Central, “Extreme Climate,” Section 5, Sep 2022, https://energycentral.com/c/cp/extreme-climate

[3] Denholm, Paul, Patrick Brown, Wesley Cole, et al. 2022. Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-81644. https://www.nrel.gov/docs/fy22osti/81644.pdf

[4] This refers to the projections in the Annual Energy Outlook (AEO) from the U.S. Energy Information Administration (EIA 2021a), https://crsreports.congress.gov/product/pdf/IF/IF11691

- ***All Options*** *is a scenario in which all technologies continue to see improved cost and performance consistent with the National Renewable Energy Laboratory's (NREL's) Annual Technology Baseline.*[5] *This scenario includes the development and deployment of direct air capture (DAC) technology, while the other three main scenarios assume DAC does not achieve the cost and performance targets needed to be deployed at scale.*[6]

Table ES-1. 100% Clean Electricity Scenarios and Sensitivities Evaluated in This Study



Scenario	Demand Assumptions	Generation Resource Assumptions				
		Renewable Resources	CCS Technologies	Transmission	Nuclear	Other Infrastructure
All Options	ADE	Reference	All including DAC	Reference interregional AC expansion	Reference	Reference
Infrastructure Renaissance			No DAC	HVDC macrogrid		Lower-cost transport and storage for H2, CO2, biomass
Constrained		Reduced land available for wind, solar, and biomass		Intraregional transmission only, higher (5x) costs	Not allowed in regions with current legislative restrictions	Higher-cost transport and storage for H2, CO2, biomass
No CCS		Reference	No CCS, bioenergy with CCS, or DAC	Reference	Reference	Reference
Sensitivities (applied to each of the four core scenarios)	Annual Energy Outlook (AEO) and the U.S. Long-Term Strategy (LTS) demand cases Supply-side sensitivities include renewable energy costs, storage costs, nuclear costs, electrolyzer costs, CCS cost and performance, transmission constraints, new natural gas restriction, natural gas fuel costs, expanded biomass supply, low-cost geothermal, and allowing DAC in the Infrastructure Renaissance and Constrained cases.					

Acronyms: ADE: accelerated demand electrification, CCS: carbon capture and storage, DAC: direct air capture, HVDC: high-voltage direct current.

- ***Infrastructure Renaissance*** *assumes improved transmission technologies as well as new permitting and siting approaches that allow greater levels of transmission deployment with higher capacity.*

- ***Constrained*** *is a scenario where additional constraints to deployment of new generation capacity and transmission both limits the amount that can be deployed and increases costs to deploy certain technologies.*

- ***No CCS*** *assumes carbon capture and storage (CCS) technologies do not achieve the cost and performance needed for cost-competitive deployment. This scenario*

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[5] Authors, see linked site, National Renewable Energy Laboratory (NREL), "2021 Annual Technology Baseline." https://data.openei.org/submissions/4129

[6] Executive Order 14057 defines "carbon pollution-free electricity" as "electrical energy produced from resources that generate no carbon emissions, including marine energy, solar, wind, hydrokinetic (including tidal, wave, current, and thermal), geothermal, hydroelectric, nuclear, renewably sourced hydrogen, and electrical energy generation from fossil resources to the extent there is active capture and storage of carbon dioxide emissions that meets EPA requirements". The inclusion of non-generation, negative emission technologies such as direct air capture is not consistent with the Administration's 2035 clean electricity goal but are considered in the study's All Options Scenarios because of their potential deployment, emissions, and cost impacts. https://www.federalregister.gov/documents/2021/12/13/2021-27114/catalyzing-clean-energy-industries-and-jobs-through-federal-sustainability

> *also acts as a point of comparison to demonstrate the potential benefits of achieving cost-competitive deployment of CCS at scale. This is the only scenario that includes no fossil fuel capacity or generation in 2035, and therefore it is the only scenario that includes zero direct GHG emissions in the electric sector.*

Beyond the four core 100% scenarios, 142 additional sensitivities were also analyzed to capture future uncertainties related to technology cost, performance, and availability. Of these 142 sensitivities, 122 cases model 100% carbon-free electricity by 2035. We also evaluated all scenarios with a sensitivity case using electricity demand from the Long-Term Strategy of the United States (LTS)[7] *to reflect an alternative demand-side pathway to reaching a net-zero emissions economy by 2050. The LTS reflects higher levels of energy efficiency and demand-side flexibility, resulting in slower annual load growth of 1.8%/year (compared to 3.4%/year under ADE) and, importantly, lower demand peaks that occur predominantly in summer as compared to the sharp winter peaks assumed for our primary ADE scenarios. In addition to direct electricity demand, both ADE and LTS assumptions include demand for clean hydrogen production for transportation and industrial applications, which may be produced from electrolysis or from natural gas with CCS depending on scenario. Non-power sector demand for hydrogen is an input to the analysis; however, hydrogen demand for electricity generation (for seasonal storage) is also considered and is an outcome of the scenarios. Electricity generation and capacity needed to produce hydrogen—for both power and non-power applications—are also considered in the modeling.*

