CLEAN ENERGY FUTURES

# An 80x30 Clean Electricity Standard: Carbon, Costs, and Health Benefits

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## Key Take-Aways

An analysis of an illustrative 80x30 clean electricity standard (CES) by the Clean Energy Futures project shows that achieving the Biden Administration's clean electricity goal through a CES would have modest costs and large benefits. Furthermore, if a CES were passed through budget reconciliation, many of the costs of the clean energy transition would shift to the federal government and electricity rates would likely fall. Our analysis is the first to map the air quality and related health benefits for an 80x30 CES. The results show that they are widely distributed across all states in the coterminous U.S. and that the illustrative 80x30 CES has the largest total benefits, climate-related net benefits, and health benefits of eight policies examined. The present value of the estimated climate benefits through 2050 ($637 billion) outweigh the estimated costs ($342 billion). This 80x30 CES would also prevent an estimated 317,500 premature deaths between now and 2050 and generate estimated present value health benefits of $1.13 trillion due to cleaner air, bringing the estimated present value net benefits to $1.43 trillion for 2020 to 2050.

## I. Policy Context: A Clean Electricity Standard for Budget Reconciliation

The Biden Administration has called for a 100 percent carbon-free power sector by 2035 with an interim target of 80 percent clean electricity by 2030. This goal coupled with accelerated electrification of the transportation and building sectors would position the U.S. to meet its 2030 greenhouse gas emission reduction target under the Paris agreement.

One policy pathway to achieving the electric sector goal would be for Congress to adopt a package of appropriate financial incentives through the budget reconciliation process as part of an initiative to rebuild America's infrastructure. The reconciliation process is restricted to legislation that has direct impacts on the federal budget. However, by using spending or taxing authority, a bill could be designed to provide a powerful package of incentives for investment in clean energy, including direct procurement, that would ensure that 80 percent of electricity by 2030 (80x30) is generated with carbon-free resources. Reaching this target will require unprecedented levels of investment in new clean generation from wind and solar, as well as incentivizing utilities to preserve generation from existing clean energy resources including hydropower and nuclear energy.[1]

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[1] Eighty percent clean energy corresponds roughly to 80 percent reduction in carbon dioxide emissions in the electricity sector relative to 2005 levels.

One widely studied policy to achieve 80x30 is a flexible clean energy standard (CES). A CES would require utilities to achieve annual clean-energy milestones, which would create a financial incentive for clean energy while indirectly lowering the value of other types of generation. Variations of this approach have been proposed in Congress for a decade, but in forms that are unsuitable for the reconciliation process. Consequently, legislators are considering ways to re-envision a CES with the federal government playing a central and coordinating role using budgetary instruments (spending and taxation). We refer to this as a "reconciliation CES." A reconciliation CES would not be a standard but rather a clean energy program consisting of economic incentives that are designed to achieve specific clean energy targets. However, we have retained the use of the term CES here to reflect the emphasis on specific clean energy outcomes (See Box 1 for a further description).

**Box 1: What would a Reconciliation CES Do?**

- Use federal financial investments, incentives, and/or penalties to achieve a carbon-free electricity system by a specified date.
- Lower the energy cost burden for ratepayers by rewarding utilities with federal payments for achieving clean energy goals.
- Ensure that all regions of the US reduce emissions and gain employment opportunities and air quality and health benefits.
- Be budget neutral after ten years.

Under a reconciliation CES, federal investments would pay for a large portion of the incremental cost of adding new clean generation through the budget process, while redirecting private sector investment from fossil to clean energy resources and leveraging substantial additional private sector investment to keep existing clean energy resources in service. Federal investment and incentives would minimize the energy cost burden of ratepayers by keeping wholesale electricity prices and consumer costs at or below today's levels. The investments would also be structured to ensure that all regions of the country receive economic, air quality, and health benefits with progress towards the clean energy goals.

In this policy brief the Clean Energy Futures (CEF) team describes the transition in generation sources, air quality and health co-benefits, and costs for an illustrative CES design that reaches the 80x30 target. We also briefly discuss insights from other electricity sector carbon policies such as additional CES options, and cap and trade policies, and rulemaking under Section 111 of the Clean Air Act.

The analyses in this brief were conducted as part of the Clean Energy Futures project, an independent collaboration with researchers from Syracuse University; Harvard T.H. Chan Center for Climate, Health, and the Global Environment; Georgia Institute of Technology; and Resources for the Future.

## II. Benefits of 80 Percent Carbon-Free Electricity by 2030

### Illustrative 80x30 Clean Electricity Standard

As part of the Clean Energy Futures project, we analyzed eight power-sector carbon pollution policy options that achieve various emissions reduction targets, including an illustrative CES that achieves the goal of 80 percent clean electricity by 2030.[2] The energy, economic, environmental and health outcomes for the 80x30 CES scenario offer important information on the costs and benefits of such a policy. The policy specifications for this illustrative "80x30 CES" are outlined below along with a discussion of how the design of a reconciliation CES may vary from this scenario. See Appendix 1 for supplemental assumptions and modeling methods.

### Illustrative 80x30 CES Scenario Specifications (CES40-B)

- The modeled policy scenario specifies a target of 100 percent total (net) clean electricity generation by 2040.
- Use of banked clean energy credits earned through early compliance is allowed through 2050.
- The policy sets an *initial* carbon intensity benchmark of 0.82 metric tons/MWh.
- This benchmark allows partial crediting for natural gas at a level proportional to a plant's emission rate until the year 2040.
- With these features, the policy achieves 80 percent clean electricity by the year 2030.
- The policy scenario is compared to a reference case with existing federal and state policies as of December 2020 and assumes that federal renewable production tax credits expired after 2019.

*The outcomes of a CES developed for the budget reconciliation process would be similar to our CES policy but instead of achieving those changes via a regulatory standard, the federal government would provide incentive payments to utilities for clean energy generation.*

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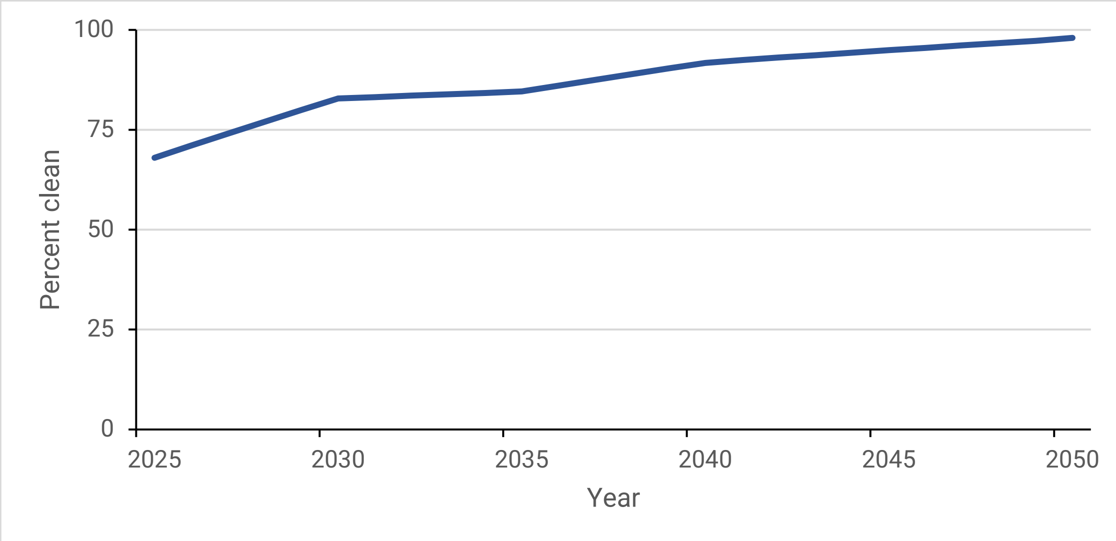
[2] An 80% reduction in carbon dioxide emissions from the power sector below 2005 levels is 67% below 2020 due to reductions between 2005 and 2020. Carbon dioxide emissions in the CES40-B scenario featured here achieves a 63% reduction from 2020 levels in 2030.

