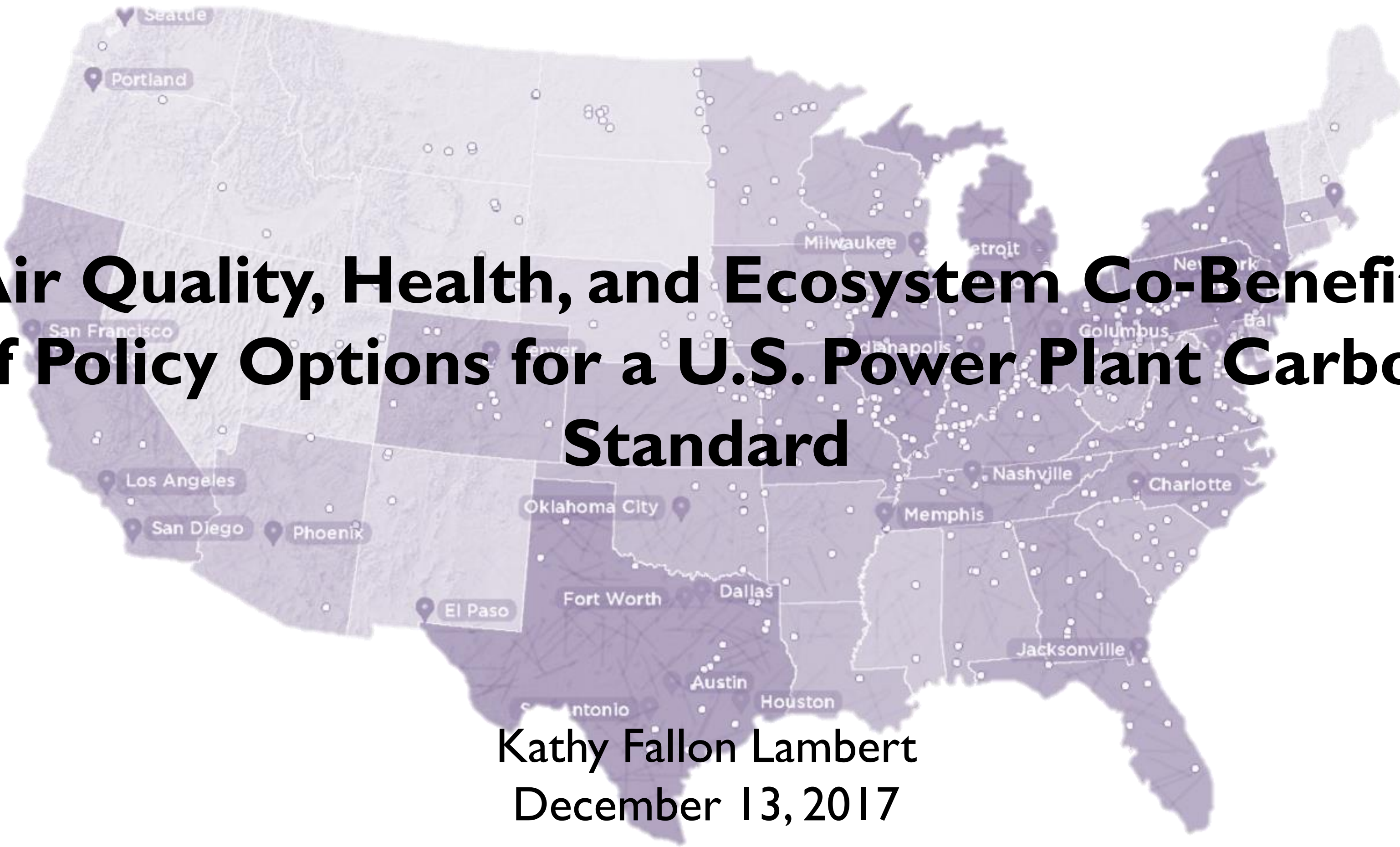

Air Quality, Health, and Ecosystem Co-Benefits of Policy Options for a U.S. Power Plant Carbon Standard

Kathy Fallon Lambert

December 13, 2017

HARVARD FOREST

SCIENCE POLICY EXCHANGE

Acknowledgements

- Charles Driscoll – Syracuse University
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- Pam Templer – Boston University
- Jana Milford – University of Colorado, Boulder
- Shannon Capps – Drexel University
- Ken Craig – Sonoma Technologies

Scenarios: BPC, NRDC, MJB

Accounting for Full Benefits

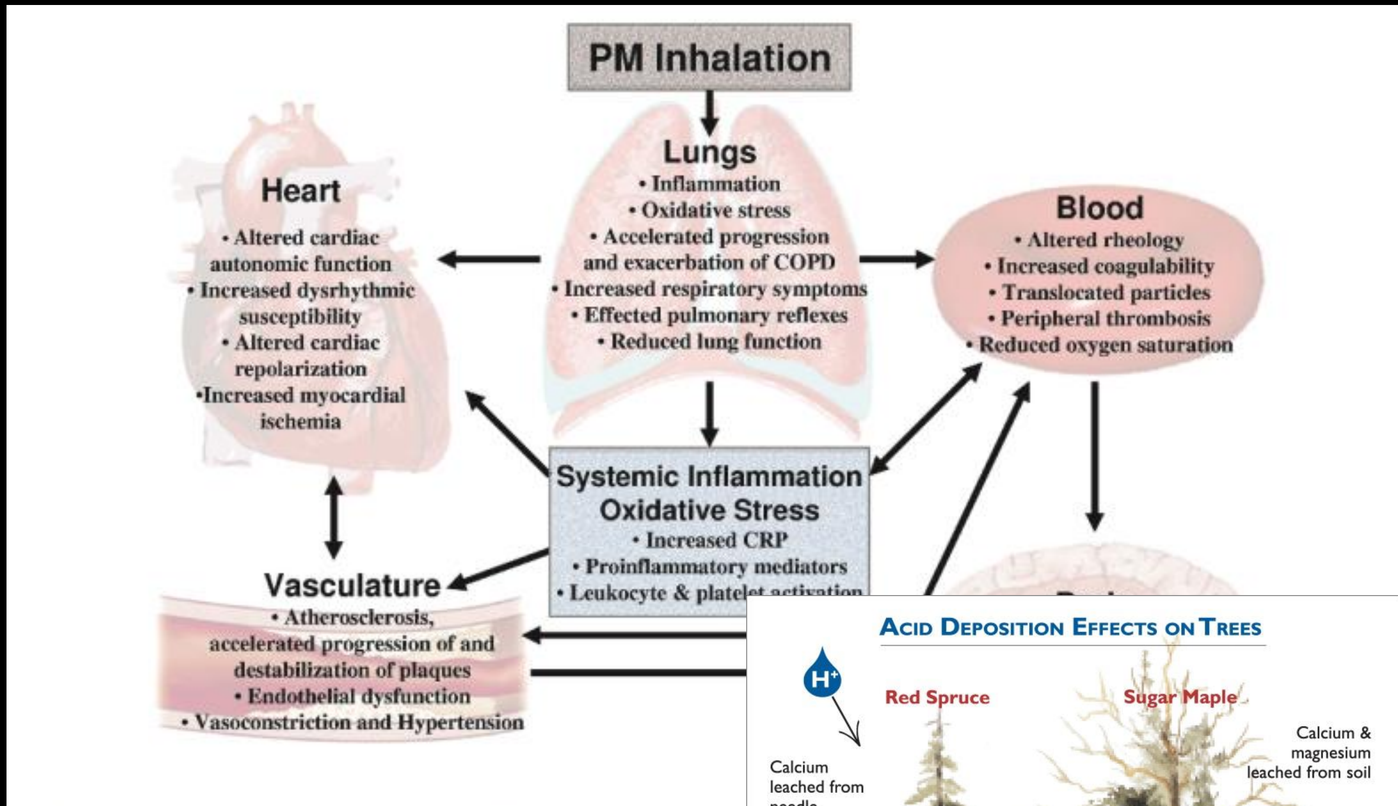
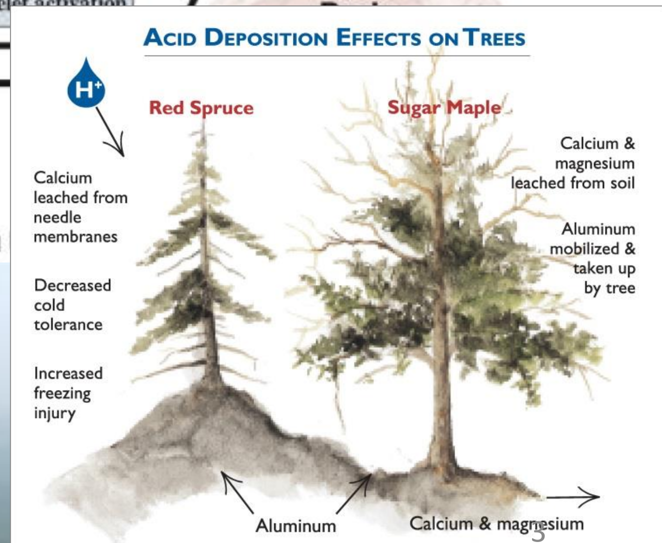
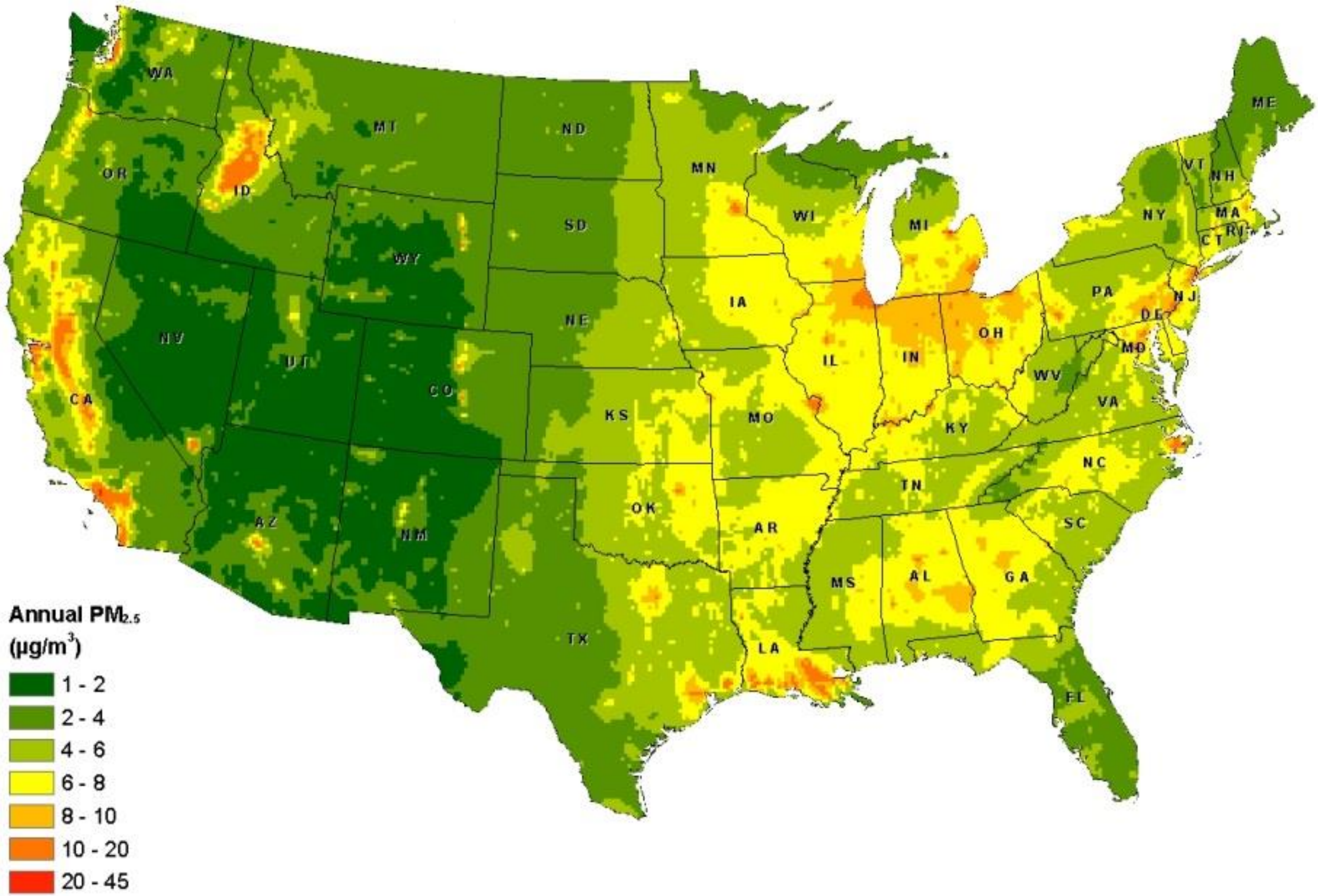


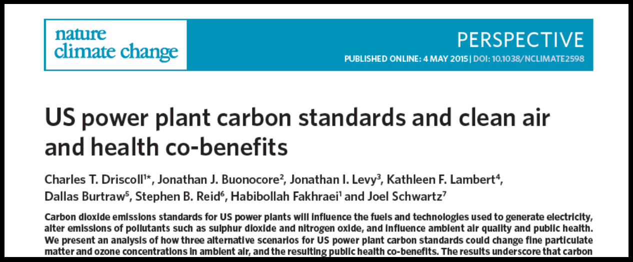
Figure 4. Potential general pathophysiological pathways linking



Average Annual PM2.5 in 2020 - Reference Case



Power Plant Carbon Standards Co-Benefits Study



nature climate change

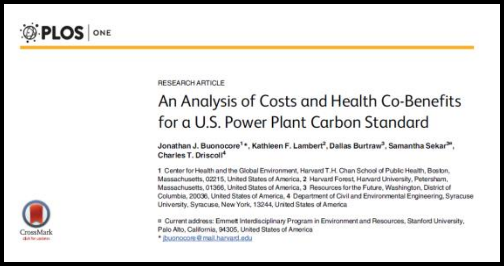
PERSPECTIVE

PUBLISHED ONLINE: 4 MAY 2015 | DOI: 10.1038/NCLIMATE2598

US power plant carbon standards and clean air and health co-benefits

Charles T. Driscoll[1*], Jonathan J. Buonocore[2], Jonathan I. Levy[3], Kathleen F. Lambert[4], Dallas Burtraw[5], Stephen B. Reid[6], Habibollah Fakhraei[1] and Joel Schwartz[7]

Carbon dioxide emissions standards for US power plants will influence the fuels and technologies used to generate electricity, alter emissions of pollutants such as sulphur dioxide and nitrogen oxide, and influence ambient air quality and public health. We present an analysis of how three alternative scenarios for US power plant carbon standards could change fine particulate matter and ozone concentrations in ambient air, and the resulting public health co-benefits. The results underscore that carbon



PLOS | ONE

RESEARCH ARTICLE

An Analysis of Costs and Health Co-Benefits for a U.S. Power Plant Carbon Standard

Jonathan J. Buonocore[1*], Kathleen F. Lambert[2], Dallas Burtraw[3], Samantha Sekar[3¤], Charles T. Driscoll[4]

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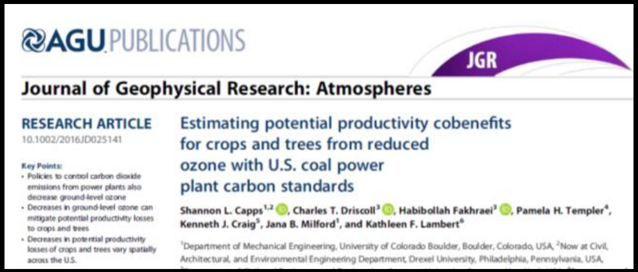


AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Atmospheres

RESEARCH ARTICLE

10.1002/2016JD025141

Key Points:
- Policies to control carbon dioxide emissions from power plants also decrease ground-level ozone
- Decreases in ground-level ozone can mitigate potential productivity losses to crops and trees
- Decreases in potential productivity losses of crops and trees vary spatially across the U.S.

Estimating potential productivity cobenefits for crops and trees from reduced ozone with U.S. coal power plant carbon standards

Shannon L. Capps[1,2], Charles T. Driscoll[3], Habibollah Fakhraei[3], Pamela H. Templer[4], Kenneth J. Craig[5], Jana B. Milford[1], and Kathleen F. Lambert[6]

[1]Department of Mechanical Engineering, University of Colorado Boulder, Boulder, Colorado, USA, [2]Now at Civil, Architectural, and Environmental Engineering Department, Drexel University, Philadelphia, Pennsylvania, USA,

- Scenario 1: Inside the Fence line
- Scenario 2: Beyond the Fence line - resembles CPP
- Scenario 3: Social Cost of Carbon

- Reference Case: AEO 2013 for demand

Study Model Platform

IPM
Power Sector
Analysis
&
Emissions
Estimates

CMAQ
Air Quality
Projections
&
Deposition
Estimates

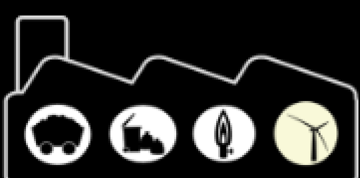
BenMap
Human Health
Benefits

PnET-BGC
Acidification Benefits

Ozone benefits for
timber & crops

Visibility
Improvements

Reference Case
Scenario 1: Inside Fence line
Scenario 2: Beyond Fence line/CPP
Scenario 3: Cost of Carbon



Scenario Assumptions

Beyond the Fence line

- State-specific rate-based performance standard
- Establishes benchmark emissions rate for each state
- For 2020, the national emission rate targets are 1,500 lbs/MWh for coal and 1,000 lbs/MWh for gas.
- Also allows averaging and trading
- Allows states to develop alternative plans, including mass-based standards, provided they achieve equivalent emission reductions

Inside the Fence line

- Uses "best-in-class" heat rates for different coal plant categories
- Emission rate equivalent to closing gap to best in class by 40%
  - Unit Retrofits
  - Co-fire or convert to natural gas or biomass
  - Combination of modest plant efficiency retrofit and co-firing
- Improves fleet-wide average heat rate 4%; national average emissions rate of 2000 lbs/MWh for coal and 1000 lbs/MWh for gas
- No new coal plants built

Change in National Emissions 2005 & 2020

Beyond the Fence line

CO_2 = -35% from 2005

SO_2 = -27%

NO_x = -22%

Inside the Fence line

CO_2 = -17% from 2005

SO_2 = +3%

NO_x = -3%

Final Clean Power Plan

Mass-based Illustrative Case

CO_2 = -32% from 2005 by 2030

SO_2 = -21% (2015 RIA) or -31% (2017 RIA)

NO_x = -21% (2015 RIA) or -23% (2017 RIA)

Note: actual emissions reductions depend on State Implementation Plans

Air Quality Results

Beyond the Fence line

- All lower 48 states experience an improvement in air quality in 2020 compared to reference case