Across these scenarios, this work uses NREL's Regional Energy Deployment System (ReEDS) model[8] *to identify the resulting least-cost investment portfolios from a range of different generation, storage, and transmission technologies while considering the significant geographical variation in demand and resource availability, including the regional and temporal variations in the output of renewable resources. The geographical and temporal variability of various resources is evaluated by ReEDS, including additional transmission costs needed for remote resources and the need to maintain an adequate supply of energy during all hours of the year. A detailed list of limitations of the modeling approach and key caveats regarding scope, and cost elements included is provided in the Key Caveats…*

Author's note: Key Caveats are in Section 4 of this paper.

Based on assumed growth in demand due to end-use electrification, and electric demand associated with hydrogen production (for direct use or for production of other clean fuels), total electricity generation grows by about 95%–130% from 2020 to 2035. Total generation is shown for all end-use loads plus the additional generation needed for transmission losses and generation used by the electric sector to produce hydrogen for seasonal electricity storage. There are differences between scenarios in absolute amounts of generation based on differences in storage (and associated losses) and hydrogen production. The need for new generation capacity would be even higher without the energy efficiency and demand-side flexibility measures assumed in the ADE trajectory. Results from the LTS sensitivity cases result in a 16%–20% reduction in the

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[7] The White House, Washington, D.C., "The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050," 2021, https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf

[8] https://www.nrel.gov/analysis/reeds/

need for new installed capacity compared to the ADE cases due, in part, to the higher levels of energy efficiency assumed in LTS.

Wind and solar provide most (60%–80%) of the generation in the least-cost electricity mix in all the main scenarios. Nuclear capacity more than doubles in the Constrained scenario, reaching 27% of generation, while limited growth in the other three core scenarios results in a contribution of 9%–12%, largely from the existing fleet. The overall generation capacity grows to roughly three times the 2020 level by 2035, including a combined 2 TW of wind and solar. This would require growth rates in the range of 43–90 GW/year for solar and 70–145 GW/year for wind by the end of the decade, which would more than quadruple the current annual deployment levels for each technology in many scenarios. Across the four core scenarios, 5–8 GW of new hydropower is deployed by 2035 by adding capacity at unpowered dams and uprates at existing facilities, while geothermal capacity increases by about 3–5 GW by 2035.

Author's comment: I believe that geothermal and nuclear have the potential to grow more than projected above (the latter for all but "Constrained" scenarios). See the earlier post below regarding geothermal.

Hot Rocks Part 3 – Widespread Geothermal Power: *The title of this post indicated it's the third part in this series. The first part was posted a little over a year ago, and the second this spring. This post is about Enhanced Geothermal Systems (EGS).*

The principal elements of heat, water, and permeability—when found together and in sufficient amounts—can support cost-competitive rates of geothermal energy extraction. Independent of water and permeability, thermal energy (heat) exists everywhere on Earth and increases with depth. At the most basic level, EGS are manmade geothermal reservoirs. Where the subsurface is hot but contains little permeability and/or fluid, pumping water into wells could stimulate the formation of a geothermal reservoir capable of supporting commercial rates of energy extraction.

https://energycentral.com/c/gn/hot-rocks-part-3-%E2%80%93-widespread-geothermal-power

3. BIL and IRA Adjustments

The analysis presented in the above report was conducted prior to the passage of the Bipartisan Infrastructure Law (BIL) of 2021 and the Inflation Reduction Act (IRA) of 2022, which include incentives for and investments in clean energy technologies along with other energy system modernization provisions. Initial analyses estimate that the energy provisions of these new laws can help lower U.S. economy-wide greenhouse gas emissions by approximately 40% below 2005 levels by 2030.[9] *The impacts of these provisions are expected to be most pronounced for the power sector, with grid emissions initially estimated to decline to 68-78% below 2005 levels by 2030 and the share of generation from clean electricity sources estimated to rise to 60-81%. Investments in end-use sector decarbonization measures, including efficiency and electrification, are also supported by the IRA provisions. While the longer-term implications of these new*

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[9] Example analyses: https://www.energy.gov/articles/doe-projects-monumental-emissions-reduction-inflation-reduction-act ; https://rhg.com/research/climate-clean-energy-inflation-reduction-act/ ; https://energyinnovation.org/wp-content/uploads/2022/08/Modeling-the-Inflation-Reduction-Act-with-the-US-Energy-Policy-Simulator_August.pdf ; https://repeatproject.org/docs/REPEAT_IRA_Prelminary_Report_2022-08-04.pdf

laws are more uncertain, they are unlikely to drive 100% grid decarbonization and the levels of electrification envisioned by 2035 in the primary scenarios analyzed in this report.