**Figure 1. Percent Clean Electricity Generation Realized under the Illustrative 80x30 CES**

The percent of total electricity generation that is clean under the Clean Energy Future's illustrative 80x30 clean electricity standard increases from current levels to 83 percent in 2030.




### Box 2. What is Credit Banking?

- Under a CES with banking, utilities surrender clean energy credits each year commensurate with the annual CES target.
- Utilities can earn extra clean energy credits by over-complying with clean energy targets in the early years of a policy.
- These extra credits can be saved ("banked") for use in a subsequent year when a policy is typically more stringent.
- The opportunity for banking tends to accelerate emissions reductions and promotes early substitution away from coal, delivering larger air quality and health benefits sooner. However, it extends the use of fossil fuel longer than a non-banking alternative.

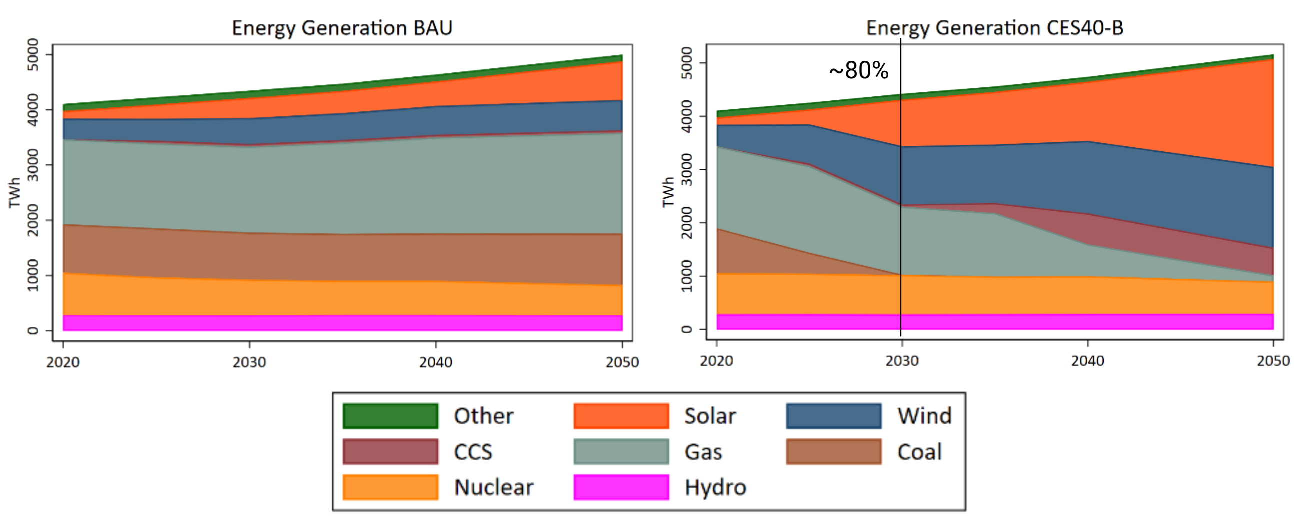
## Electricity Generation Results

Using output from the Integrated Planning Model (IPM), we projected changes in national scale electricity generation over time by major source category. Total generation is held constant between the business-as-usual (BAU) no-policy reference case and the 80x30 CES as shown in Figure 2.

- Compared to a no-policy reference case, the illustrative 80x30 CES results in large increases in solar and wind generation by 2030 through 2050.
- A rapid reduction of coal generation is projected, reaching nearly zero by 2030.
- Natural gas generation is lower than in the no-policy case but persists as a generation source through 2050, with an increasing fraction using carbon capture and storage (CCS) technology.
- Generation from nuclear, hydropower, and other sources such as biomass remain low and similar to the no-policy case at a national scale.
- Renewable energy builds are projected to occur in each of the lower 48 states (Alaska and Hawaii are not modeled), resulting in economic development, air quality improvements, and health and ecosystem benefits.

### Figure 2. Change in Electricity Generation Sources Changes from 2020 to 2050

The BAU case represents a "business as usual" scenario with no carbon policy. The CES40-B case represents an illustrative 80x30 CES. The "Other" category includes hydropower, biomass, and other minor sources. The CCS category represents carbon capture and sequestration, which is nearly entirely associated with natural gas.



## Electricity Sector Emissions

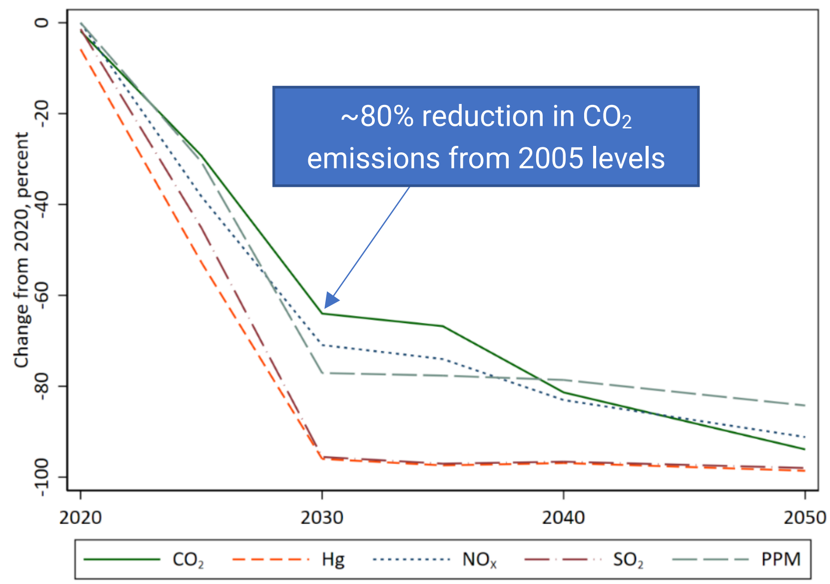
As fossil sources of electricity generation decrease over time, so do emissions of carbon dioxide ($CO_2$) and other pollutants emitted from fossil-fuel-fired facilities including sulfur dioxide ($SO_2$), nitrogen oxides ($NO_x$), directly emitted particulate matter (primary PM), and mercury (Hg). Sulfur dioxide, nitrogen oxides, and primary PM degrade air quality through the formation of fine particulate matter ($PM_{2.5}$). Nitrogen oxides also exacerbate ground-level ozone ($O_3$). Mercury is a highly toxic hazardous air pollutant. While important progress has been made, the electricity sector remains one of the largest sources of directly emitted particulate matter, nitrogen oxides, sulfur dioxide, and mercury emissions in the U.S.