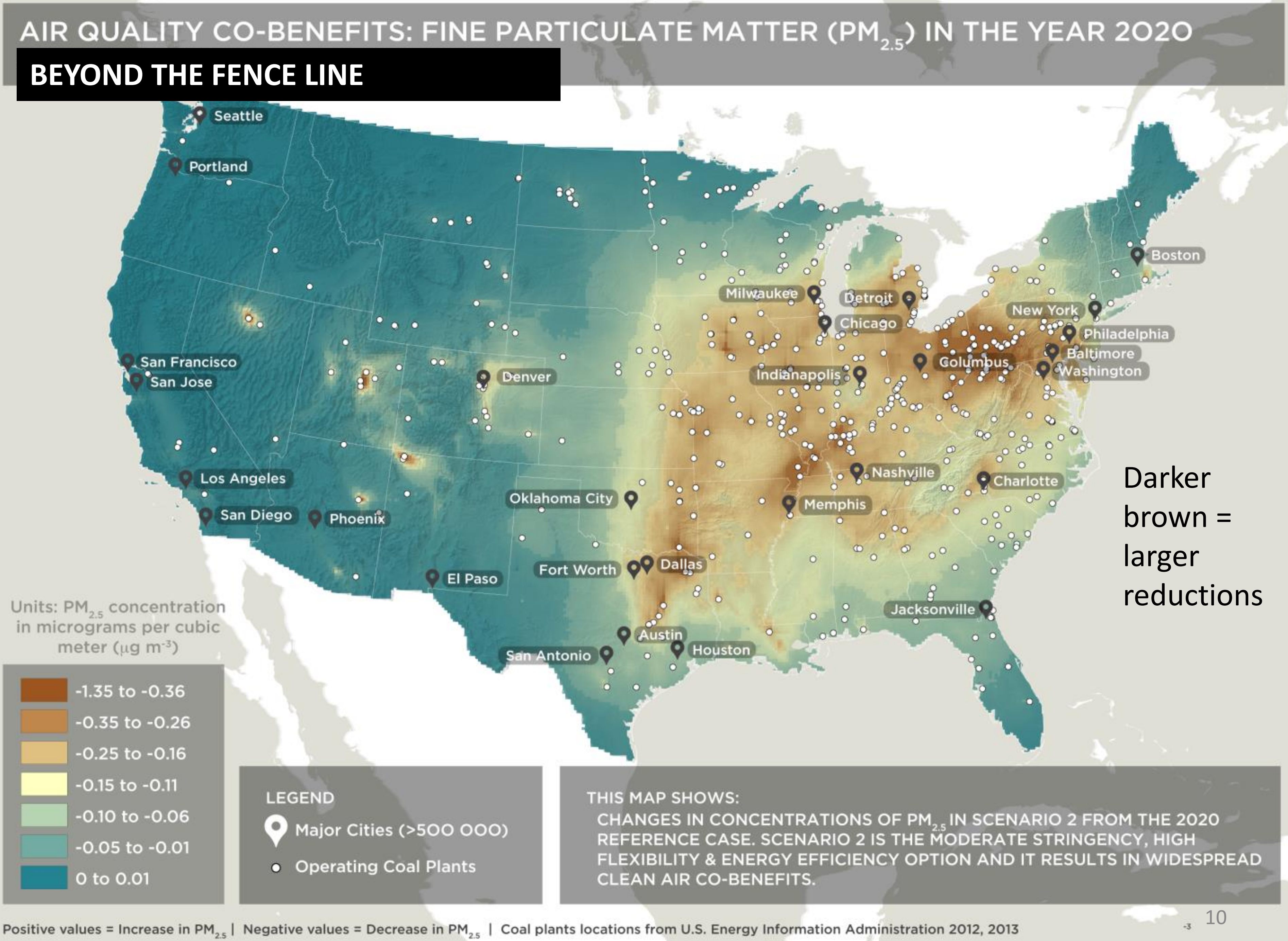
- States with largest statewide average decreases in air pollution detrimental to human health include: OH, PA, MD, WV, IL, KY, MO, IN, AR, CO, AL, WV

- 41 million people in 41 large cities would gain higher air quality

Inside Fence line

- Large areas of eastern and western US experience decrease in air quality in 2020 compared to reference case

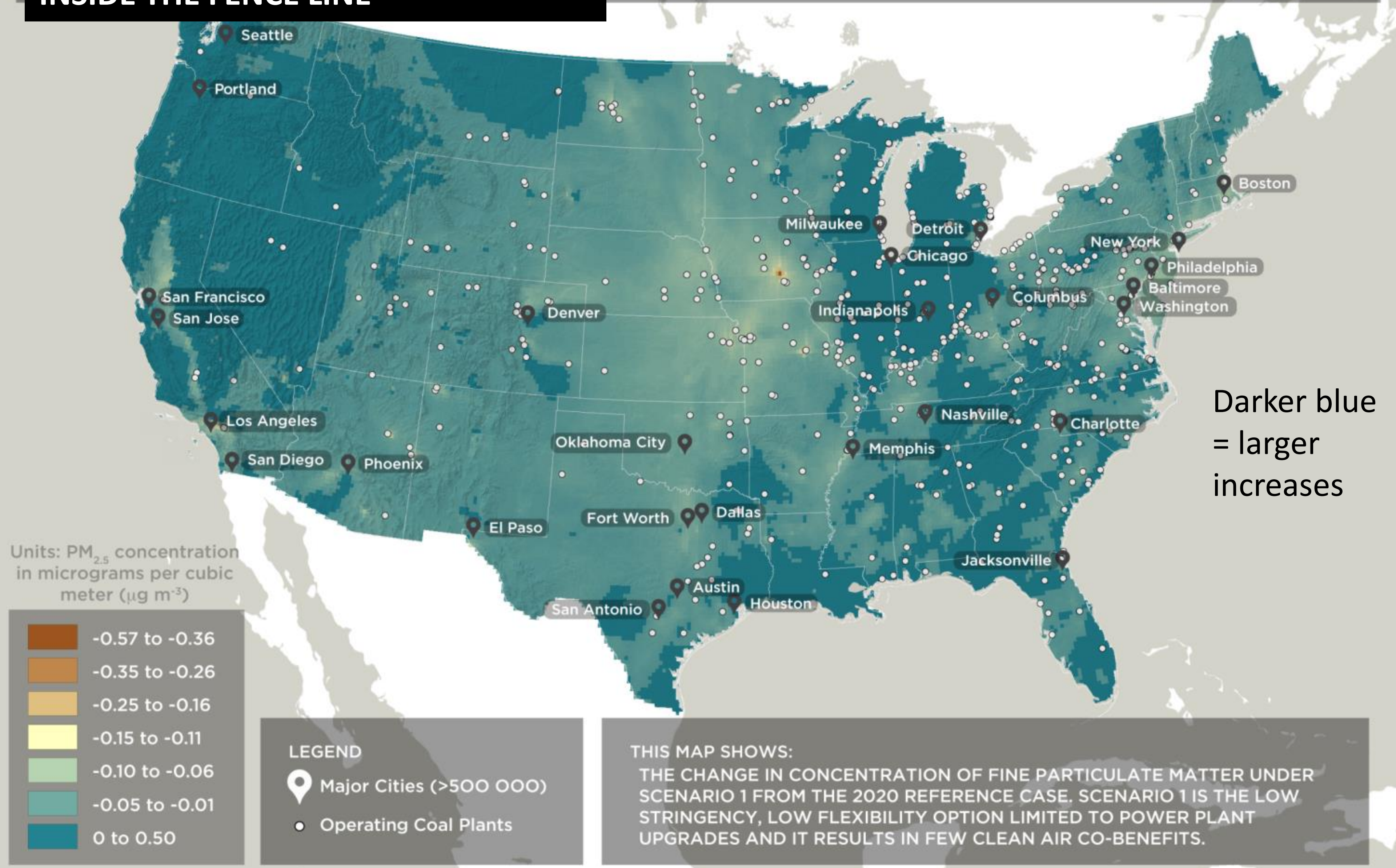
BEYOND THE FENCE LINE



Darker brown = larger reductions

AIR QUALITY CO-BENEFITS: FINE PARTICULATE MATTER ($PM_{2.5}$) IN THE YEAR 2020

INSIDE THE FENCE LINE

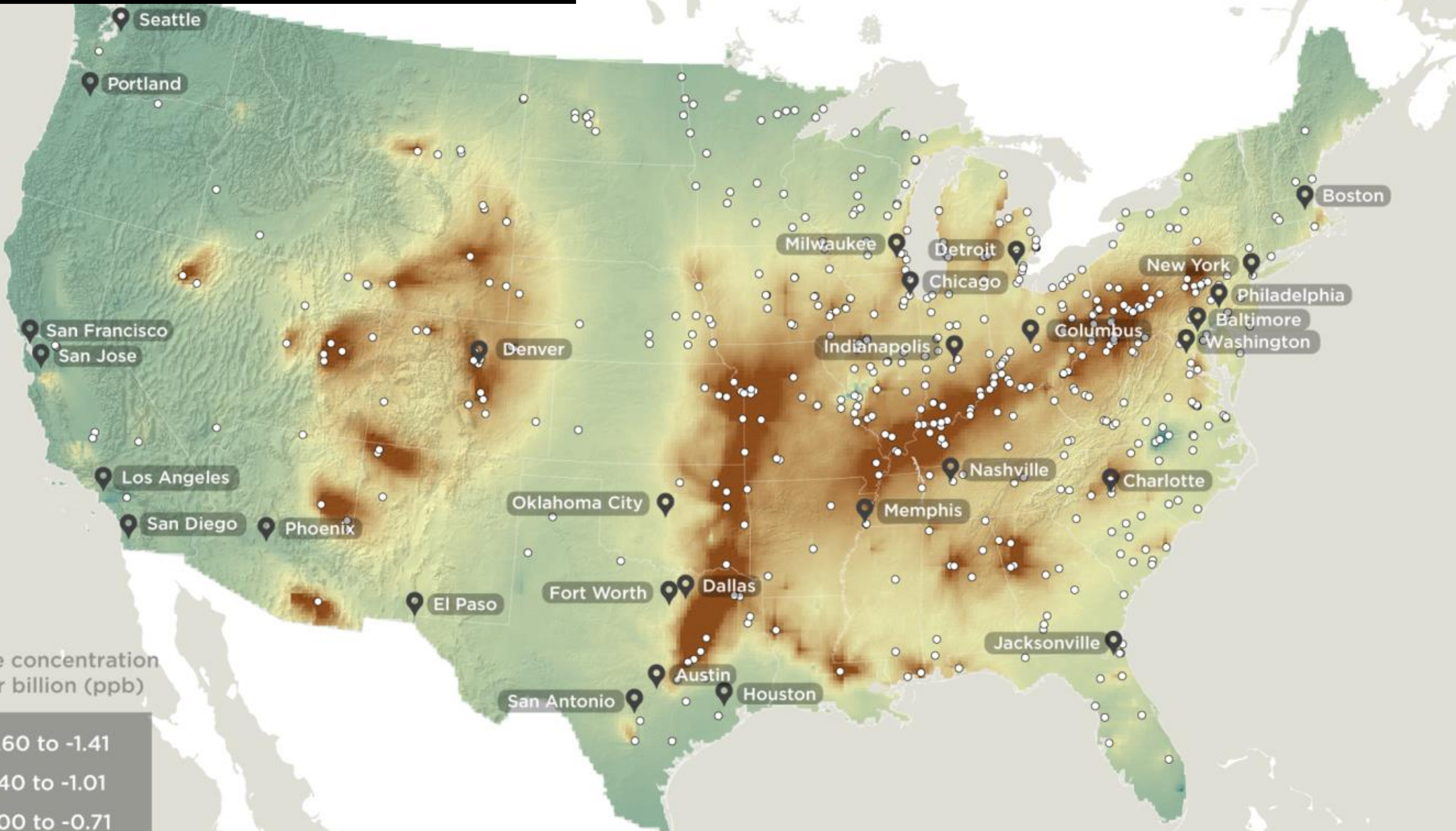


Darker blue = larger increases

Positive values = Increase in $PM_{2.5}$ | Negative values = Decrease in $PM_{2.5}$ | Coal plants locations from U.S. Energy Information Administration 2012, 2013

AIR QUALITY CO-BENEFITS: PEAK SUMMER OZONE IN THE YEAR 2020

BEYOND THE FENCE LINE



Units: Ozone concentration in parts per billion (ppb)

- -3.60 to -1.41
- -1.40 to -1.01
- -1.00 to -0.71
- -0.70 to -0.51
- -0.50 to -0.31
- -0.30 to -0.01
- 0 to 0.70

LEGEND

- Major Cities (>500 000)
- Operating Coal Plants

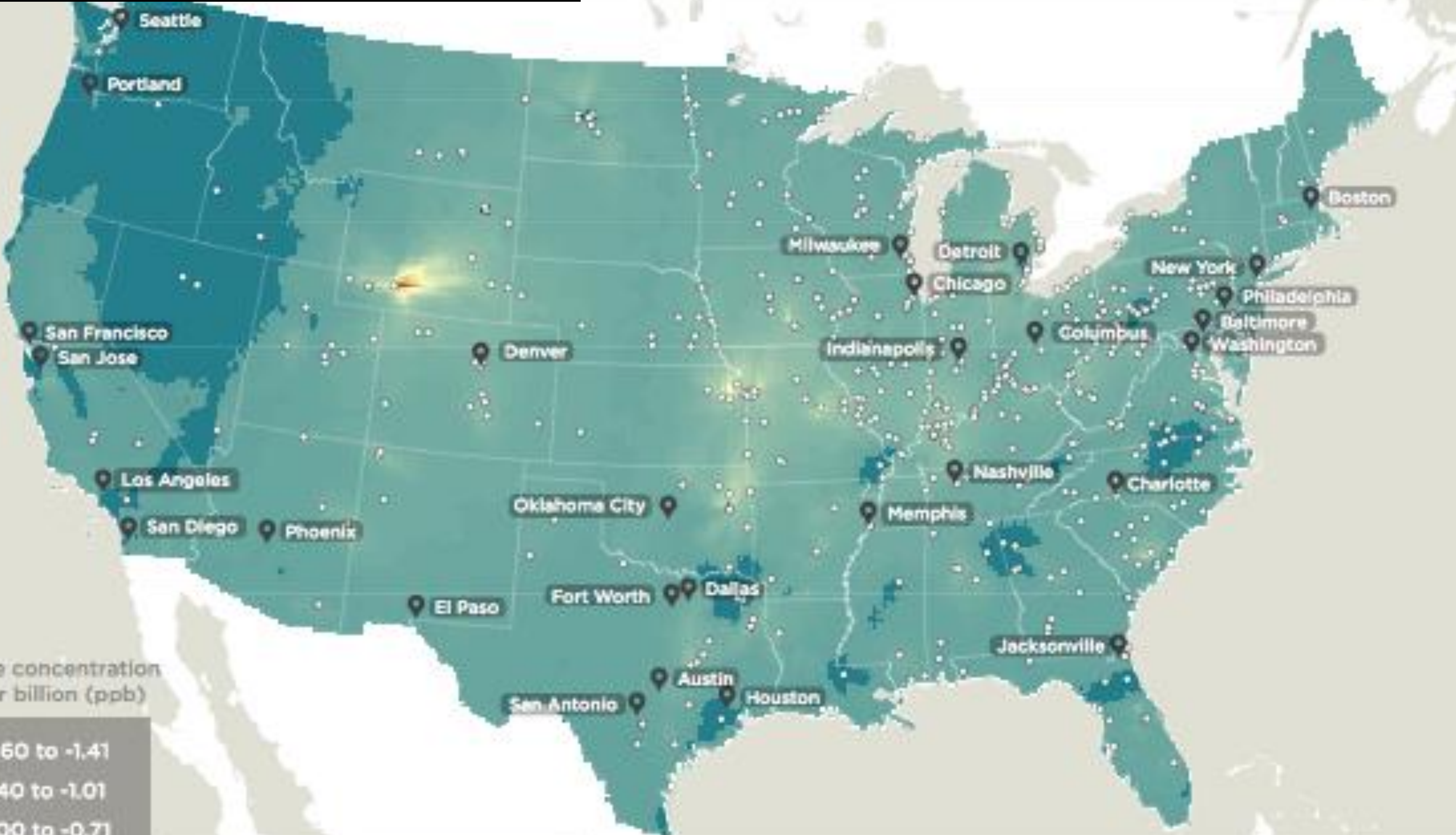
THIS MAP SHOWS:

CHANGE IN CONCENTRATIONS OF PEAK SUMMER OZONE IN SCENARIO 2 FROM THE 2020 REFERENCE CASE. SCENARIO 2 IS THE MODERATE STRINGENCY, HIGH FLEXIBILITY & ENERGY EFFICIENCY OPTION AND IT RESULTS IN WIDESPREAD CLEAN AIR CO-BENEFITS.

Positive values = Increase in summer ozone | Negative values = Decrease in summer ozone | Coal plants locations from U.S. Energy Information Administration 2012, 2013

AIR QUALITY CO-BENEFITS: PEAK SUMMER OZONE IN THE YEAR 2020

INSIDE THE FENCE LINE



Units: Ozone concentration in parts per billion (ppb)

- -3.60 to -1.41
- -1.40 to -1.01
- -1.00 to -0.71
- -0.70 to -0.51
- -0.50 to -0.31
- -0.30 to -0.01
- 0 to 0.70

LEGEND

- Major Cities (>500 000)
- Operating Coal Plants

THIS MAP SHOWS:

CHANGES IN CONCENTRATIONS OF PEAK SUMMER OZONE IN SCENARIO 1 FROM THE 2020 REFERENCE CASE. SCENARIO 1 IS THE LOW STRINGENCY, LOW FLEXIBILITY OPTION LIMITED TO POWER PLANT UPGRADES AND IT RESULTS IN FEW CLEAN AIR CO-BENEFITS.