More specifically, existing state and federal policies relevant to the power sector as of October 2021 are represented in the modeled scenarios; none of the scenarios presented in this report includes the energy provisions from the IRA or BIL, or other newer enacted federal or state policies or actions. As the addition of IRA and BIL provisions are not expected to enable the U.S. power system to reach 100% carbon-free electricity by 2035, their inclusion is not expected to significantly alter the 100% systems explored in this study. As such, the study's qualitative findings for the implications of achieving 100% are expected to still apply. ***However, given the potential significant impact of these new laws, the incremental differences between the Reference and 100% scenarios are expected to be lower than estimated here. Including IRA and BIL provisions would likely lower emissions in the Reference scenarios, resulting in a smaller gap between them and the 100% scenarios. As a result, the incremental electricity system costs of the 100% scenarios are expected to be lower with the inclusion of the IRA and BIL provisions.*** *Similarly, the climate and air quality benefits of the 100% scenarios (relative to the Reference scenarios) would also be reduced. These changes have not been quantified and it is important to note that the analysis in this report does not provide any estimates of the impacts of these new laws.*

4. Key Caveats

Although NREL's Regional Energy Deployment System (ReEDS) model is designed to simulate many aspects of the power grid, the large scope of the model necessitates simplifications. One limitation of ReEDS is that its scope is limited to the bulk power system and the model does not directly consider an economy-wide optimization.

The accelerated demand electrification (ADE) trajectory assumes electrification plays a very large role, consistent with other recent literature. But there is uncertainty about the degree of electrification, which this study does not seek to resolve. The Long-Term Strategy of the United States (LTS) scenario represents a demand pathway that does not use as much electrification and can be a proxy for any other non-electrification heavy scenario of decarbonization. But additional economy-wide analysis would be required to assess optimal portfolios across the entire economy. For example, the non-electricity costs and benefits associated with electrification and demand-side changes (e.g., costs of electric vehicles and avoided gasoline expenditures) are outside the study scope. Similarly, we do not include analysis of the evolving workforce needs for the transition described in this work, or how some clean energy pathways may be more compatible with the existing workforce. We also do not consider repurposing existing fossil infrastructure that could reduce system costs, beyond retrofits of existing generators to run on clean hydrogen. Other economy-wide impacts such as manufacturing requirements and trends, and international trade balance are not considered. Broader national and regional benefits, such as national security and many aspects of environmental justice, including distributional aspects of costs and benefits, are also not considered.

Within the power sector, this study does not consider the costs or impacts related to changes that may occur on the distribution system; for this study, a single, predetermined projection is used to specify rooftop PV capacity by region and year in all ADE scenarios explored. Additional research is needed to understand the opportunities *and operational impacts of widespread deployment of distributed generation in 100% scenarios. Electricity demand profiles and demand flexibility are also determined outside the model framework. There are many factors that could result in substantial changes in electricity demand patterns not considered here. These include the impacts of climate change and extreme weather, changing work patterns resulting from the COVID-19 pandemic, and other social and macroeconomic factors.*

Though ReEDS considers a large range of supply-side technologies, it does not represent all possible technologies that may be important in decarbonized energy systems. In particular, it represents a small subset of possible energy storage technologies and fuel production pathways, and it does not include all generation technologies that might be deployed by 2035. Therefore, results should be interpreted as representative but not determinate, as a variety of solutions may be cost-competitive. Though the model includes a variety of factors that can restrict development of individual technologies, including cost, siting restrictions, access to transmission, and contribution to resource adequacy, it does not consider limits to growth that could result from supply chain issues, financing, and local or regional factors. It also does not consider the interaction of resource limits that could result from competition from other sectors, such as the supply of critical materials. Likewise, fossil fuel prices are based on AEO projections and do not consider the additional impact of significant reduction in the demand for these fuels in the 100% clean electricity scenarios.