The estimated changes in national emissions over time are shown in Figure 3 for the illustrative 80x30 CES compared to a no-policy case. The results show:

- When the electricity sector reaches the 80 percent clean target, national carbon dioxide emissions are approximately 80 percent below 2005 levels. While the policy is designed to reach 100 percent clean in 2040, clean energy credit banking brings renewable builds and emissions reductions forward in time causing the policy to achieve the 80 percent by 2030 target.
- National electricity sector emissions of nitrogen oxides, sulfur dioxide, and mercury decline by 71 percent, 96 percent, and 96 percent respectively, in 2030 compared to the no-policy case.
- The trends in national sulfur dioxide and mercury emissions closely track coal generation.
- The trends in national nitrogen oxide emissions closely track with total fossil fuel generation. Emissions decrease rapidly until 2030 under the illustrative 80x30 CES but remain higher than under a no-banking CES scenario in later years as banked allowances are expended in future years.

### Figure 3. Percent Change in Electricity Sector Emissions from 2020 Levels for an Illustrative 80x30 CES

Change in electricity sector emissions of carbon dioxide ($CO_2$, solid dark green line), mercury (Hg, dashed orange line), nitrogen oxides ($NO_x$, dotted blue line), sulfur dioxide ($SO_2$, dashed red line), and directly emitted, or primary, particulate matter (PPM, dashed light green line).




## Air Quality & Health Benefits

Emissions from the electricity sector not only contribute to climate change but also impact air quality (warming also exacerbates air pollution, acting as a feedback). Large areas of the U.S. currently exceed the National Ambient Air Quality Standards for $PM_{2.5}$ and $O_3$ and the latest estimates suggest that approximately 60,000[3] people die prematurely in the U.S. each year from exposure to these pollutants. Mercury is an air toxic that bioaccumulates and is biomagnified through food webs leading to elevated human exposure through fish consumption. Twenty-four states have statewide freshwater advisories for mercury and 15 states have statewide coastal advisories. Elevated air pollution also affects water quality and the productivity of trees and crops.

Concentrations of fine particulate matter and ozone in the U.S. in 2020 are shown in Figure 4 and projected changes by 2030 for an illustrative 80x30 CES are given in Figure 5. Estimated county-scale changes in premature deaths avoided from air quality improvements compared to a no-policy alternative in 2030 are provided in Figure 6. Air

[3] Global Burden of Disease, https://vizhub.healthdata.org/gbd-compare/ (2019 data).

quality results are based on air quality modeling conducted using the Community Multi-scale Air Quality model (CMAQ version 5.0.2). Premature mortality estimates were produced using the environmental Benefits Mapping and Analysis Tool (BenMAP) created by the U.S. Environmental Protection Agency (see Appendix 1 for additional model details).

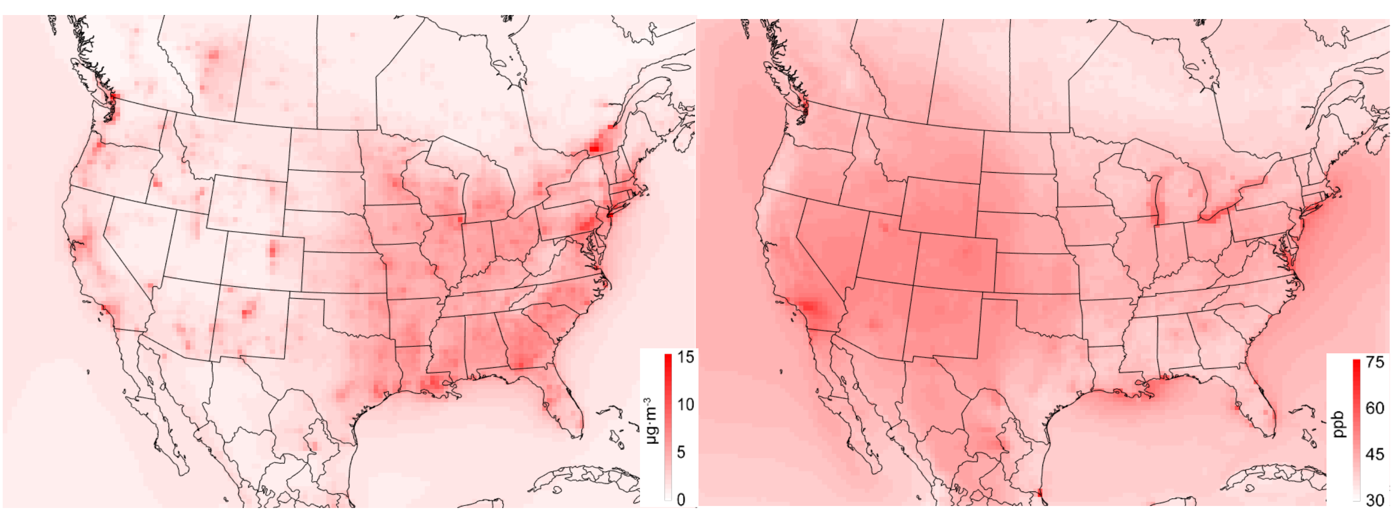
## Air Quality Benefits

- Air quality benefits associated with reductions in fine particulate matter ($PM_{2.5}$) and ozone ($O_3$) under the illustrative 80x30 CES are large and occur in all states.
- The estimated change in population-weighted exposure to $PM_{2.5}$ in the coterminous U.S is -0.19 µg/m$^3$ in 2030 and -0.23 µg/m$^3$ in 2050 (annual average of 24-hour averages).
- The estimated change in population weighted exposure to $O_3$ in the coterminous U.S is -0.42 ppb in 2030 and -0.67 ppb in 2050 (seasonal average of maximum daily 8-hour averages).
- Air quality improvements are projected to occur for all racial and ethnic groups. Nationally, non-Hispanic Black people are estimated to experience the largest reductions in average population-weighted exposure in absolute terms (-0.50 ppb for ozone and -0.23 µg/m$^3$ for fine particulate matter in 2030).

### Figure 4. Air Quality in 2020: Fine Particulate Matter and Ozone

Fine particulate matter ($PM_{2.5}$) concentrations at 36x36 kilometers for the annual average of 24-hour averages in micro-grams per cubic meter (µg/m$^3$) (A). Ozone ($O_3$) concentrations at the same resolution for the seasonal average of maximum 8-hour averages in parts per billion (ppb) (B).