Positive values = Increase in summer ozone | Negative values = Decrease in summer ozone | Coal plants locations from U.S. Energy Information Administration 2012, 2013

Health Benefits

Health outcome	Pollutant	Inside Fence line CE (95% CI)	Beyond Fence line CE (95% CI)
Total premature deaths avoided	$PM_{2.5}$ and Ozone	-11 (-23 to 2)	3500 (780 to 6100)
Total hospitalizations avoided (respiratory and cardiovascular)	$PM_{2.5}$ and Ozone	15 (3 to 27)	1000 (530 to 1500)
Total heart attacks avoided (acute non-fatal myocardial infarction)	$PM_{2.5}$	-3 (-5 to -2)	220 (130 to 310)

Study	Health Outcome	Pollutant	Metric	Response (% increase or decrease in rate)	Standard Error (% increase or decrease in rate)	
Roman et al. 2008	Premature death (all causes)	$PM_{2.5}$	Annual average concentration ($\mu g/m^3$)	1.0	0.4	>= 25 years
Levy et al. 2012, Zanobetti et al. 2009, pooled	Respiratory hospitalizations	$PM_{2.5}$	Daily average concentration ($\mu g/m^3$)	0.11	0.027	=>65 years
Levy et al. 2012, Zanobetti et al. 2009, pooled	Cardiovascular hospitalizations	$PM_{2.5}$	Daily average concentration ($\mu g/m^3$)	0.094	0.015	=>65 years
Mustafic et al. 2012	Heart attack (acute non-fatal myocardial infarction)	$PM_{2.5}$	Daily average concentration ($\mu g/m^3$)	0.25	0.0536	>18 years
Jerrett et al. 2009	Premature death (respiratory causes)	Ozone	April – Sept. average of the 1-hour maximum (ppb)	0.39	0.13	=>30 years
Ji et al. 2011	Respiratory Hospitalizations	Ozone	Annual average of the 8-hour maximum (ppb)	0.16	0.052	=>65 years

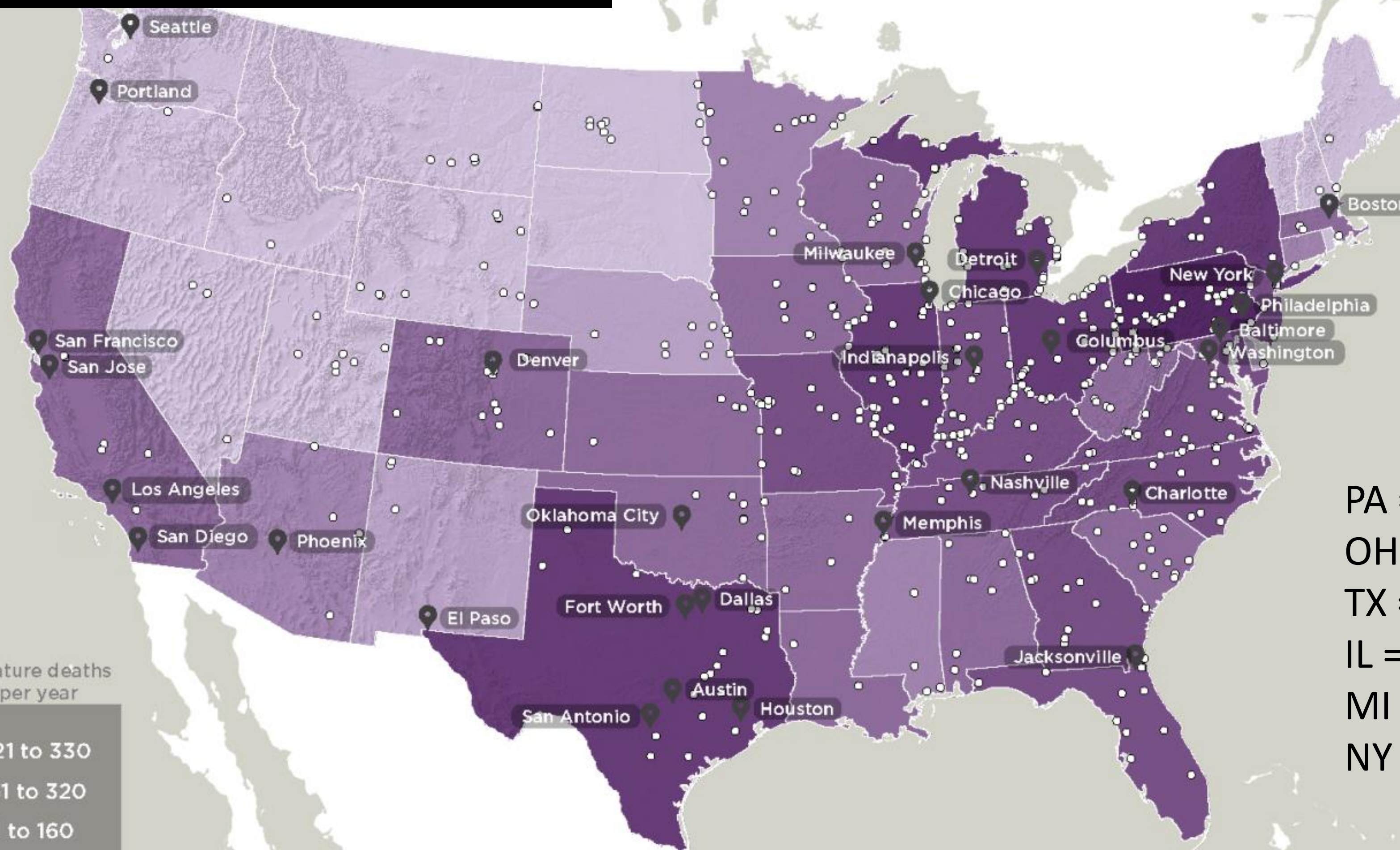
Recent Research – Qi et al. NEJM 2017

- Medicare beneficiaries 2000 - 2012
- 61 m people
- Across US/exposures
- 460 million person-years of follow-up

- Relationship between $PM_{2.5}$, ozone, and all-cause mortality almost linear, with no signal of threshold down to 5 µg per cubic meter and 30 ppb.
- Significant association between $PM_{2.5}$ exposure and mortality when the analysis was restricted to concentrations below 12 µg/m^3, with a steeper slope below that level.
- Health benefit per-unit decrease in the concentration of $PM_{2.5}$ is larger below the current annual NAAQS than above.
-

HEALTH CO-BENEFITS: LIVES SAVED IN THE YEAR 2020

BEYOND THE FENCE LINE



PA = 330
OH = 280
TX = 230
IL = 210
MI = 190
NY = 190

Units: premature deaths avoided per year

- 321 to 330
- 161 to 320
- 81 to 160
- 41 to 80
- 21 to 40
- 11 to 20
- 1 to 10

LEGEND

- Major Cities (>500 000)
- Operating Coal Plants

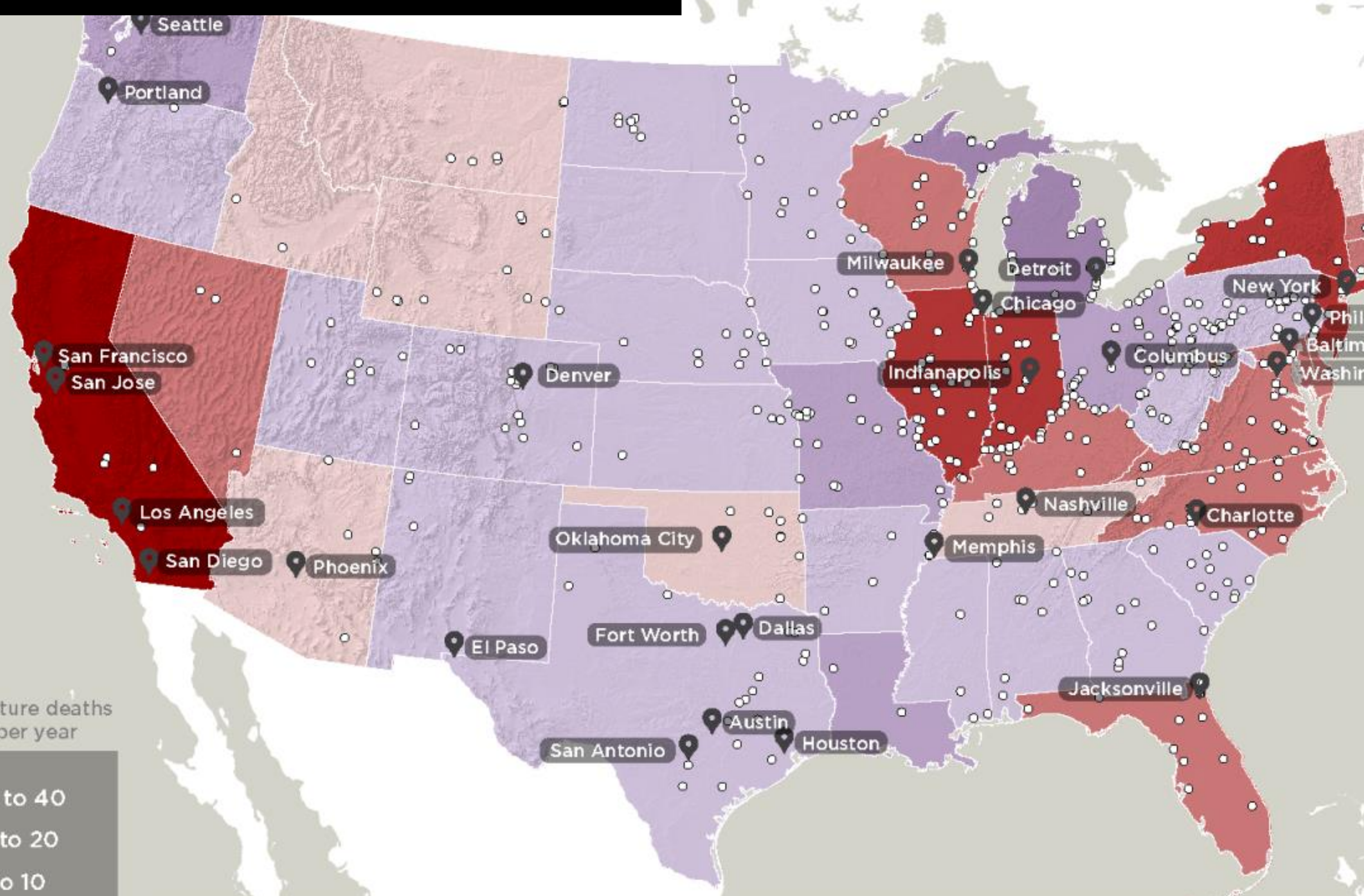
THIS MAP SHOWS:

THE CHANGE IN NUMBER OF PREMATURE DEATHS AVOIDED PER YEAR UNDER SCENARIO 2 FROM THE 2020 REFERENCE CASE BY STATE. SCENARIO 2 IS THE MODERATE STRINGENCY, HIGH FLEXIBILITY & ENERGY EFFICIENCY OPTION AND IT RESULTS IN THE LARGEST HEALTH CO-BENEFITS.

Positive values = Increase in # of lives saved per year | Coal plant locations from U.S. Energy Information Administration 2012, 2013

HEALTH CO-BENEFITS: LIVES SAVED IN THE YEAR 2020

INSIDE THE FENCE LINE



CA = -33
NY = -16
IL = -15
IN = -12

Units: premature deaths avoided per year

- 21 to 40
- 11 to 20
- 1 to 10
- 0
- -9 to -1
- -19 to -10
- -33 to -20

LEGEND

- Major Cities (>500 000)
- Operating Coal Plants

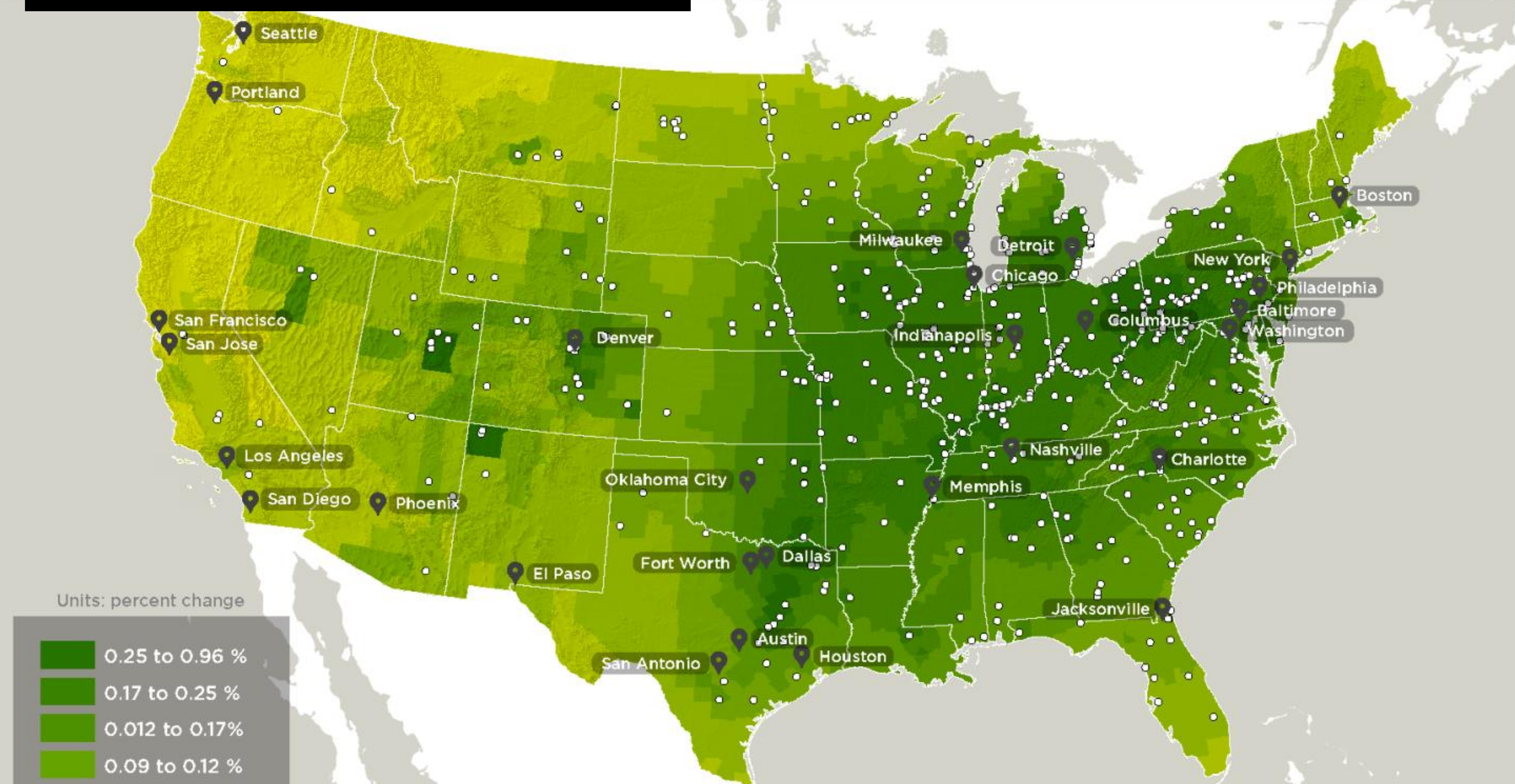
THIS MAP SHOWS:

THE CHANGE IN NUMBER OF PREMATURE DEATHS AVOIDED PER YEAR UNDER SCENARIO 1 FROM THE 2020 REFERENCE CASE BY STATE. SCENARIO 1 IS THE LOW STRINGENCY, LOW FLEXIBILITY OPTION LIMITED TO POWER PLANT UPGRADES AND IT RESULTS IN THE LOWEST HEALTH CO-BENEFITS.

Positive values = Increase in # of lives saved per year | Negative values = Decrease in # of lives saved per year | Coal plant locations from U.S. Energy Information Administration 2012, 2013

HEALTH CO-BENEFITS: PRECENT CHANGE IN LIVES SAVED IN YEAR 2020

BEYOND THE FENCE LINE



Units: percent change

- 0.25 to 0.96 %
- 0.17 to 0.25 %
- 0.012 to 0.17%
- 0.09 to 0.12 %
- 0.06 to 0.09 %
- 0.03 to 0.06 %
- 0.01 to 0.03 %
- 0 to 0.01 %

LEGEND

- Major Cities (>500 000)
- Operating Coal Plants

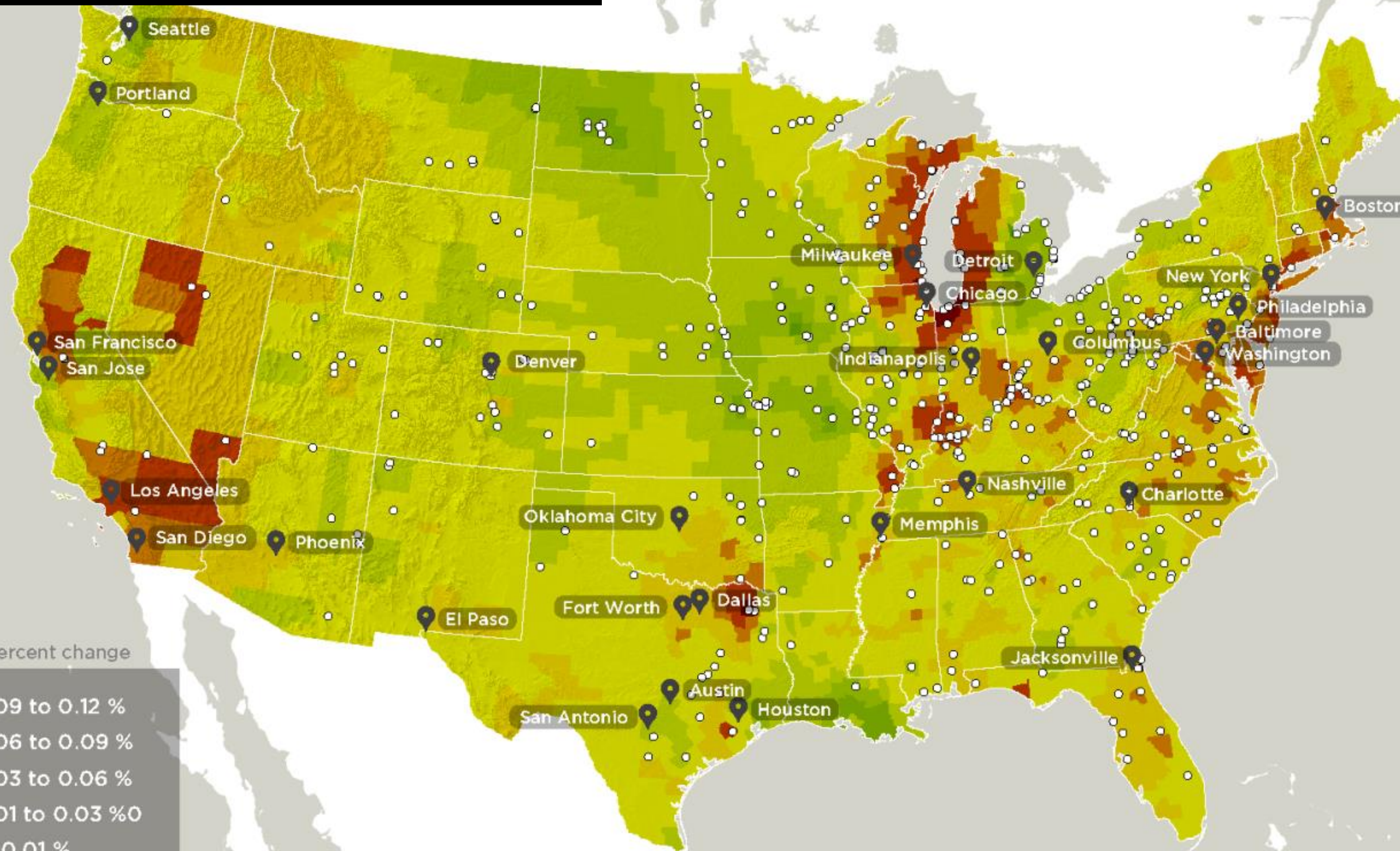
THIS MAP SHOWS:

THE CHANGE IN RATE OF LIVES SAVED UNDER SCENARIO 2 FROM THE 2020 REFERENCE CASE BY COUNTY. SCENARIO 2 IS THE MODERATE STRINGENCY, HIGH FLEXIBILITY & ENERGY EFFICIENCY OPTION AND RESULTS IN THE LARGEST HEALTH CO-BENEFITS.