Like all national-level models, ReEDS does not model specific transmission rights-of-way with detailed AC power flow simulation; transmission is modeled as aggregated regional transfer capacities with controllable flow.32 Additional intraregional network reinforcement would also be needed given the high degree of electrification that is assumed here, but this is not modeled in ReEDS. Though ReEDS performs detailed calculations to estimate the ability of the various scenarios to provide resource adequacy and operating reserves, it does not perform a comprehensive assessment of all aspects of reliability and resilience. Future analysis using detailed unit-commitment, economic dispatch, probabilistic outages, and contingency analysis will be needed to validate findings from this work. Lastly, ReEDS applies a system-wide least-cost planning approach across all technologies that may not fully reflect investment decisions made in response to competitive wholesale markets or regional, state, and local planning decisions.

The ReEDS model is used to calculate a variety of costs and benefits represented in Step 3 (Figure 1, next page). *The primary cost metric considers impacts on the bulk system, but because it does not evaluate the distribution network, total costs seen by end consumers are not calculated. Analysis of overall energy burden and electricity rate impacts, including analysis of new rate structures that could potentially unlock demand flexibility, will be an important component of future work when assessing policy options. Benefits analysis includes direct energy-sector GHG emissions that result from fossil-fuel combustion and methane leakage but does not include other life cycle GHG emissions associated with electricity production or emissions from agriculture and other land use (except BECCs). The benefits analysis associated with improved air quality is also limited to premature mortality from only the electric sector and therefore does not assess the benefits from emissions reductions in other sectors—such as industry and transportation—or include other benefits such as reduced morbidity, changes to hospitalizations, or ecosystem damage. Previous work has found that accounting for* *mortality results in the largest component of monetized benefits*[10] *and that PM2.5 exposure is the driver of 90%–95% of all mortalities related to air pollution.*[11] *So, we likely capture most of the monetized benefits related to air quality improvements related to power sector decarbonization with this method, though other additional benefits not estimated here may have more salience in particular communities. In addition, while some aspects of land use changes are modeled, several other environmental impacts, such as potentially reduced water use or localized ecosystem changes, are not.*

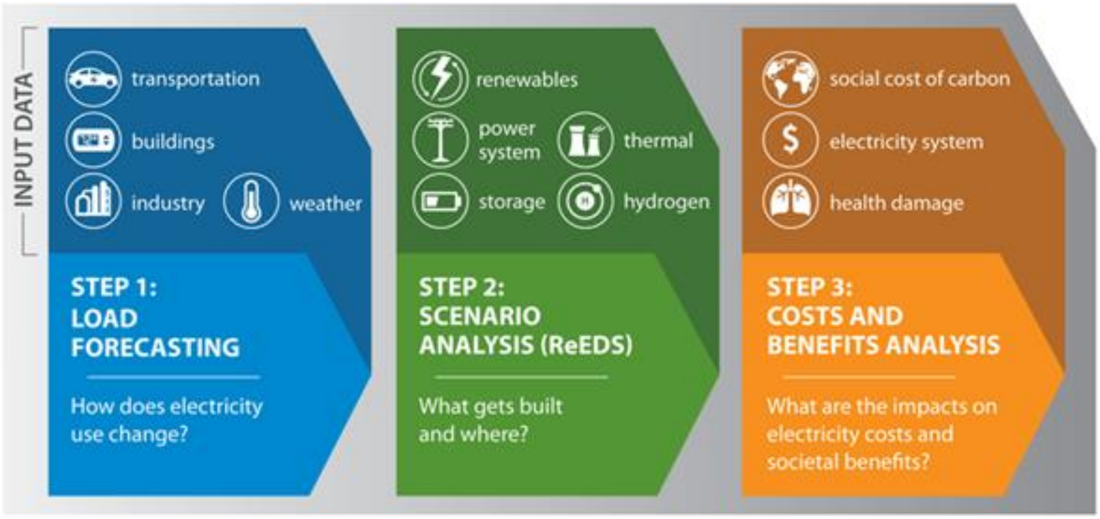

Figure 1. The three-step process conducted for this study.

ReEDS refers to the Regional Energy Deployment System model.

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[10] "The Benefits and Costs of the Clean Air Act," 1990 to 2010. U.S. Environmental Protection Agency. EPA-410-R-99-001. https://www.epa.gov/sites/default/files/2017-09/documents/ee-0295a_1-3.pdf
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[11] Tessum, Christopher W., Jason D. Hill, and Julian D. Marshall. "InMAP: A Model for Air Pollution Interventions," 2017, PLOS ONE 12 (4): e0176131. https://doi.org/10.1371/journal.pone.0176131
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