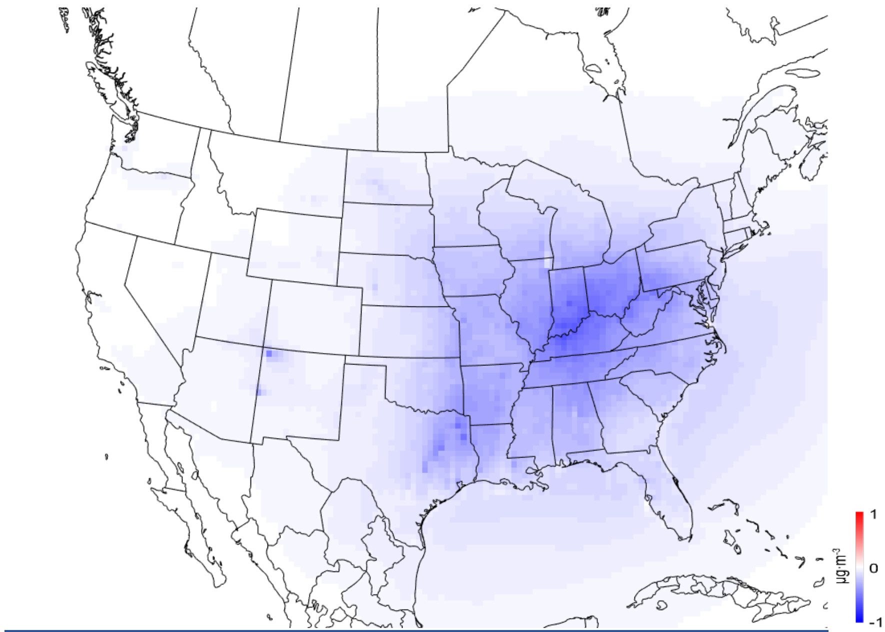
A. B.



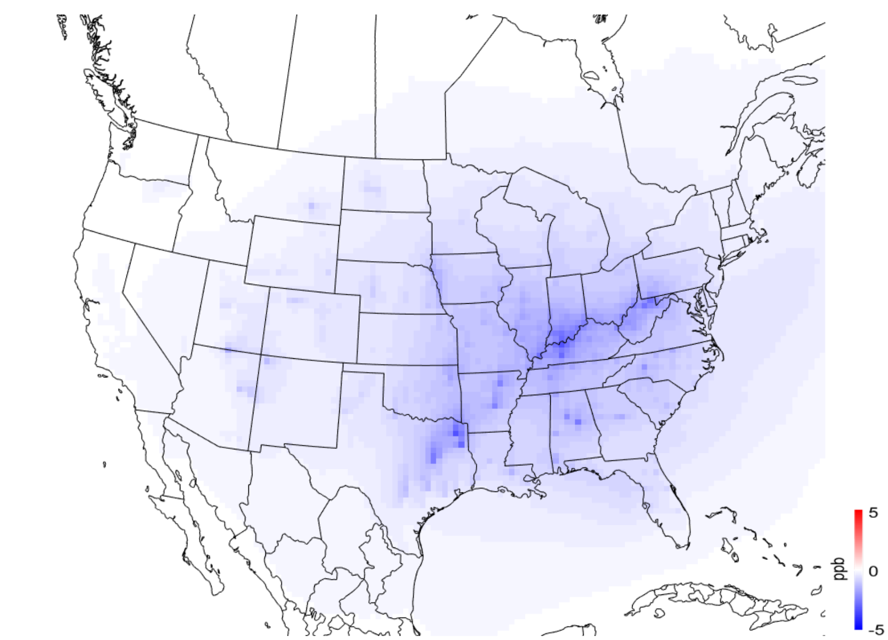
### Figure 5. Estimated Changes in Fine Particulate Matter and Ozone in 2030 for an 80x30 CES

Changes in fine particulate matter ($PM_{2.5}$) concentrations compared to BAU at 36x36 kilometers for the annual average of 24-hour averages in micro-grams per cubic meter (µg/m$^3$) (A). Changes in ozone ($O_3$) concentrations compared to BAU for the seasonal average of maximum 8-h averages in parts per billion (ppb) (B).

A.




B.



## Health Benefits

Extensive research has shown that as air quality improves the incidence of air quality-related health impacts including asthma attacks and severity, heart attacks, respiratory illness, pre-term births, low birth weight, and premature deaths declines. We estimated premature deaths avoided at the county level in the coterminous U.S. from projected reductions in ozone and fine particulate matter concentrations that were modeled at 36x36 kilometers. We then monetize the health benefits associated with these projected air quality improvements. The monetized health benefits are conservative as they do not account for potential benefits from reduced nitrogen dioxide exposures ($NO_2$) and decreases in climate impacts, such as heat-related illnesses and deaths.

- For the illustrative 80x30 CES, total health benefits include an estimated 9,200 premature deaths avoided in 2030 in the coterminous U.S. growing to 17,000 in the year 2050 from reduced air pollution exposure.
- For the period 2020 to 2030, an estimated 50,000 cumulative premature deaths are avoided from reduced exposure to fine particulate matter and ozone. For 2020 to 2050, this increases to 317,500 premature deaths avoided.
- Approximately 2 million asthma attacks would be prevented in the year 2030, growing to 12 million annually in 2050.
- The present value of the monetized health benefits from the premature deaths and illnesses avoided is approximately $1.13 trillion (2019 U.S. dollars) for 2020 to 2050, using a 5 percent discount rate.
- Tables 1 and 2 show the top ten states and counties with the largest number of premature deaths avoided in 2030 (see Appendix 3 for estimates for results for all states in 2030 and 2050).

### Table 1: Top Ten States for Premature Deaths Avoided in the Year 2030

| State | Premature Deaths Avoided in 2030 |
|---|---|
| Ohio | 771 |
| Texas | 737 |
| Pennsylvania | 582 |
| Illinois | 529 |
| Florida | 463 |
| North Carolina | 453 |
| Indiana | 441 |
| Tennessee | 424 |
| Michigan | 396 |
| Georgia | 377 |

**Figure 6. Estimated Premature Deaths Avoided by County from Air Quality Improvements in 2030 (A) and 2050 (B) Under an 80x30 CES**