Positive values = Increase in rate of premature deaths avoided | Coal plant locations from U.S. Energy Information Administration 2012, 2013

HEALTH CO-BENEFITS: PERCENT CHANGE IN LIVES SAVED IN YEAR 2020

INSIDE THE FENCE LINE



Units: percent change

- 0.09 to 0.12 %
- 0.06 to 0.09 %
- 0.03 to 0.06 %
- 0.01 to 0.03 %0
- to 0.01 %
- -0.01 to 0 %
- -0.02 to -0.01 %
- -0.06 to -0.02 %
- -0.19 to -0.06 %

LEGEND

- Major Cities (>500 000)
- Operating Coal Plants

THIS MAP SHOWS:

THE CHANGE IN RATE OF LIVES SAVED UNDER SCENARIO 1 FROM THE 2020 REFERENCE CASE BY COUNTY. SCENARIO 1 IS THE LOW STRINGENCY, LOW FLEXIBILITY OPTION LIMITED TO POWER PLANT UPGRADES AND IT RESULTS IN THE LOWEST HEALTH CO-BENEFITS.

Positive values = Increased rate of premature deaths avoided | Negative values = Decreased rate of premature deaths avoided | Coal plant locations from U.S. Energy Information Administration 2012, 2013

Costs & Benefits (2010 USD)

Beyond the Fence Line
(billions of USD 2010 and 2011)

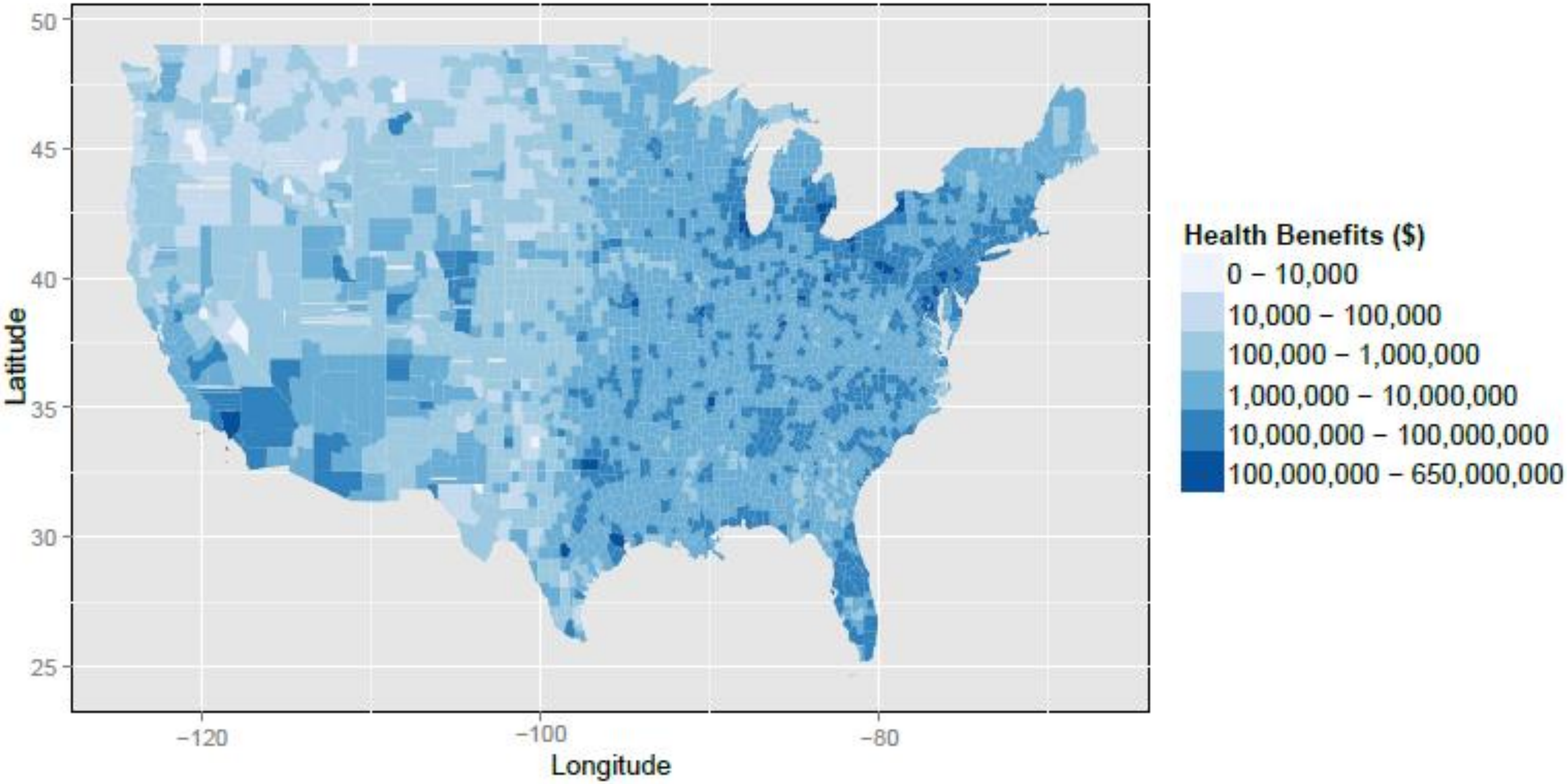
- Estimated health co-benefits = $29 per year
- Carbon benefits = $21 per year
- Estimated cost in 2020 = $17

- Net benefits = $33 per year

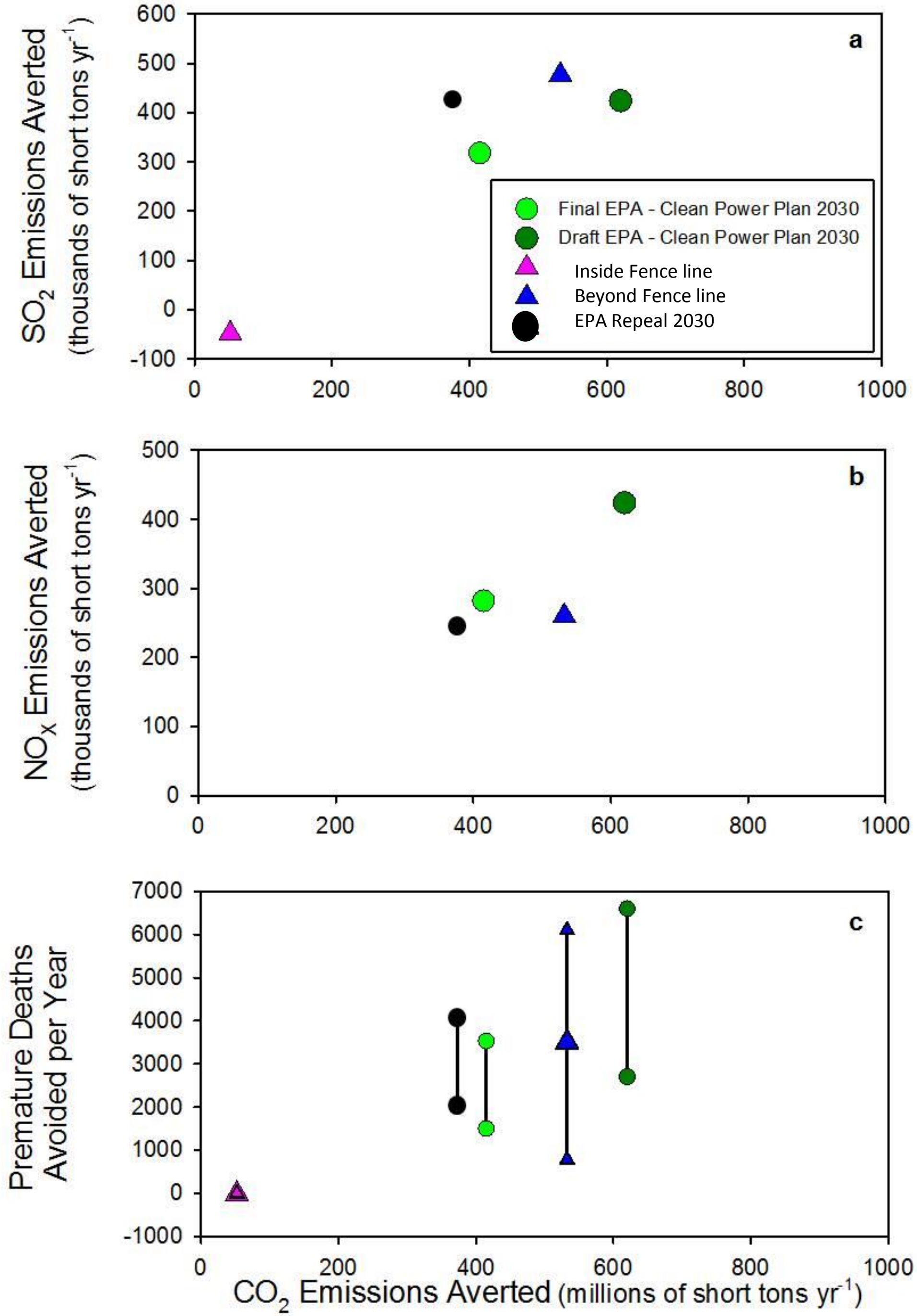
- 2015 RIA net benefits = $25 to $43
- 2017 RIA net benefits = $15 to $38
  $-12.7 to $2.1

Buonocore et al. Plos One; EPA RIA 2015, 2017

Value of Health Benefits Beyond Fence line



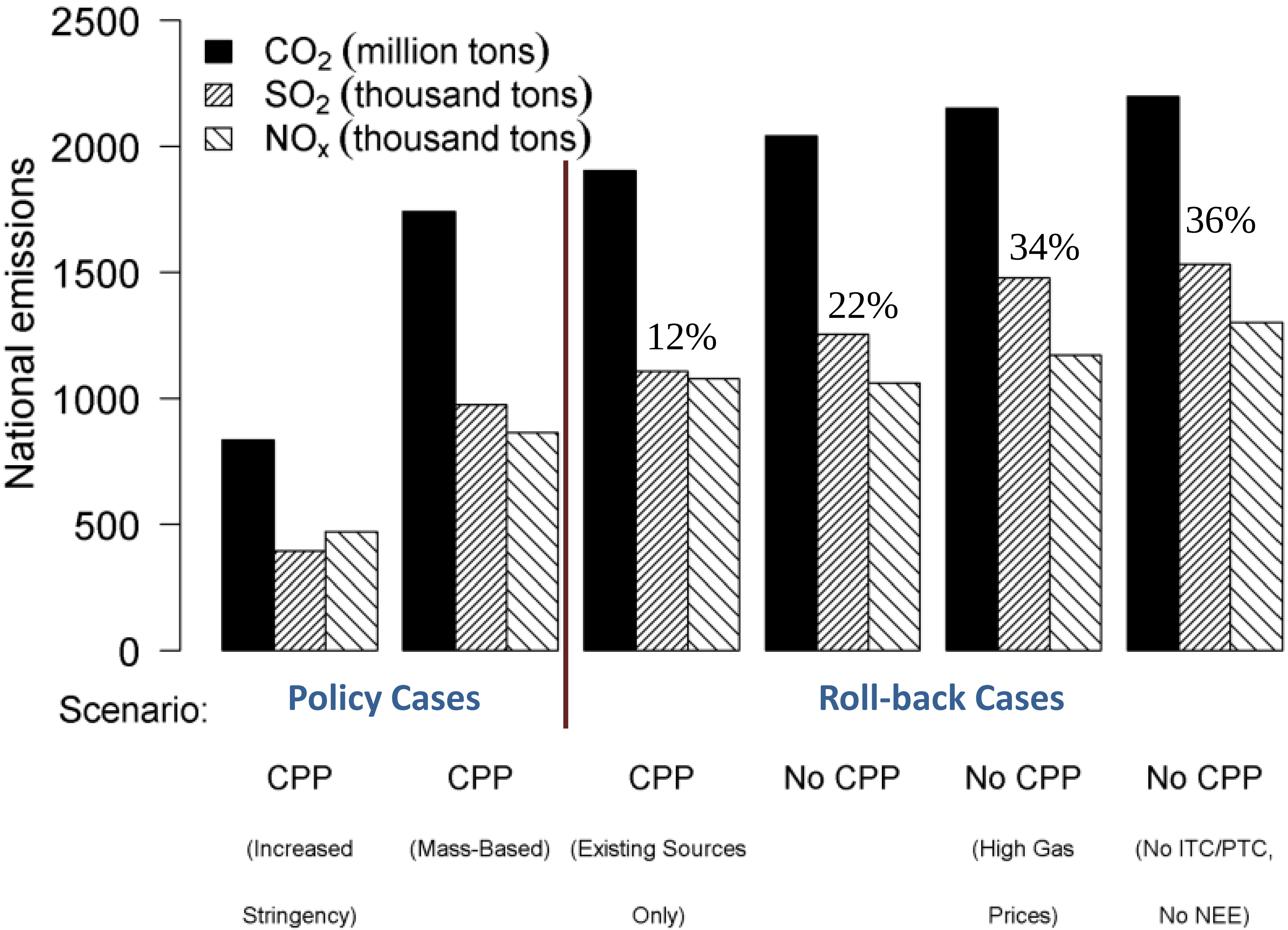
Policy Comparison



Study Take-Aways

- Carbon standards can produce large and widespread improvements in air quality and health outcomes that far exceed costs.
- But design of power plant carbon standards strongly influences the magnitude, and distribution of benefits.
- Inside the Fence line standards could generate disbenefits.
- Results demonstrate the importance of comparing full costs and benefits for a range of policy alternatives and reference cases.

Total national emissions in 2030



Take-Aways for Future Policy

1. Multi-pollutant approach illuminates emission interactions, unintended disbenefits, and policy approach with the largest benefits per ton of CO_2 reduced.

2. Scientific understanding of benefits for multiple endpoints and at various levels of exposure is increasing.

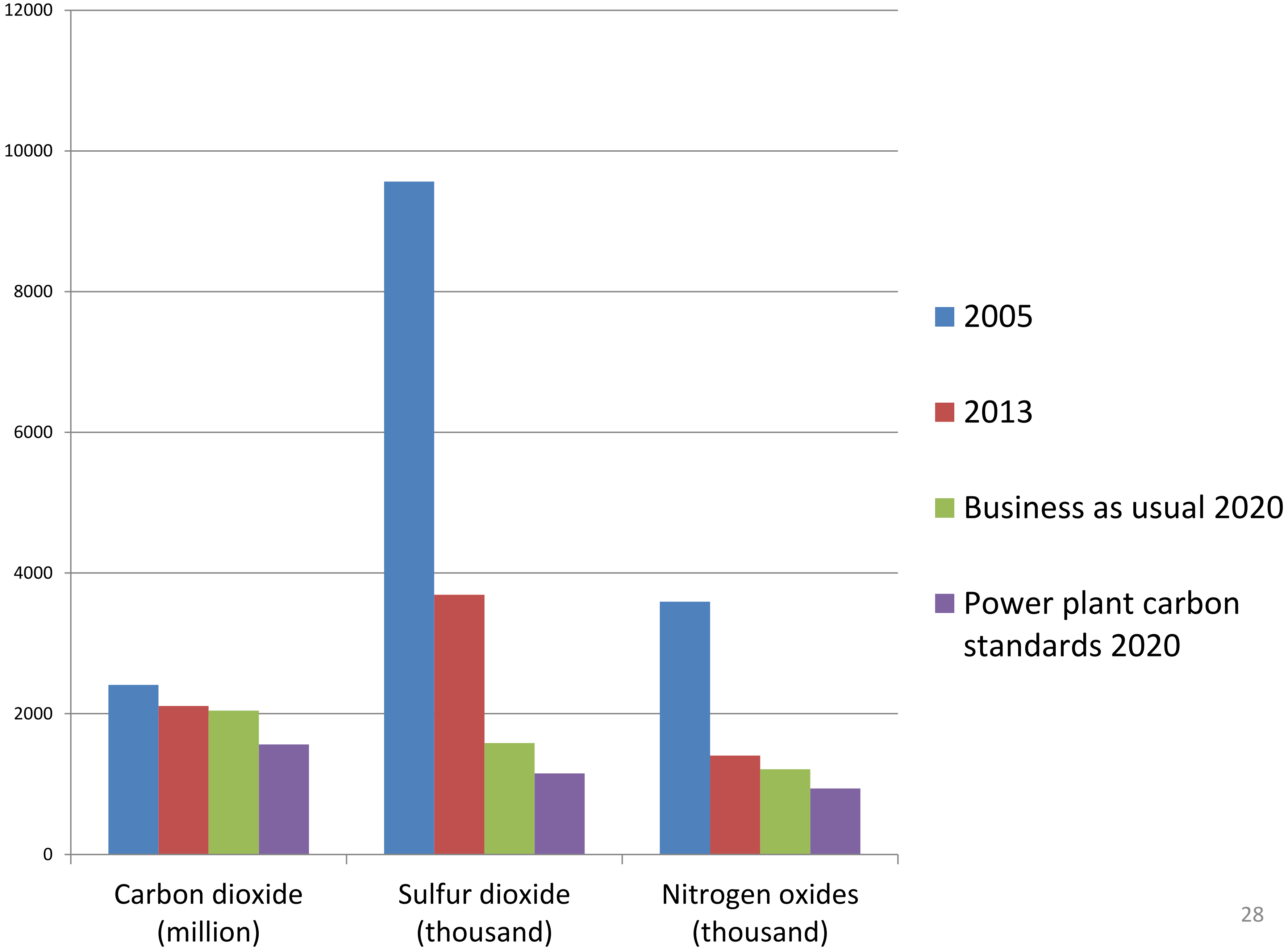
3. An RIA that under-estimates benefits could be vulnerable to overturn, weaken policy rationale perpetuate regulatory uncertainty for electricity sector.

4. Federal standard important for coherent approach to cross-boundary pollution. City/state approach important but patchwork may result; leading states currently tend to be lower emitting.

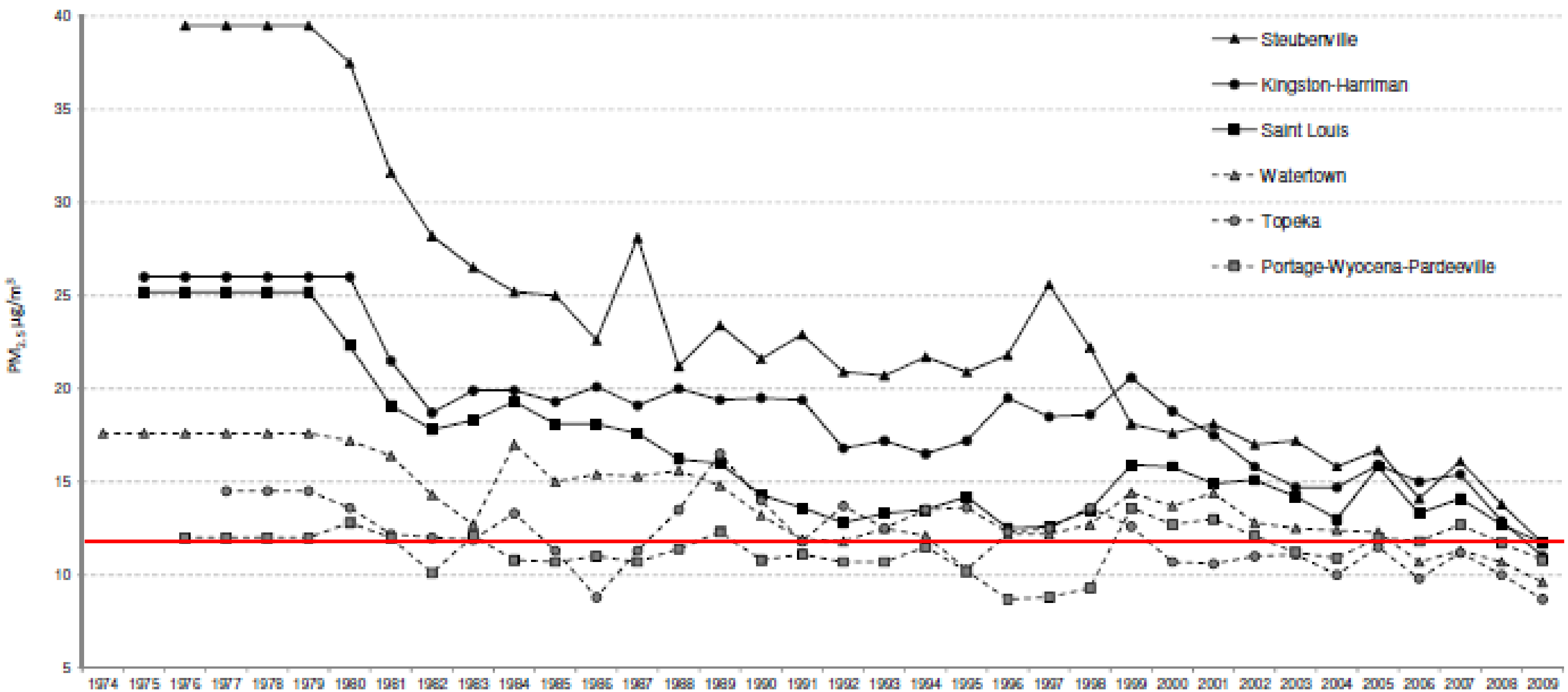
5. Need to codify acceptable practices for cost-benefit analysis with guidelines for addressing full benefits and costs.

Back Pocket

U.S. Electricity Sector Emissions (metric tons)



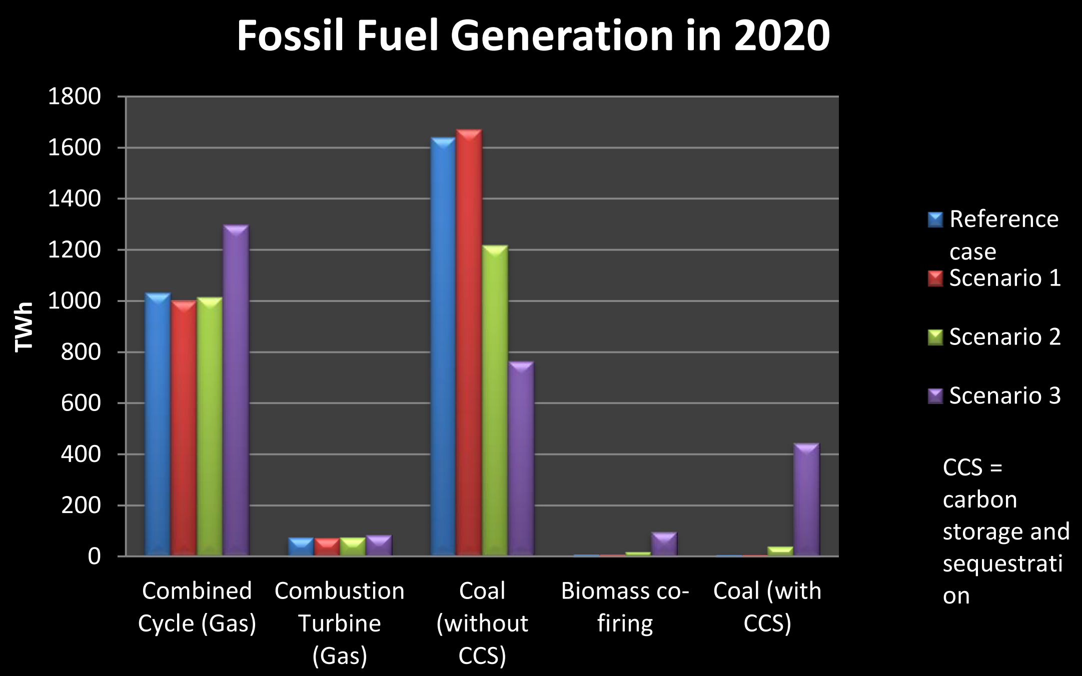
Trends in Average Annual PM2.5



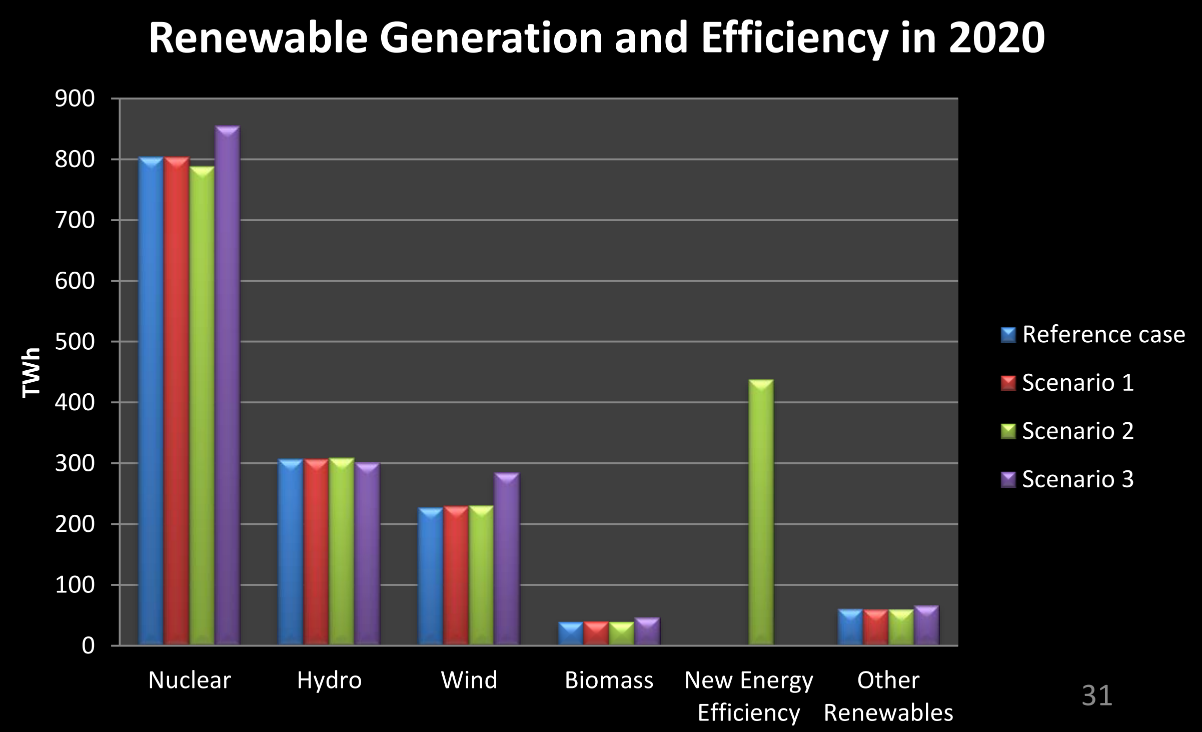
Reference case – 2013 AEO

- EIA 2013 Annual Energy Outlook determines energy demand
- Mercury and Air Toxics Standards (MATS) implemented
- Clean Air Interstate Rule implemented, including Phase II in 2015
- Regional Greenhouse Gas Initiative (RGGI) model rule for emissions trading included (w/out NJ)
- CA Assembly Bill 32 (AB32) included
- Regional haze rule included
- Wind power production tax credit (PTC) expires
- Onshore wind costs: DOE/LBL 2012 Wind Technologies Report
- Nuclear units re-licensed, 20-year extension
- existing state-level require-ments for power sector emissions reductions and renewable energy portfolio standards are implemented under this scenario

- By 2020, the reference case results in modest shifts in energy generation from 2005 and achieves an estimated 15.2% decrease in annual CO2 emissions from the electricity sector (Table 1).

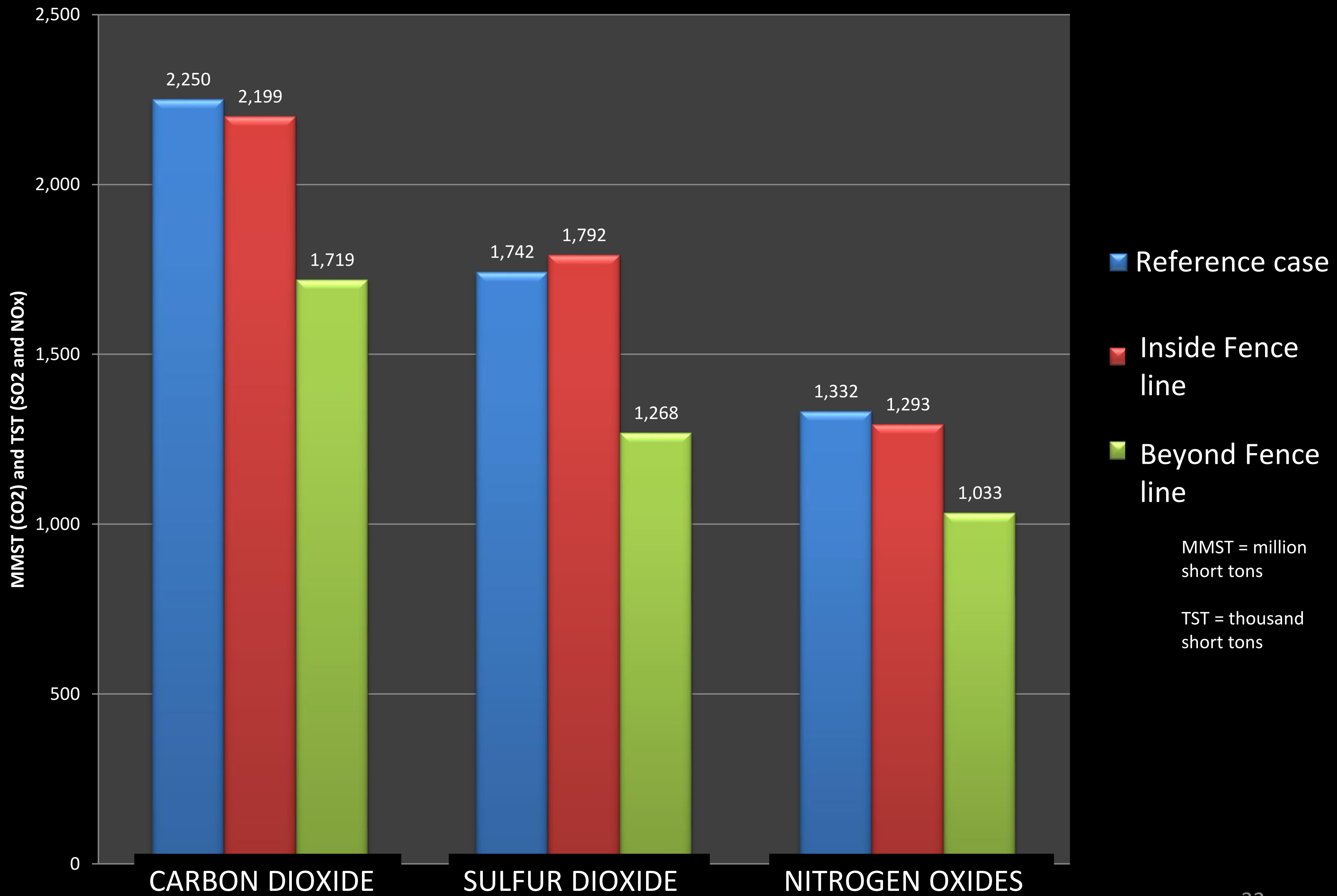


Fossil Fuel Generation in 2020
TWh
1800
1600
1400
1200
1000
800
600
400
200
0
Combined Cycle (Gas)
Combustion Turbine (Gas)
Coal (without CCS)
Biomass co-firing
Coal (with CCS)
Reference case
Scenario 1
Scenario 2
Scenario 3
CCS = carbon storage and sequestration



Renewable Generation and Efficiency in 2020
TWh
900
800
700
600
500
400
300
200
100
0
Nuclear
Hydro
Wind
Biomass
New Energy Efficiency
Other Renewables
Reference case
Scenario 1
Scenario 2
Scenario 3

Annual Power Sector Emissions in 2020



IPM

- 2417 unique power plants in the U.S.
- IPM is a dynamic power sector production cost linear optimization model for North America. It incorporates many drivers of generation and power sector demands, including wholesale power, system reliability needs, environmental limitations, fuel selection, power transmission, capacity, and operational elements of generators on the power grid, to estimate generation and resulting emissions.
- By running IPM the least-cost means of meeting electric generation energy and capacity requirements are determined, while complying with the requirements specified in each of the policy scenarios.
- The results suggest that generation mix, coal retirements, cost of electricity, and building of new generation capacity are all sensitive to varying levels to natural gas price and cost of demand-side energy efficiency.

Scenario A1: Low Stringency On-Site Rate Reductions

- Policy: coal plants are required to either
  - invest in on-site efficiency (heat rate) retrofits, OR
  - Satisfy equivalent CO2 emission rate reduction through:
    - Co-fire or convert to natural gas or biomass
    - Combination of modest plant efficiency retrofit and co-firing
  - Unit-specific HR improvement & cost based on analysis of available data
  - Coal units with on-site gas or nearby pipeline can co-fire 15% natural gas
  - Coal units can co-fire up to 15% biomass (EIA biomass supply and cost)

BPC Heat Rate Approach

First, coal units were split into categories based on the unit's capacity, fuel type, steam cycle, and boiler type. These parameters were found to be correlated with a unit's heat rate in an analysis conducted for the BPC by Andover Technology Partners. In general, within each category, the unit with the lowest heat rate set a "best-in-class" heat rate standard for the group. The best-in-class heat rates developed for the BPC modeling approach are shown in Table 1.

For BPC's simplified approach, each unit that is not best-in-class has the option to select one of two heat rate investments that would bring it closer to the best-in-class heat rate for its group. Each unit can select either a 25 percent investment option that improves its heat rate by an amount that closes the gap between its unit-specific heat rate and the best-in-class heat rate by 25 percent or a 40 percent investment option that closes the gap by 40 percent.

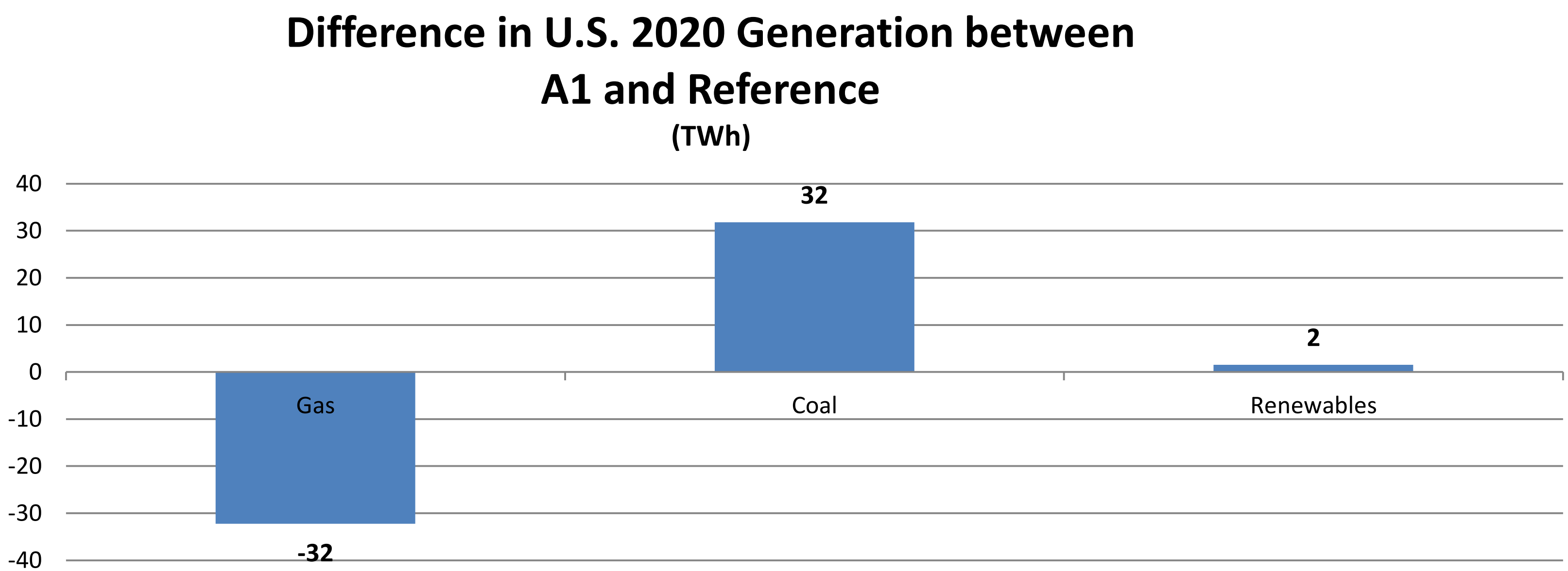
Heat rate data is derived from NEEDS v.4.10.