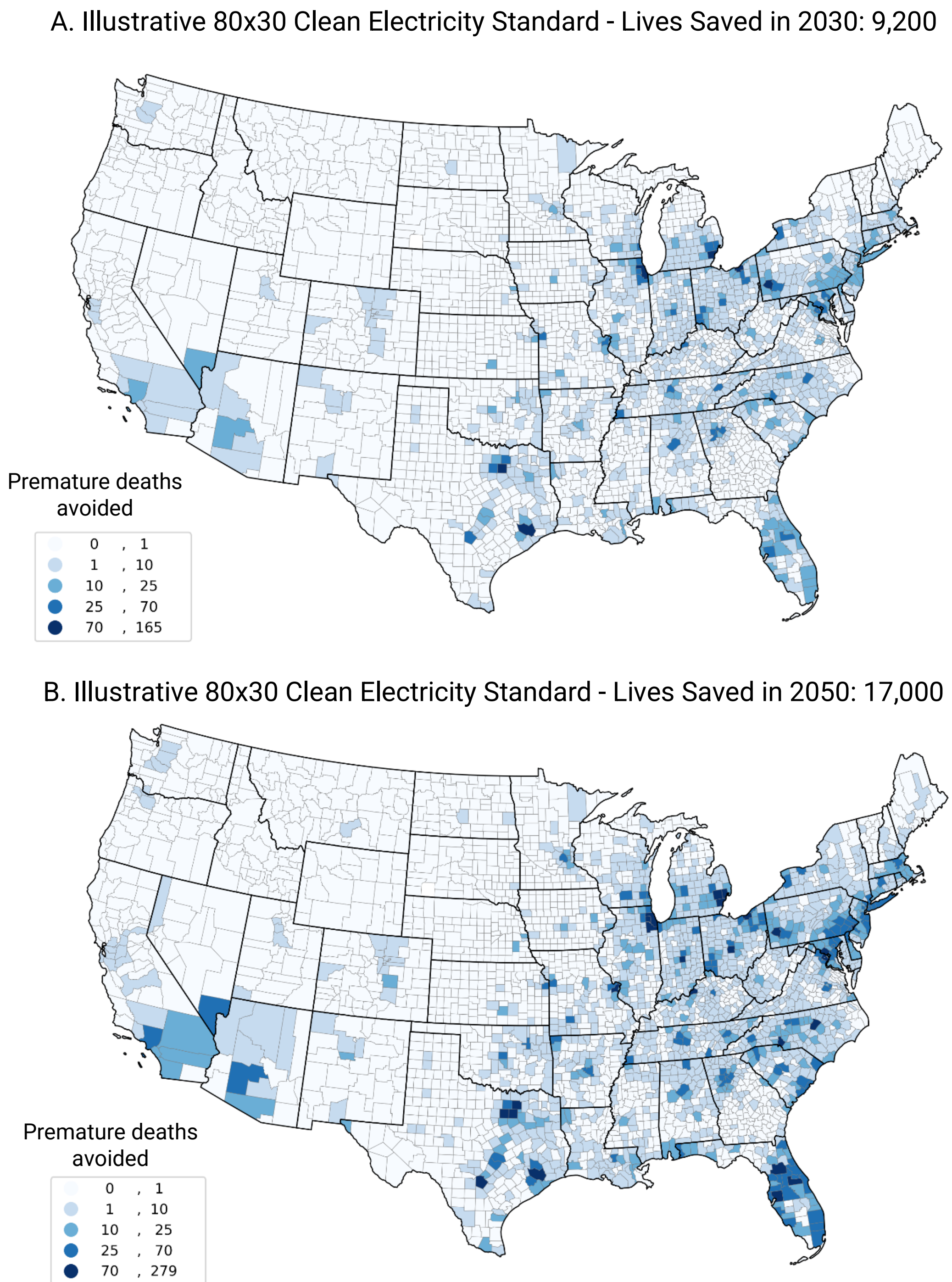


**Table 2: Top Ten Counties for Premature Deaths Avoided in the Year 2030**

| State | County | County Seat | Premature Deaths Avoided in 2030 |
|---|---|---|---|
| Illinois | Cook | Chicago | 166 |
| Texas | Harris | Houston | 105 |
| Pennsylvania | Allegheny | Pittsburgh | 87 |
| Texas | Dallas | Dallas | 85 |
| Ohio | Cuyahoga | Cleveland | 74 |
| Michigan | Wayne | Detroit | 72 |
| Kentucky | Jefferson | Louisville | 67 |
| Indiana | Marion | Indianapolis | 63 |
| Ohio | Franklin | Columbus | 63 |
| Texas | Tarrant | Fort Worth | 58 |

## Costs and Monetized Benefits

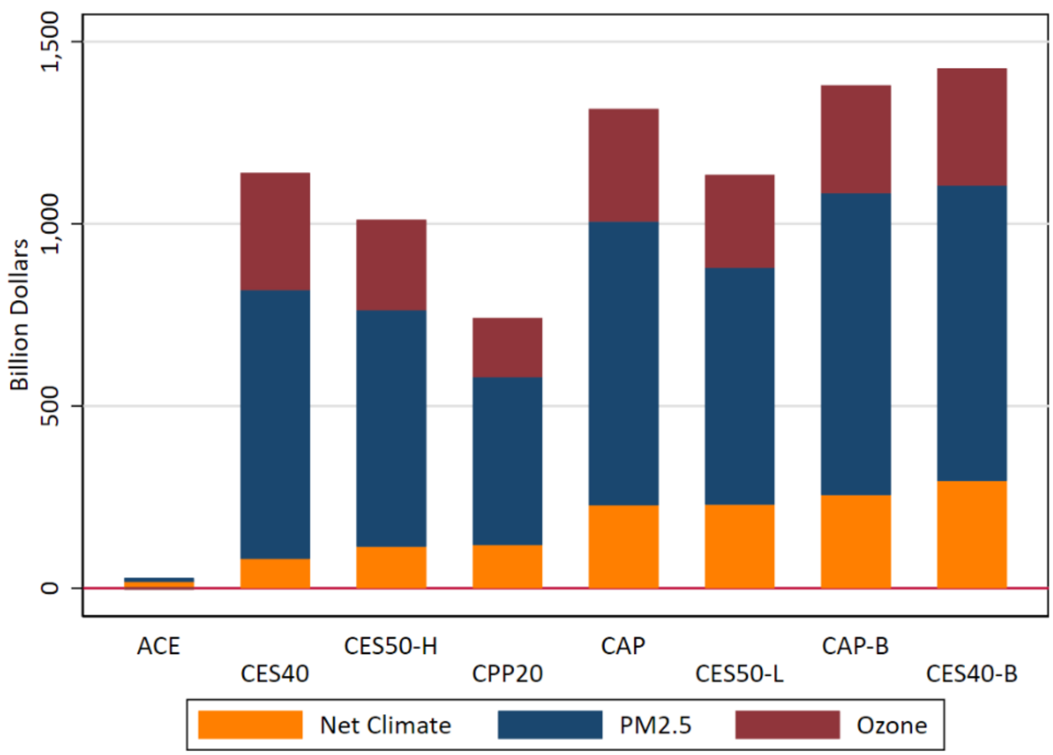
We analyzed the change in annual system costs and estimated the present value costs and benefits of eight policy options for reducing carbon emissions from the electricity sector, including our illustrative 80x30 CES (CES40-B). System costs include the cost of fuel, building new capital projects and retrofitting existing facilities, and operating energy facilities. Over the full study period (2020-2050), savings in fuel costs offset most of the cost of new capital, so net present value system costs only increase by 13 percent compared to no policy, even under conservative assumptions regarding the costs of renewables and battery storage. Given the use of banking, the policy is estimated to have higher annual system costs in 2025 than a similar CES without banking, as utilities do more to reduce emissions in the near term in order to bank permits for the future. However, access to banked allowances in 2040 to 2050 decreases the costs in those future years.

We estimated the present value costs, air quality-related benefits, climate benefits, and net benefits for the illustrative 80x30 CES and other policies over the period 2020 to 2050. The climate benefits are calculated using a constant real social cost of carbon of $50 in 2019 dollars. The health benefits from decreased ozone and fine particulate matter concentrations are based on the mortality benefits from BenMAP and a value of a statistical life of $9.3 million in 2019 dollars. Future benefits and costs are discounted at a rate of 5 percent. Nationally, the estimated present value of health benefits is large

($1.13 trillion) and alone, without consideration of climate-related benefits, far outweigh the net system costs ($342 billion). In addition, the climate benefits alone ($637 billion) are larger than the estimated costs of the policy (Figure 7). The illustrative 80x30 CES has the largest estimated total benefits, climate-related net benefits, and health benefits of the policies analyzed in the Clean Energy Futures project (eight are shown in Figure 7).