	Subcritical				Supercritical
Capacity in MW	Bituminous	Subbituminous	Lignite	CFB	
MW <100	9,792	10,000	*	10,000	*
100 ≤ MW <200	9,290	9,633	*	9,497	*
200 ≤ MW < 500	8,763	8,763	9,243	8,763	8,687
MW ≥500	8,518	8,763	8,763	**	8,518

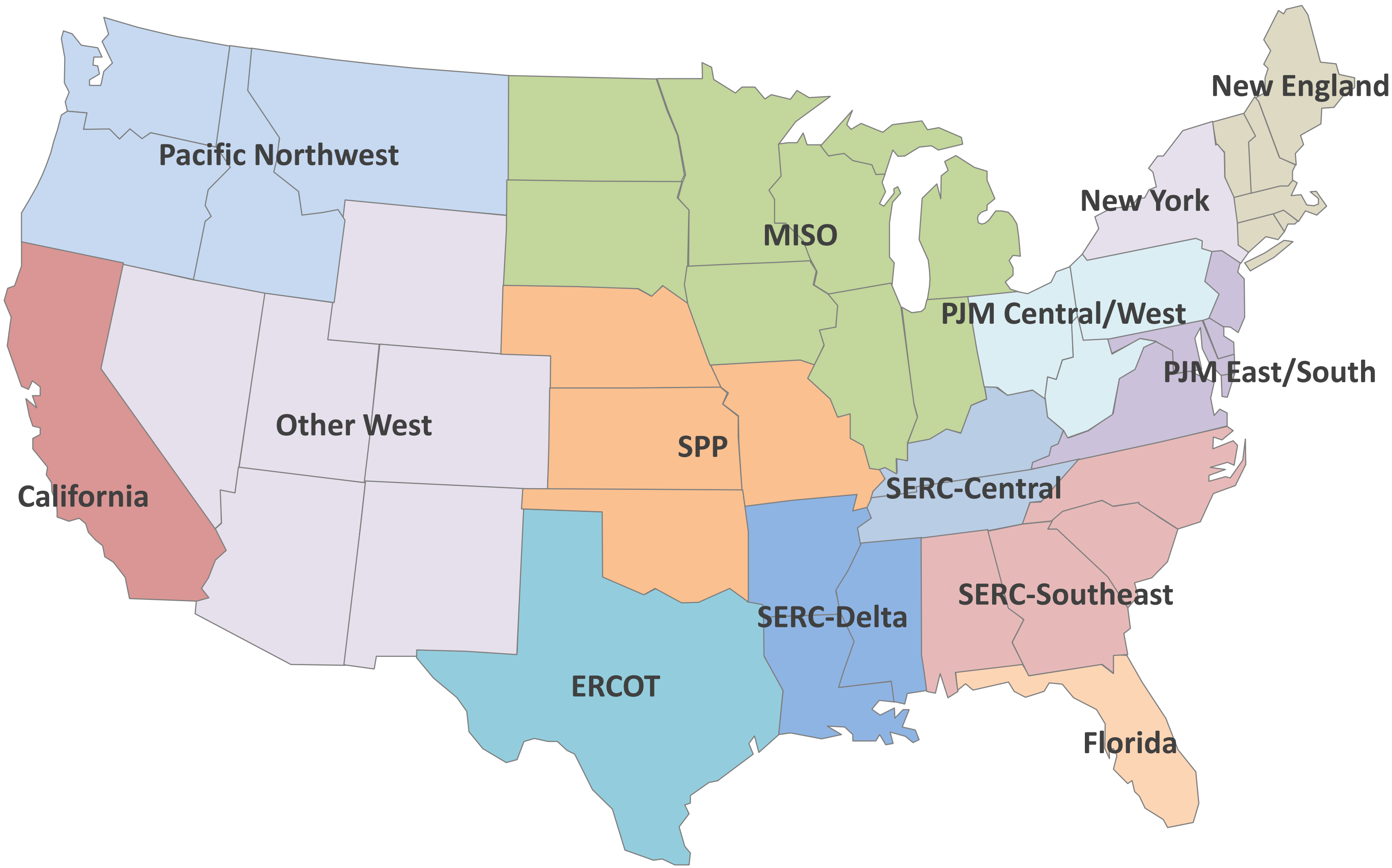
***There are not enough supercritical or lignite units under 200 MW to establish a best-in-class category. **There are no CFB units larger than 500 MW.**

A1: low stringency scenario has modest changes from reference case

- 0.8% increase in generation from coal
  - Plant efficiency upgrades = more electricity generated per coal burned
- 0.8% decrease in gas generation
  - Plant upgrades at coal units allow them to better compete with gas
- Slightly fewer coal retirements (2 GW)
- Total US generation in 2020 projected to be 4212 TWh



Illustrative Map of Key States in Reporting Regions

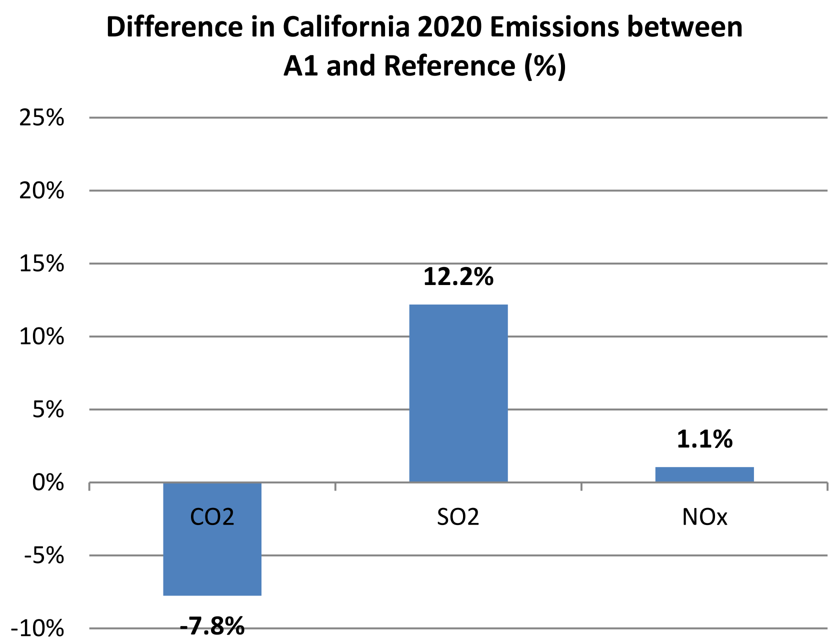


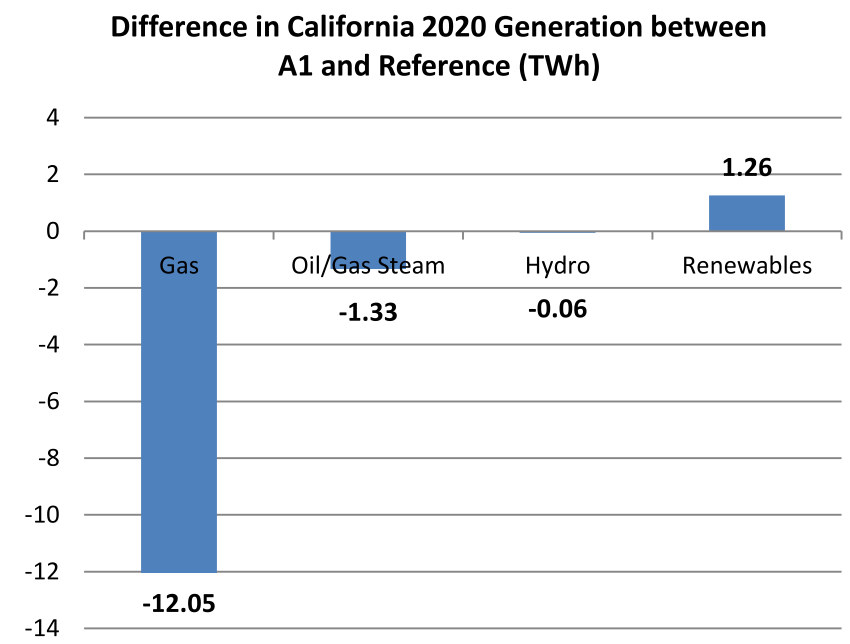
*SERC-Gateway covers a portion of Illinois, Iowa, and Missouri.

Note: This map shows groups of states that approximate the aggregate reporting regions. Actual regions cross state lines in many instances. This map is illustrative and does not show exact regional boundaries.

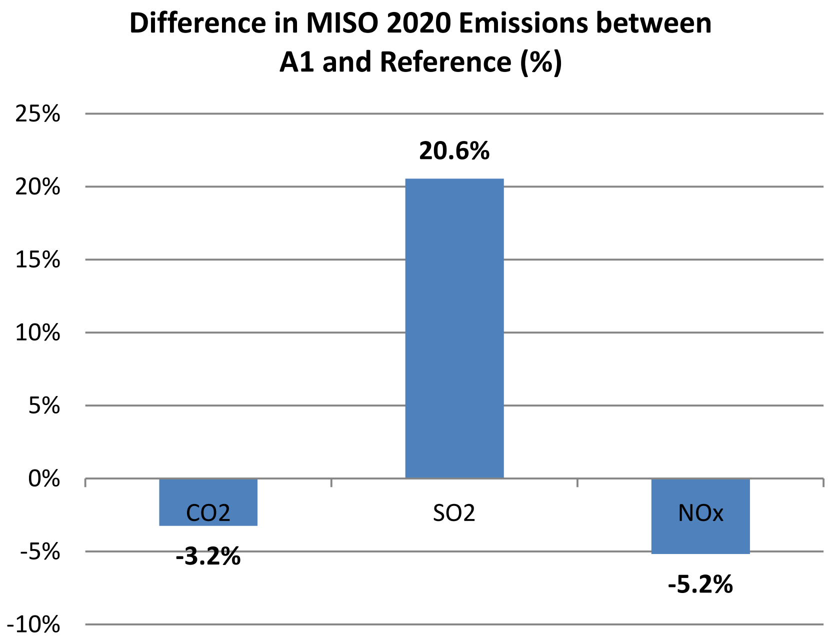
Percent Change in 2020 Emissions between A1 and Reference

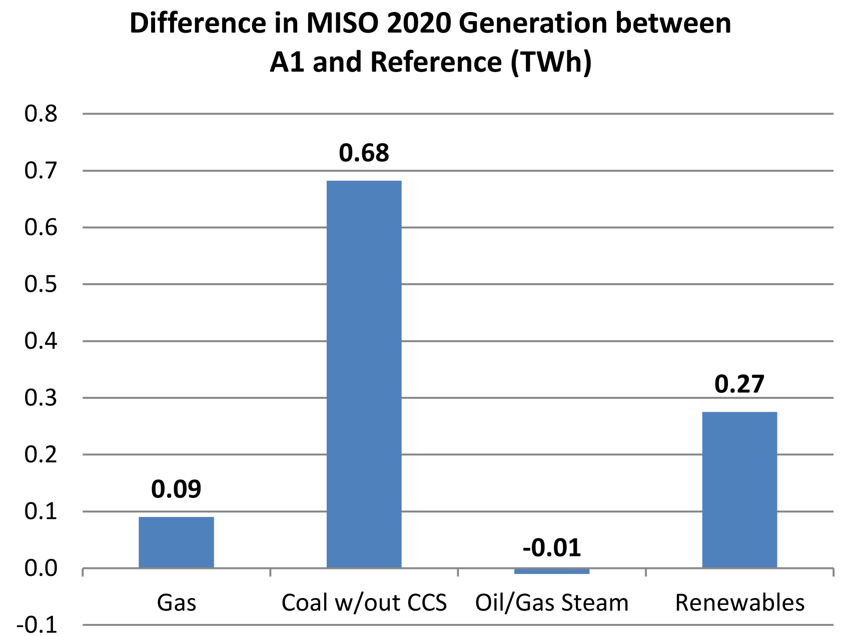
	CO_2	SO_2	NO_x
California	-7.8%	12.2%	1.1%
ERCOT	-0.2%	4.6%	-0.1%
FRCC	0.1%	4.7%	-3.1%
ISONE	-2.7%	-7.9%	-2.8%
MISO	-3.2%	20.6%	-5.2%
NYISO	-4.6%	-8.5%	-4.7%
OTHERWES	-1.6%	-3.6%	-1.2%
PJMC	-2.7%	-2.5%	-1.6%
PJME	-3.9%	-7.6%	-3.2%
PNW	0.9%	1.6%	-10.4%
SERCC	-3.5%	-1.9%	-2.7%
SERCD	-2.2%	-2.2%	-2.2%
SERCG	-0.4%	-4.5%	-0.1%
SERCSE	-1.2%	0.8%	0.5%
SPP	-2.7%	-3.9%	-5.1%
US	-2.2%	2.8%	-2.9%





The apparent significant % increase in SO_2 is actually a function of very low SO_2 emissions (no coal) which increase with biomass generation





Dispatch changes w/in the coal fleet, due to changing costs after efficiency upgrades, are likely cause of seemingly contradictory emissions results

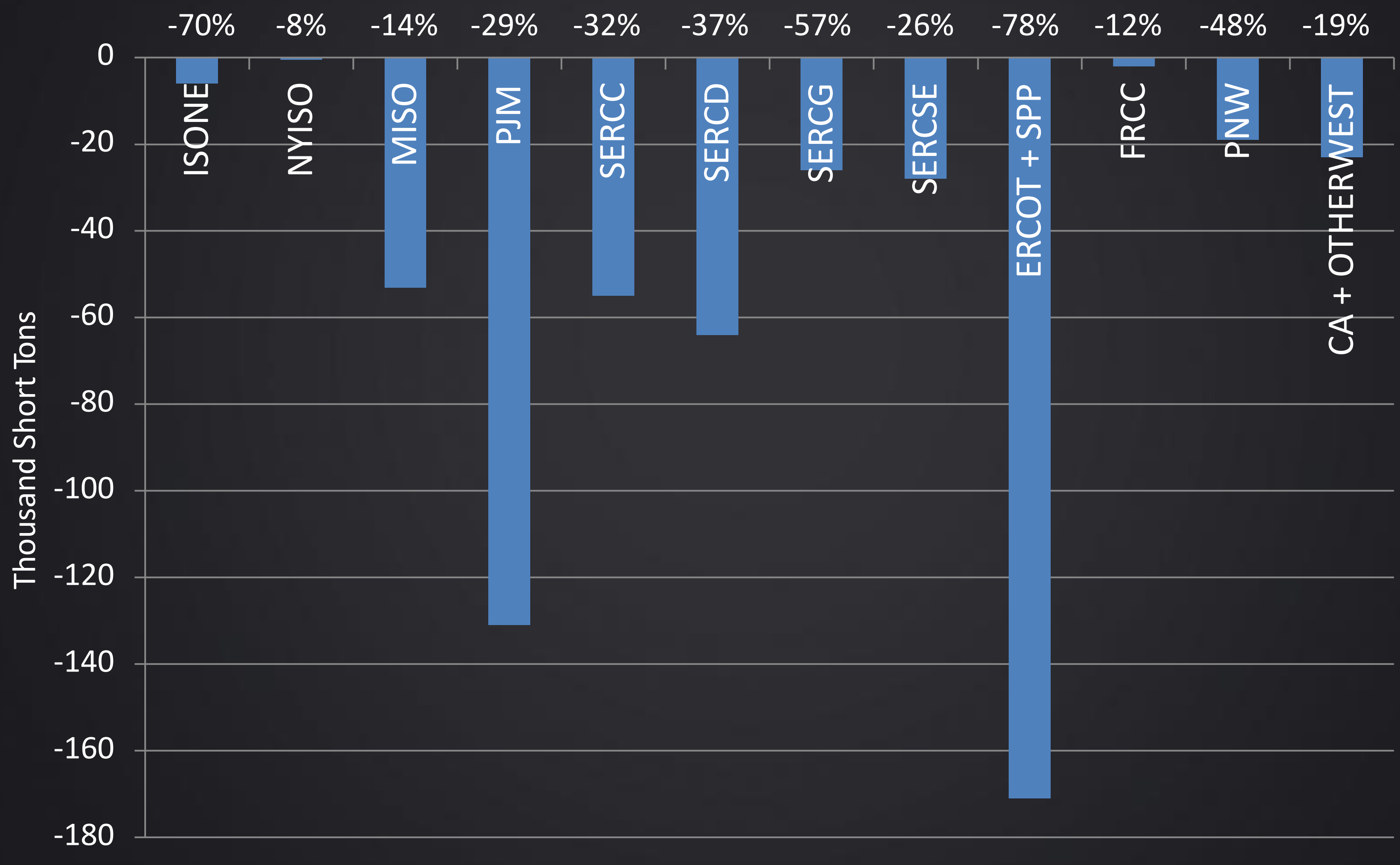
MISO = IA, IL, IN, MI, MN, MO, MT, ND, NE, OH, SD, WI