### Figure 7. Monetized Present Value Net Benefits through 2050 for 10 Electricity Sector Carbon Policies

The orange bar represents the monetized climate benefits of the policy minus the policy's estimated cost (net climate benefits) for 2020-2050. The bars are ordered by net benefits. The blue bar represents the monetized health benefits from estimated reductions in fine particulate matter. The red bar reflects the monetized health benefits from decreased ozone. The illustrative 80x30 policy (CES40-B) has the largest health benefits, total net benefits, and the net benefits from the climate benefits of $CO_2$ emissions reductions.




ACE = Affordable Clean Energy rule

CES40 = 100% clean energy by 2040 no banking

CPP20 = updated Clean Power Plan

CES50-H = 100% clean energy by 2050, partial crediting

CES50-L = 100% clean energy by 2050

CAP = 100% net zero carbon emissions in 2040, cap and trade

CAP-B = 100% net zero carbon emissions in 2040, cap and trade with banking

CES40-B = 100% clean energy by 2040 reaching `80% by 2030 with bankin

## III. Policy Insights from the Clean Energy Futures Project

In addition to the illustrative 80x30 CES discussed above, the Clean Energy Futures Project analyzed a set of other policy scenarios that represent different approaches to reducing carbon pollution from the electricity sector. The full set of scenarios are described at cleanenergyfutures.syr.edu. Together the full set of policy scenarios offer several key insights.

1. Emissions of all pollutants under the 80x30 CES are dramatically lower than a no-policy reference case and prior policies proposed under Section 111 of the Clean Air Act (e.g., the Clean Power Plan and the Affordable Clean Energy rule), leading to substantial reductions in carbon pollution and air quality benefits in all regions of the coterminous U.S.
2. For a given carbon reduction target, banking affects both the timing and cost of compliance. With banking, emissions reductions and health benefits occur sooner, cumulative emissions reductions through 2050 are larger, and costs are lower. However, fossil generation persists longer, and emissions of carbon dioxide and other pollutants are higher in 2040-2050 than under a similar policy without banking.
3. Large early emissions reductions, and associated climate and health outcomes, that are realized in the banking case can also be achieved without banking by establishing an equivalent clean energy requirement in 2030.
4. Partial crediting for natural gas has only a modest impact on the energy generation mix if the long-term emissions target is zero. The long lifespan of investments in the electric sector results in compliance strategies that are strongly driven by the long-term requirements.
5. Treatment of small generators (<25 megawatts) strongly affects nitrogen oxide emissions and public health outcomes. If these plants are not included in the policy, and are otherwise unconstrained, nitrogen oxide emissions could increase in some areas.

## IV. Conclusions

The analysis of an illustrative 80x30 CES shows that the costs of achieving the Biden Administration's clean electricity goal through a CES are modest. If the CES were adopted through budget reconciliation, the costs of this transition to clean energy would shift to the government and electricity rates would likely fall. The estimated net benefits of our illustrative 80x30 CES are large, widespread, and far outweigh the costs. Even with conservative assumptions, the estimated present value climate benefits of $637 billion outweigh the estimated policy costs of $342 billion (2019 U.S. dollars). The additional health benefits would be immediate, widespread, and substantial. We estimate 9,200 lives saved in 2030 alone and an estimated 317,500 lives saved from 2020 to 2050 with $1.13 trillion in cumulative health benefits, leading to net benefits of $1.43 trillion. Air quality-related health benefits are broadly distributed across all states in the coterminous U.S.

## About the Clean Energy Futures Project

The Clean Energy Futures project is a multi-institutional research initiative with experts from Syracuse University; Center for Climate, Health, and the Global Environment at the Harvard T.H. Chan School of Public Health; Resources for the Futures; and Georgia Institute of Technology. The CEF project explores tradeoffs among electricity sector policies to mitigate carbon emissions that are relevant to current national discussions.

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## Acknowledgements

IPM simulations were conducted by ICF. The Clean Energy Futures project is solely responsible for the scenario specifications and all assumptions used in the IPM analysis.

The CEF team thanks Jonathan Buonocore of Harvard Chan C-CHANGE for assistance with the BenMAP software and for advising on the health functions used in the analysis.

Major funding for this project was provided by a grant from The JPB Foundation to Syracuse University.

## Appendix 1: Policy case descriptions, models, and methods

**No-policy reference case:** The no-policy reference case is based on 2019 forecasts of electricity demand (pre-COVID) and natural gas prices and 2018 forecasts of technology costs. It incorporates applicable state, regional, and federal standards for air quality (e.g., Clean Air Interstate Rule), GHG emissions (e.g., Regional Greenhouse Gas Initiative and California AB32) and the federal 45Q tax credit for carbon capture and sequestration. No federal carbon standard is included in the reference case.

**Affordable Clean Energy Rule:** The ACE rule is a source-based standard that is limited to heat rate improvements at existing coal plants. It does not set an emissions reduction requirement. The ACE rule is modeled assuming one heat rate improvement option available for all coal plants, achieving a 4.5% average fleetwide heat rate improvement. CCS is allowed as a compliance option.

**Updated Clean Power Plan:** The CPP takes a systems approach and allows compliance through renewables adoption, fuel-switching, heat rate improvements, and trading. National emission targets under the updated CPP are set for existing coal, oil/gas, and combined cycle units to achieve a 65 percent reduction from 2005 levels by 2035. Existing units in California are excluded due to the state's more stringent limits.

**Net-Zero Cap and Trade:** This national cap and trade case sets a cap on total emissions equivalent to a 78% decline from 2020 levels in 2035, with a net-zero emissions requirement by 2050. The cap covers existing and new fossil and biomass units. Options with and without banking are included. The CAP run without banking allows utilities to purchase carbon offsets in 2040 and 2050. The offsets cause the model to reduce emissions less than the banking case, but also to have lower system costs of compliance (since emissions are reduced less).

**Clean Energy Standard (CES):** A Clean Energy Standard is a technology-neutral portfolio standard that sets requirements for the percentage of total electricity sales or generation that must come from non- or low-emitting sources. A CES has two defining features: (1) a carbon intensity benchmark used for defining what sources are "clean," which also allows for partial crediting for low-emitting sources (e.g., 0.46 or 0.82 metric tons/MWh), and (2) a percent-clean target with a timeline and ramp-up rate (e.g., 100% clean by 2050 with linear reductions from current levels). The CES cases examined here include cases with and without banking. See Table 1 for the CES policy options presented in this report.

## Models & Methods

An engineering-economic dynamic linear programming model, the Integrated Planning Model (IPM), is used to forecast least-cost capacity changes and retrofit investments in pollution controls, operations of the electricity system, and fuel markets with endogenous price formation (https://icftechnology.com/). IPM is used to simulate illustrative policy and reference scenarios in the electricity power sector in over 100 linked geographic regions in the contiguous US and in Canada, which contain representations of the actual generating facilities in those areas. EPA uses IPM to simulate reference scenarios that include only existing regulations and to perform regulatory impact analyses of potential new policies. For each scenario, IPM projects various outcomes at model plants including generation, carbon dioxide and criteria air pollutant emissions, including $NO_x$, $SO_2$ and mercury, as well as investments in existing and new generating facilities.

To estimate air quality patterns and changes the Community Multiscale Air Quality (CMAQ) model was used. CMAQ is a dynamic air quality model that combines current knowledge in atmospheric science and air quality modeling to predict the concentration and deposition of airborne gases and particles (USEPA 2014). We use the CMAQ version 5.0.2, and the adopted physical and chemical schemes previously used in a study of air quality across the contiguous U.S. (Appel et al. 2011). Our modeling domain covers the entire contiguous U.S. and portions of southern Canada and northern Mexico at a horizontal resolution of 36 km x 36 km with 13 vertical layers extending to ~16 km above ground. The US Environmental Protection Agency 2011 National Emission Inventory platform (USEPA 2011b) is used as the baseline emission inventory. The future trends in pollutants emissions from the electricity power sector are projected by IPM and used as an input of CMAQ modeling. Projections of future meteorology and emissions from other sectors are held constant at 2010 base year levels specified in a previous study (Shen et al. 2019). CMAQ produces air quality projections at a 36km$^2$ raster scale.

The results of the CMAQ runs were input to BenMAP CE v.1.5 (US EPA 2015), a Geographic Information System (GIS) model designed to calculate health impacts of air pollution, air quality management scenarios, and other applications. We used BenMAP to estimate the number of premature deaths and non-fatal illnesses avoided based on the difference between the policy scenario and BAU. For mortality estimates due to changes in ozone we used a concentration response function for adults 25 years and older from Turner et al (2016) based on the seasonal average of the 8-hour daily maximums. For mortality estimates due to changes in fine particulate matter we used a concentration response function for adults 25 years and older from Vodonos et al. (2018) based on the annual average of 24-hour average concentrations. Mortality impacts were valued using a VSL 0f $9.3 million adjusted for a cessation lag of approximately three years.

For morbidity, we include the following outcomes for exposure to fine particulate matter: asthma exacerbations (Orellano et al. 2017), acute myocardial infraction (Mustafic et al. 2012), non-fatal cardiovascular hospital admissions (Levy et al. 2012), and non-fatal respiratory hospital admissions (Levy et al. 2012). For ozone-related morbidity we include only non-fatal respiratory hospital admissions (Ji et al. 2011). The population projections for 2030 and 2050 were from Woods and Poole Economic, Inc, as provided by  BenMAP CE v 1.5 (US EPA 2021). For valuing changes in morbidity, we used BenMAP's defaults. The health benefits in this analysis are conservative and do not include possible benefits from reducing other health effects, such as autism (Talbott et al. 2015); benefits associated with decreased emissions of hazardous air pollutants (e.g., mercury)(EPA 2011a); pediatric benefits (Curtis et al. 2006); or the direct health benefits of climate change mitigation  (Garcia-Menendez et al. 2015; St. Louis et al. 2008).

Finally, the benefits of reductions in $CO_2$ emissions are calculated using a constant real social cost of carbon of $50 in 2019 dollars with present value benefits estimated using a 5 percent discount rate. IPM runs provide results for six simulation years spread over the interval from 2020 to 2050. Emissions and costs are estimated for other years by interpolating between adjacent IPM simulation years. We then compute the present value of the electric sector's costs over the period 2020-2050 using a real interest rate of 5%. Improvements in health resulting from emissions reductions are monetized and discounted using a real interest rate of 5%.

Note that because IPM focuses on the supply side of the electric sector and holds electricity demand constant, cost estimates only include the sector's direct costs and do not include any costs to downstream electricity users. In addition, IPM does not capture the benefits that would arise from using the revenue from carbon taxes or sales of tradable permits to lower distortionary taxes elsewhere in the economy. The first issue will tend to raise the full economic costs of a given policy relative to the costs reported by IPM, while the second issue will tend to lower them. To avoid confusion, therefore, IPM's cost estimate is referred to as the "system cost" of the policy rather than the economic cost.

Model assumptions for each of the policy runs are summarized in Appendix 2.

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# Appendix 2: Assumptions for reference and policy cases

## Reference Case Assumptions

| Variable | Reference Case Proposed Sources/Approach |
|---|---|
| Electric Demand | EIA Annual Energy Outlook (AEO) 2019 Reference Case |
| Peak Demand | AEO 2019 Reference |
| Capacity Build Costs - Conventional | EPA Reference Case version 6 (v.6)/AEO 2019 Reference |
| Capacity Build Costs - Renewable | NREL 2018 ATB. ITC and PTC assumed per 2015 omnibus |
| Coal Supply/Prices | EPA Reference Case version 5.15 (v.5.15) |
| Gas Supply/Prices | Fuel Supply Curves based on composite of AEO 2019 cases |
| Firm capacity additions and retrofits | Updated to include latest market information CEF input. |
| Nuclear Retirements | Any nuclear reactors that reach age 40 can receive a subsequent license renewal and operate for 20 more years. One additional 20-year renewal is allowed at age 60 (hence maximum total nuclear lifetime is 80 years). |
| Nuclear Retirement Limits | Prevent Economic Nuclear Retirements through 2020 |
| Pollution Control Retrofit Costs | EPA v.5.15 |
| CCS Retrofit cost and performance - Coal | EPA v.6 / AEO 2019 Reference |
| CCS Retrofit cost and performance - Gas | EPA v.6 / AEO 2019 Reference |
| CCS Transportation and Storage Curves | EPA v.6 (Nov 2018 Reference Case) |
| CCS Incentives | Includes 45Q representation |
| Biomass co-firing at coal facilities | EPA v.5.15 |

| | |
|---|---|
| Gas co-firing at coal facilities | EPA v.5.15 |
| Unit-level heat rates | EPA NEEDS v.5.15 |
| (Regulatory) SO2/NOx | CAIR and CSAPR |
| (Regulatory) MATS | As finalized; allow HCl compliance via low-chlorine PRB coals |
| (Regulatory) Coal Combustion Residuals | Included |
| (Regulatory) Water Intake Structures | Included |
| (Regulatory) RGGI | Included |
| (Regulatory) CA AB32 | Included |
| (Regulatory) Regional Haze | Included |
| | |
| (Structure) Run years | 2020, 2025, 2030, 2035, 2040, 2050 |
| (Structure) EE Supply Curves | 3 supply curve steps per region with utility program costs in line with 2017 analysis |
| (Structure) Heat Rate Improvements | EPA v.5.15 (not included in Reference Case) |
| EE penetration | No Incremental EE assumed in Reference Case beyond EE savings already embedded in AEO 2019. Energy Efficiency targets in NY, NJ, and CO modeled after AEO 2019. |
| Fixed and variable operating and maintenance costs (FOM and VOM) | EPA v.5.15/EPA v.6 |