A1 coal plant retirements, 2014-2020: 5 GW

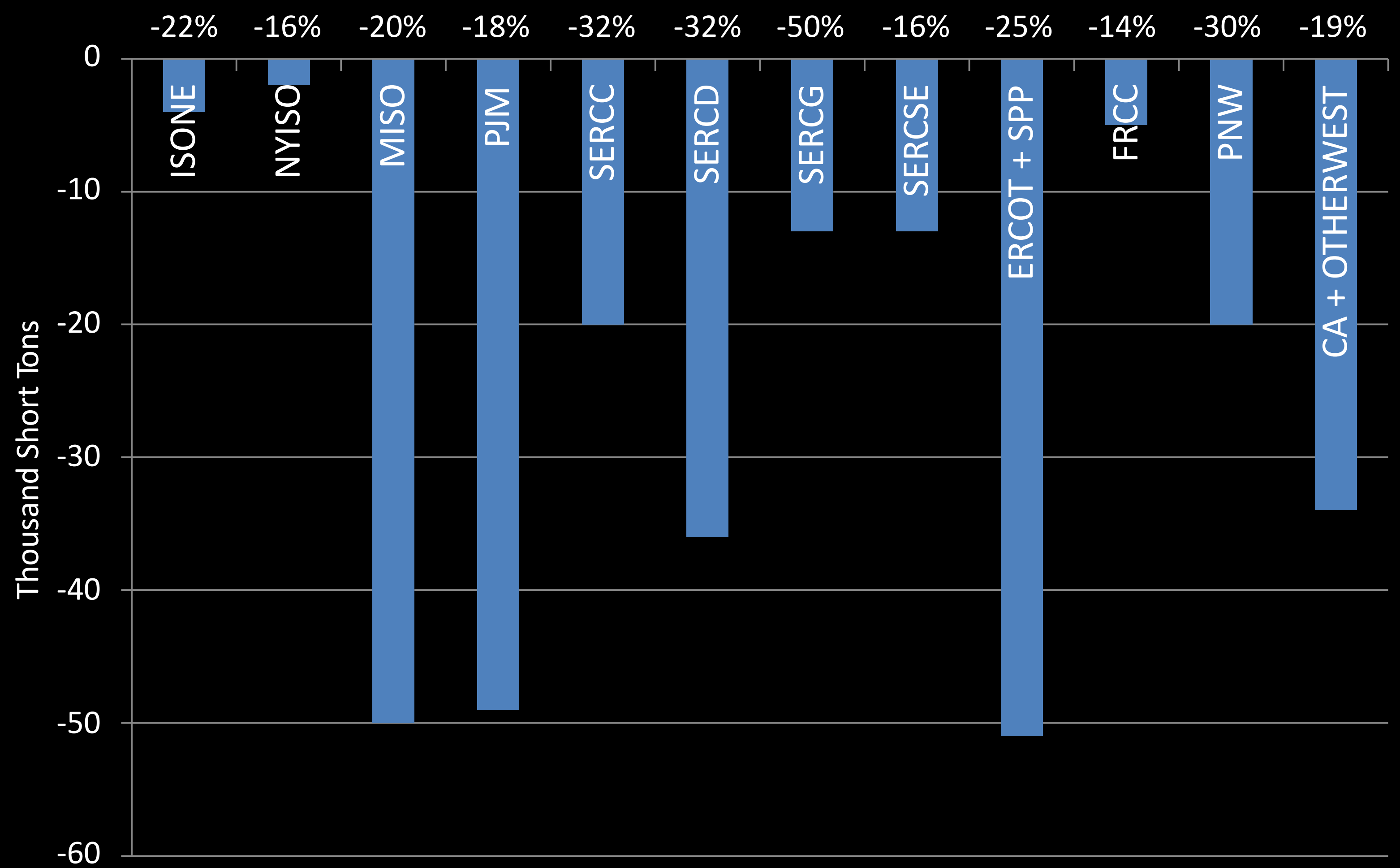
A1 heat rate upgrades, 2014-2020: 41 GW

Scenario 2: Beyond Fence line

REGIONAL SO2 EMISSION REDUCTIONS IN 2020

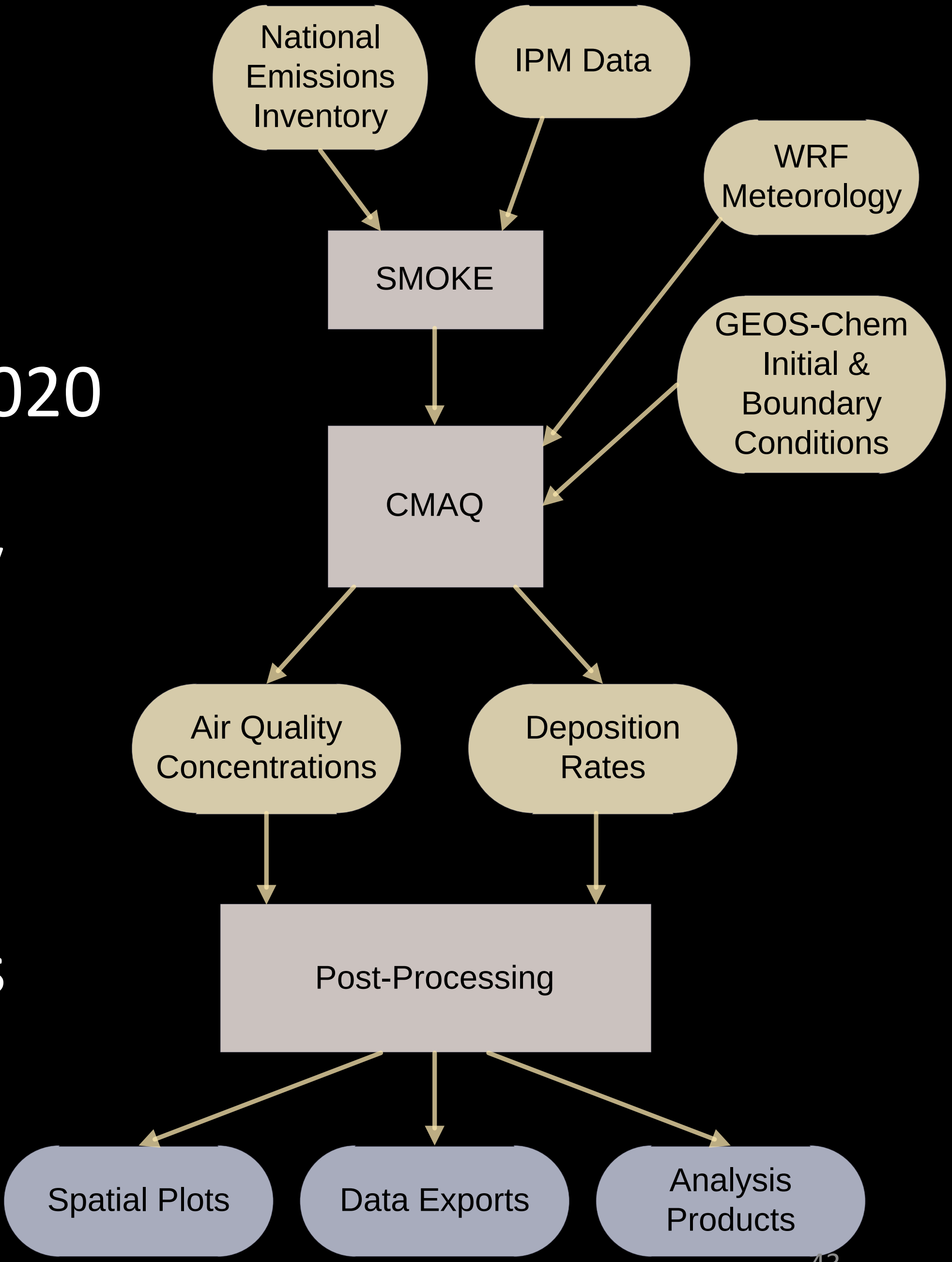


Scenario 2: Beyond Fence line



CMAQ Details

- CMAQ v4.7.1
- Based on EPA's 2007/2020 Modeling Platform
- Year 2007 meteorology from WRF v3.1 – held constant
- CB05 gas chemistry AE5 aerosol chemistry
- Multi-pollutant options engaged for mercury chemistry



Analysis Details

- 4 CMAQ Simulations
  - 2020 reference case
  - 3 future year (2020) emissions policy scenarios
- Processes simulated
  - Emissions, advection, diffusion, chemistry, deposition
- Gridded air quality concentrations and deposition rates on a 12-km CONUS domain

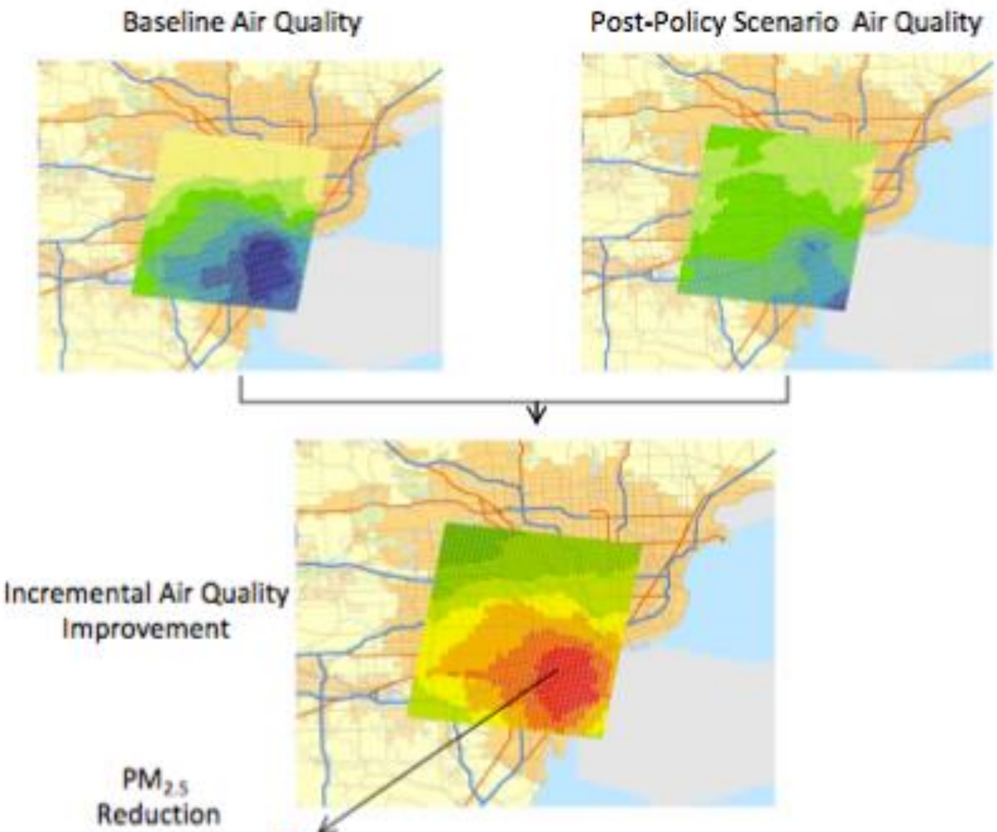
CMAQ Modeling Grid

12-km grid cell resolution

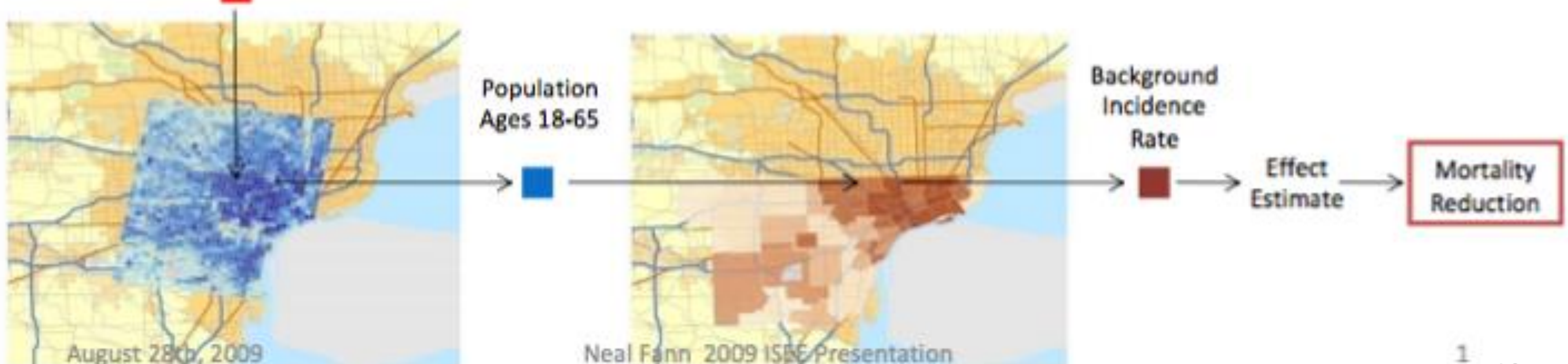
396 x 246 grid cells

BenMap

- We used BenMAP CE v1.0.8, published by the U.S. EPA (USEPA, Office of Air and Radiation, n.d.).
- BenMAP CE is a Geographic Information System (GIS)-based software tool designed for calculating the health co-benefits of air quality management scenarios. BenMAP contains data on population, demographics, and incidence and prevalence rates of health outcomes.
- We used BenMAP, with 2020 population and baseline health incidence and prevalence rates in conjunction with concentration-response functions we developed and the CMAQ results to estimate the health co-benefits of the three policy scenarios.
- We use the valuation module in BenMAP CE v1.1 with default methods and values to estimate the economic value of the co-benefits at county, power region, and national scales.



BenMAP – Community Edition v1.08
Model year 2020
- 2020 CMAQ model year
- Default 2020 population estimates, baseline disease incidence, valuation, pooling



Health Effects in U.S. (2005)

PM2.5

- 180,000 non-fatal heart attacks
- 200,000 hospital admissions and emergency room visits
- 2.5 million asthma exacerbations
- 18 million lost days of work, and other public health effects in the U.S.
- 130,000 or 320,000 premature deaths in 2005 depending on study

Ground-level ozone

- 77,000 hospital admissions and emergency room visits
- 11 million school absence days
- 4,700 or 19,000 premature deaths depending on the study

Fann et al. 2012

Roman Expert Elicitation

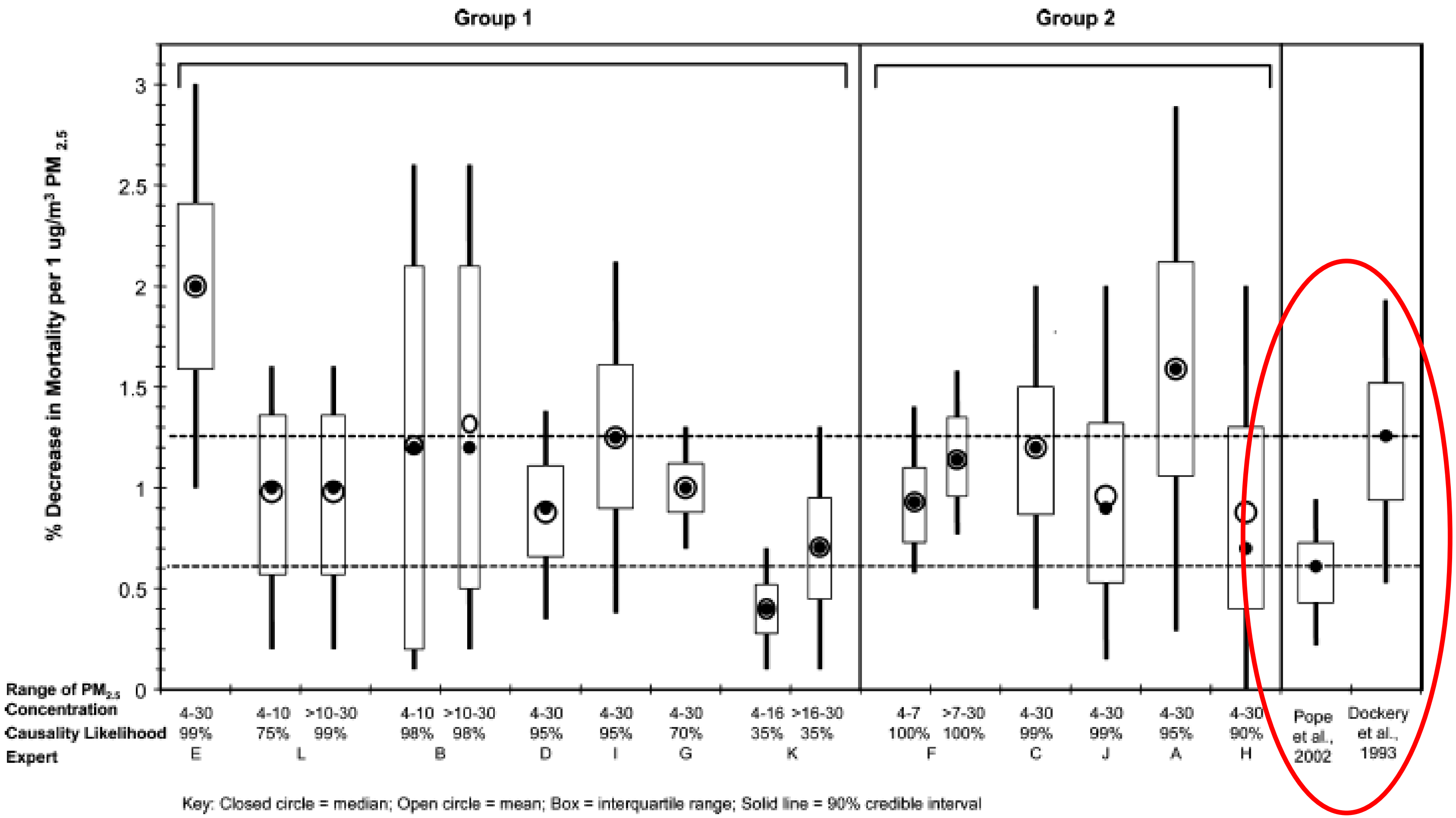


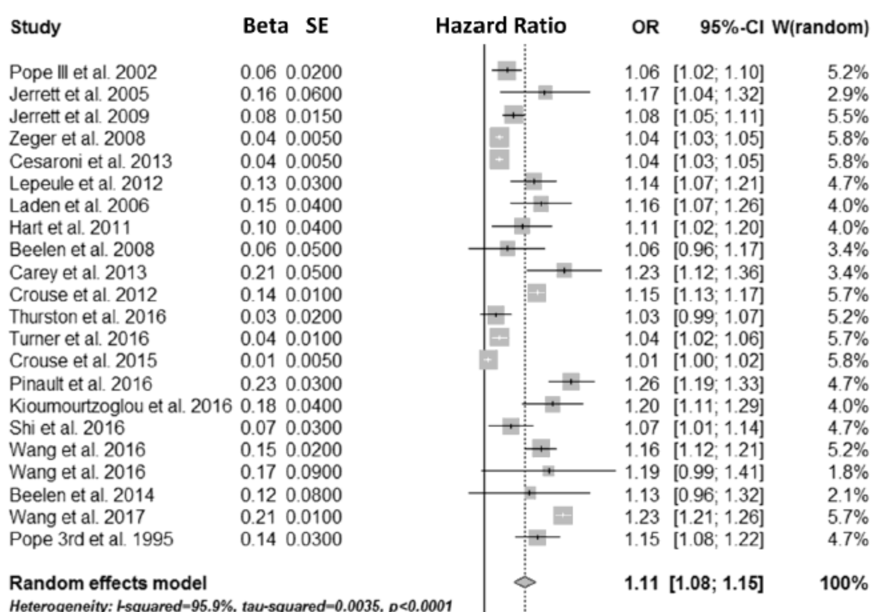
FIGURE 3. Uncertainty distributions for the $PM_{2.5}$—mortality *C—R* coefficient for annual average $PM_{2.5}$ concentrations of 4—30 $\mu g/m^3$
Note: Box plots represent distributions as provided by the experts to the elicitation team. Experts in group 1 preferred to give conditional distributions and keep their probabilistic judgment about the likelihood of a causal or noncausal relationship separate. Experts in group 2 preferred to give distributions that incorporate their likelihood that the $PM_{2.5}$—mortality association may be noncausal. Therefore, the expert distributions from these two groups are not directly comparable.