## Policy Case Specifications

| Case Name | Description |
|---|---|
| National Cap and Trade Case (CAP) | National tonnage cap with $200/ton offset price starting in 2040-2050. Covering Existing and New Fossil and Biomass units > 25 MW. No banking.<br><br>2020: 1,746,527,000 short tons<br><br>2025: 1,259,073,000 short tons<br><br>2030: 771,618,000 short tons<br><br>2035: 385,809,000 short tons (with offset option set at $200/ton price (2012$))<br><br>2040: $200/ton price (2012$)<br><br>2050: $200/ton price (2012$) |
| National Cap and Trade Case (CAP-B) | National Carbon Case described above modeled with a zero-carbon cap by 2040 and no offset price available. Covering Existing and New Fossil and Biomass units > 25 MW. Banking allowed 2020-2050.<br><br>2020: 1,746,527,000 short tons<br><br>2025: 1,259,073,000 short tons<br><br>2030: 771,618,000 short tons<br><br>2035: 385,809,000 short tons<br><br>2040: 0 short tons<br><br>2050: 0 short tons |
| Updated Clean Power Plan (CPP20) | National mass-based caps for existing units only (excluding CA) based on updated CPP targets to achieve a 32 percent reduction in carbon emissions from 2015 levels (65 percent from 2005 levels) by 2035. Cap applied to CPP covered sources (Coal, Oil/Gas, and CC units >25 MW). CA existing units excluded from existing CPP due to modeling of stronger CA decarbonization program in runs (modeled as tax).<br><br>100 lbs/MWh standard for new gas, with national trading (includes CA)<br><br>2025 Existing only target: 1,191,723,942 short tons<br><br>2030 Existing only target: 925,489,853 short tons<br><br>2035-2050 Existing only target: 760,958,908 short tons<br><br>· New gas: 100 lbs/MWh |

| | |
|---|---|
| Affordable Clean Energy Rule (ACE) | ACE rule modeled, assuming one HRI option available for all coal plants. 4.5% average heat rate improvement consistent with New Source Review reform, CCS allowed. |
| 80x30 Clean Electricity Standard (CES40-B) | Threshold of 0.82 metric ton/MWh (0.904 ton/MWh), partial crediting, 100% clean in 2040, unlimited banking allowed 2020-2050, based on total generation, CES % requirement based on total generation and applied nationally (national trading). For CCS units, plants that use their carbon for enhanced oil recovery have credit reduced by 50%.<br>% clean requirement/realized by model year:<br>2025: 58%/68%<br>2030: 72%/82%<br>2035: 86%/85%<br>2040: 100%/92%<br>2045: 100%/95%<br>2050: 100%/98% |
| Clean Electricity Standard (CES40) | Same as CES40-B but no banking allowed<br>% clean requirement and realized by model year:<br>2025: 58%<br>2030: 72%<br>2035: 86%<br>2040: 100%<br>2045: 100%<br>2050: 100% |
| Clean Electricity Standard (CES50-H) | Threshold of 0.82 metric tons/MWh, partial crediting, 100% clean and zero-emission requirement in 2050, banking restriction in 2050, based on total generation<br>% clean requirement by model year:<br>2020: 53%<br>2025: 58%<br>2030: 67%<br>2035: 75%<br>2040: 86%<br>2050: 100% |

| | |
|---|---|
| Clean Electricity Standard (CES50-L) | 100% clean and zero-emission requirement in 2050, no banking in 2050 based on total generation, flat threshold of 0.46 metric tons/MWh, partial crediting, uncontrolled NGCC does not qualify for a credit.<br><br>% clean required by model year:<br><br>2025: 43%<br><br>2030:54%<br><br>2035: 66%<br><br>2040: 81%<br><br>2050: 100% |

## Appendix 3: Premature deaths avoided

| Premature Deaths Avoided - Illustrative 80% clean by 2030 Clean Electricity Standard - Sorted by deaths avoided in 2030 | | | | |
|---|---|---|---|---|
| State | Premature Deaths Avoided 2030 | Premature Deaths Avoided 2050 | Premature Deaths Avoided Per 100,000 in 2030 | Premature Deaths Avoided Per 100,000 in 2050 |
| Ohio | 771 | 1201 | 9.14 | 13.76 |
| Texas | 737 | 1680 | 3.26 | 5.51 |
| Pennsylvania | 582 | 1027 | 6.08 | 10.35 |
| Illinois | 529 | 888 | 5.58 | 8.86 |
| Florida | 463 | 1333 | 2.57 | 5.78 |
| North Carolina | 453 | 881 | 5.42 | 8.47 |
| Indiana | 441 | 694 | 9.09 | 13.27 |
| Tennessee | 424 | 656 | 7.98 | 10.39 |
| Michigan | 396 | 684 | 5.48 | 9.3 |
| Georgia | 377 | 751 | 4.5 | 7.19 |
| Kentucky | 362 | 532 | 10.76 | 14.33 |
| Virginia | 321 | 661 | 4.7 | 7.92 |
| New York | 320 | 643 | 2.2 | 4.26 |
| Missouri | 298 | 464 | 6.51 | 9.2 |
| Alabama | 252 | 388 | 6.86 | 9.61 |
| Maryland | 227 | 492 | 4.65 | 8.48 |
| South Carolina | 204 | 466 | 5.1 | 9.47 |
| Wisconsin | 196 | 368 | 4.45 | 7.71 |
| New Jersey | 176 | 391 | 2.6 | 5.42 |
| Louisiana | 171 | 299 | 4.93 | 7.65 |
| Arkansas | 169 | 280 | 7.29 | 10.34 |
| West Virginia | 145 | 202 | 10.5 | 14.03 |
| Oklahoma | 138 | 212 | 4.75 | 6.42 |
| Mississippi | 124 | 197 | 5.66 | 8.2 |
| Iowa | 111 | 157 | 5.03 | 6.82 |
| Minnesota | 107 | 168 | 2.5 | 3.41 |

| | | | | |
|---|---|---|---|---|
| Kansas | 89 | 144 | 4.32 | 6.44 |
| California | 87 | 212 | 0.28 | 0.58 |
| Massachusetts | 72 | 144 | 1.38 | 2.62 |
| Nebraska | 51 | 73 | 3.78 | 4.9 |
| Connecticut | 50 | 104 | 1.82 | 3.67 |
| Colorado | 45 | 78 | 1.02 | 1.4 |
| Arizona | 43 | 74 | 0.73 | 0.93 |
| Delaware | 33 | 71 | 4.47 | 8.14 |
| New Mexico | 31 | 52 | 1.83 | 2.41 |
| Washington | 18 | 40 | 0.31 | 0.55 |
| Nevada | 18 | 42 | 0.69 | 1.22 |
| District of Columbia | 17 | 35 | 3.28 | 5.72 |
| South Dakota | 16 | 19 | 2.58 | 2.67 |
| New Hampshire | 16 | 32 | 1.45 | 2.64 |
| Utah | 15 | 24 | 0.68 | 0.82 |
| Rhode Island | 14 | 30 | 1.69 | 3.55 |
| Maine | 12 | 25 | 1.09 | 2.15 |
| Oregon | 10 | 23 | 0.29 | 0.57 |
| North Dakota | 10 | 13 | 1.69 | 1.93 |
| Vermont | 9 | 17 | 1.77 | 3.06 |
| Wyoming | 5 | 7 | 1.03 | 1.17 |
| Idaho | 4 | 7 | 0.33 | 0.43 |
| Montana | 4 | 5 | 0.44 | 0.56 |

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