Source	Health Endpoint	Age Group	Total Central Estimate (medical + opportunity costs)
Dockins et al. 2004	Mortality	25-99	$6,985,000
Eisenstein et al. 2001; Cropper and Krupnick, 2000	Acute Myocardial Infarction	18-65	$63,057 - $155,668
Eisenstein et al. 2001; Cropper and Krupnick, 2000	Acute Myocardial Infarction	25-44	$73,928
Eisenstein et al. 2001; Cropper and Krupnick, 2000	Acute Myocardial Infarction	45-54	$79,079
Eisenstein et al. 2001; Cropper and Krupnick, 2000	Acute Myocardial Infarction	55-64	$155,668
Eisenstein et al. 2001; Cropper and Krupnick, 2000	Acute Myocardial Infarction	65-99	$49,651
HCUP 2007	Hospital Admissions, All Respiratory	65-99	$27,116
HCUP 2007	Hospital Admission, All Cardiovascular	65-99	$32,314

NEJM Results

Table 2. Risk of Death Associated with an Increase of 10 μg per Cubic Meter in $PM_{2.5}$ or an Increase of 10 ppb in Ozone Concentration.*

Model	$PM_{2.5}$	Ozone
	hazard ratio (95% CI)	
Two-pollutant analysis		
Main analysis	1.073 (1.071–1.075)	1.011 (1.010–1.012)
Low-exposure analysis	1.136 (1.131–1.141)	1.010 (1.009–1.011)
Analysis based on data from nearest monitoring site (nearest-monitor analysis)†	1.061 (1.059–1.063)	1.001 (1.000–1.002)
Single-pollutant analysis‡	1.084 (1.081–1.086)	1.023 (1.022–1.024)



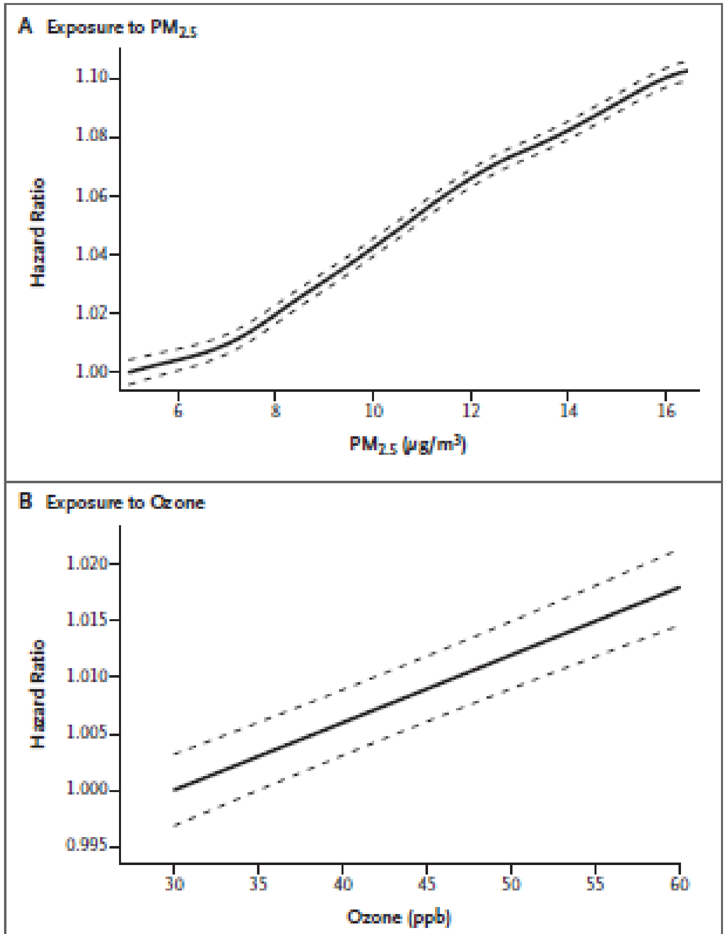


Figure 3. Concentration–Response Function of the Joint Effects of Exposure to $PM_{2.5}$ and Ozone on All-Cause Mortality.

A log-linear model with a thin-plate spline was fit for both $PM_{2.5}$ and ozone, and the shape of the concentration-response surface was estimated (Fig. S8 in the Supplementary Appendix). The concentration–response curve in Panel A was plotted for an ozone concentration equal to 45 ppb. The concentration–response curve in Panel B was plotted for a $PM_{2.5}$ concentration equal to 10 μg per cubic meter. These estimated curves were plotted at the 5th and 95th percentiles of the concentrations of $PM_{2.5}$ and ozone, respectively. The complete concentration–response three-dimensional surface is plotted in Fig. S8 in the Supplementary Appendix.

We also found that our results were robust equation as opposed to mixed effects) (Tables S3 and S4 in the Supplementary Appendix), and when we used different types of statistical software (R, version 3.3.2, vs. SAS, version 9.4). Finally, we found that our results were consistent with others published in the literature (Section 6 in the Supplementary Appendix).[5,17,24-28]

There was a significant association between $PM_{2.5}$ exposure and mortality when the analysis was restricted to concentrations below 12 μg per cubic meter, with a steeper slope below that level. This association indicated that the health-benefit-per-unit decrease in the concentration of $PM_{2.5}$ is larger for $PM_{2.5}$ concentrations that are below the current annual NAAQS than the health benefit of decreases in $PM_{2.5}$ concentrations that are above that level. Similar, steeper concentration-response curves at low concentrations have been observed in previous studies.[29] Moreover, we found no evidence of a threshold value — the concentration at which $PM_{2.5}$ exposure does not affect mortality — at concentrations as low as approximately 5 μg per cubic meter (Fig. 3); this finding is similar to those of other studies.[18,30]

The current ozone standard for daily exposure is 70 ppb; there is no annual or seasonal standard. Our results strengthen the argument for establishing seasonal or annual standards. Moreover, whereas time-series studies have shown the short-term effects of ozone exposure, our results indicate that there are larger effect sizes for longer-term ozone exposure, including in locations where ozone concentrations never exceed 70 ppb. Unlike the American Cancer Society Cancer Prevention Study II,[9,10] our study reported a linear connection between ozone concentration and mortality. This finding is probably the result of the interaction between $PM_{2.5}$ and ozone (Section 7 in the Supplementary Appendix). The significant, linear relationship between seasonal ozone levels and all-cause mortality indicates that current risk assessments,[31-33] which incorporate only the acute effects of ozone exposure on

Costs

- We use the IPM output to develop three partial equilibrium cost cases to compare with the partial equilibrium co-benefit estimates.

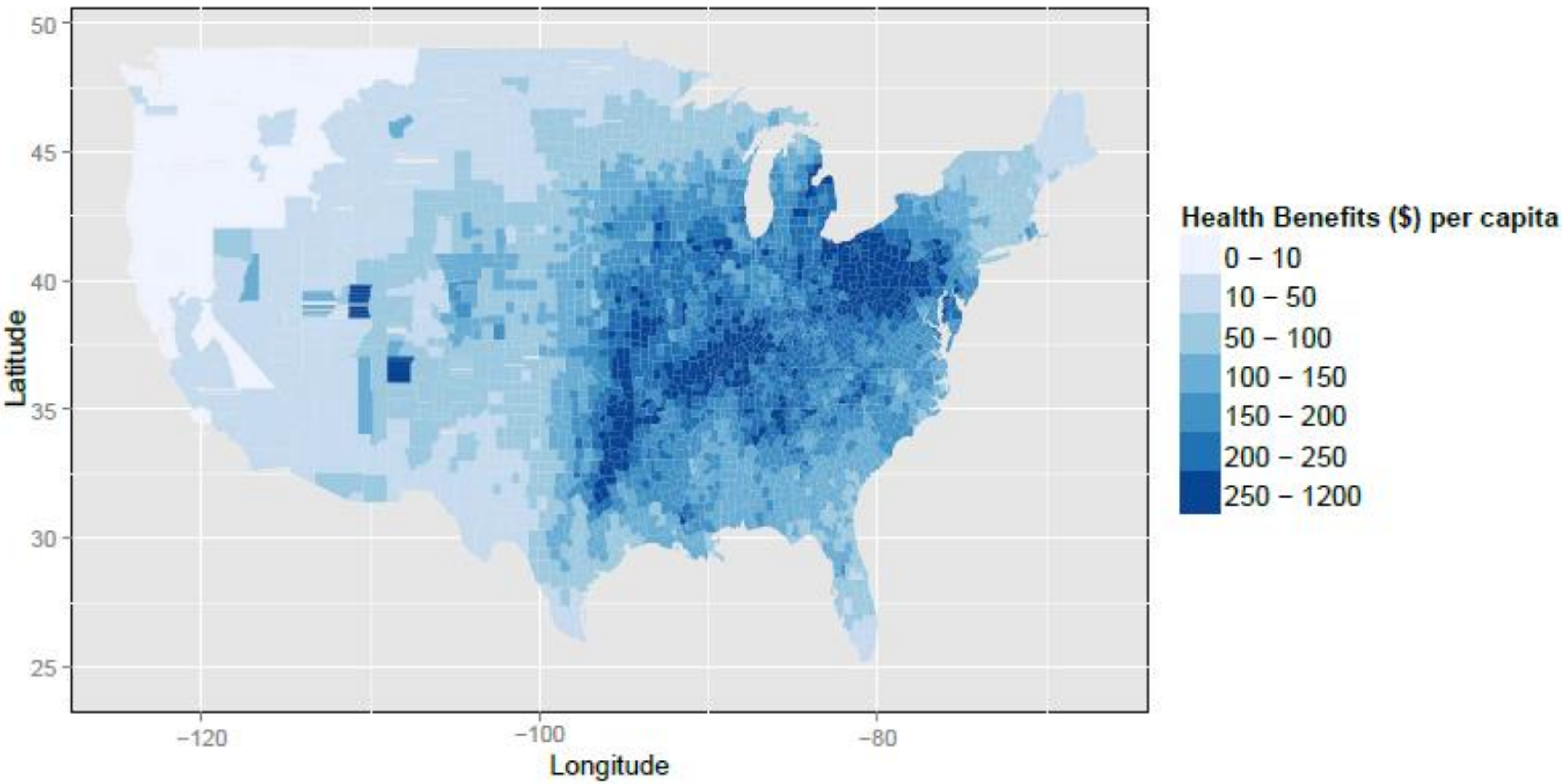
- Our measure of costs includes capital, operations and maintenance for generation and investments in energy efficiency and assumes a default real interest rate of 4.77% for all expenditures.

- The costs for capital and operations and maintenance are the same in each of the three cost cases because generation is the same. Uncertainty arises in how to account for the costs of energy efficiency, and we explore three options.

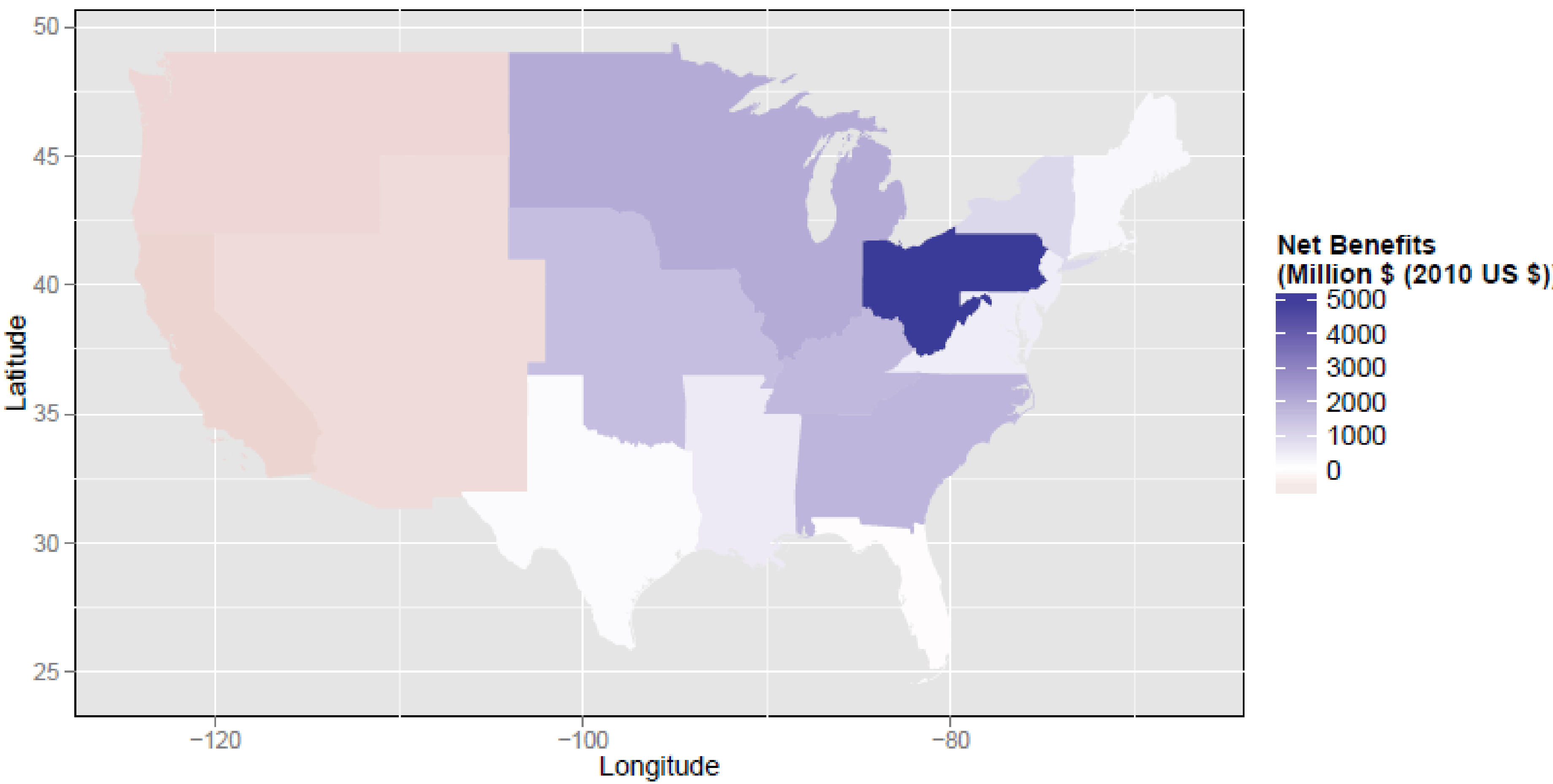
s, costs, and net co-benefits by cost case for U.S. and IPM regions in 2020 (million 2010 USD). A
cant figures, so net co-benefits may not sum perfectly.

	Lower cost case: All Costs Annualized		Central cost case: Annualized Program Costs, Overnight Consumer Costs		Upper cost case: All Costs Overnight	
o-benefits	Cost	Net Co-Benefits (95% CI)	Cost	Net Co-Benefits (95% CI)	Cost	Net Co-Benefits (95% CI)
2,300–68,000)	-450	30,000 (2,700–69,000)	17,000	12,000 (-15,000–51,000)	39,000	-10,000 (-37,000–2
1,100)	360	110 (-330–760)	1,400	-960 (-1,400–-310)	2,700	-2,300 (-2,700–-1,6
50–4,500)	170	1,800 (-14–4,400)	1,800	100 (-1,700–2,700)	3,800	-1,900 (-3,700–690
2,100)	-140	1,000 (210–2,300)	960	-56 (-880–1,200)	2,300	-1,400 (-2,200–-17
2,100)	220	660 (-150–1,900)	690	190 (-630–1,400)	1,300	-390 (-1,200–810)
40–13,000)	140	5,500 (290–13,000)	3,600	2,100 (-3,100–9,700)	7,800	-2,100 (-7,300–5,5
20–3,700)	110	1,400 (5.7–3,600)	610	950 (-490–3,100)	1,200	350 (-1,100–2,500)
2,300)	740	220 (-660–1,500)	1,800	-820 (-1,700–480)	3,100	-2,100 (-3,000–-80
20–13,000)	-1,600	7,100 (2,100–14,000)	310	5,100 (110–13,000)	2,700	2,700 (-2,300–10,0
30–7,000)	890	2,100 (-660–6,100)	2,500	440 (-2,300–4,500)	4,500	-1,500 (-4,300–2,5
130)	320	-260 (-320–-190)	980	-920 (-970–-850)	1,800	-1,700 (-1,800–-1,6
30–4,000)	-930	2,600 (1,100–4,900)	-26	1,700 (160–4,000)	1,100	610 (-950–2,900)
00–3,000)	-120	1,400 (220–3,100)	790	490 (-690–2,200)	1,900	-620 (-1,800–1,100
60–7,700)	-570	3,900 (830–8,300)	1,500	1,800 (-1,200–6,200)	4,000	-760 (-3,800–3,700
60–4,700)	11	2,000 (150–4,700)	450	1,600 (-290–4,300)	990	1,000 (-830–3,700)

$ Health Co-benefits



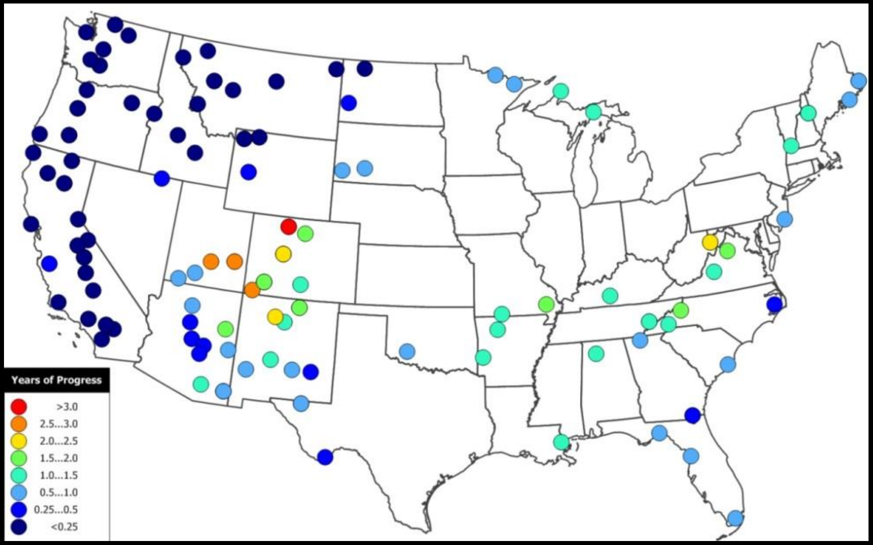
Net Benefits by Region

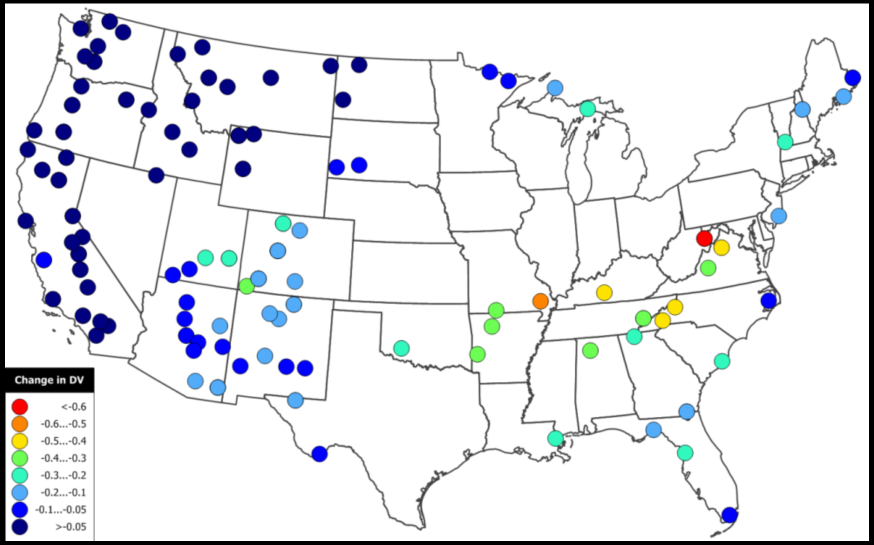


Tree & Crop Results

- Map of change in W126 – Reference case, scenario 2
- Table showing : Initial productivity decrease and Reduction in productivity decrease for specific species
- Corn = Reference case PPL = 1.5%; 15.6% decrease in productivity losses from reference case in 2020
- Soybean = Reference case PPL = 1.64%; 8.4% decrease in productivity losses (PPL) from reference case in 2020
- Eastern cottonwood = Reference case PPL = 32%; 8.4%decrease in productivity losses from reference case in 2020
- Black cherry = Reference case PPL = 10%; 7.6% 8.4%decrease in productivity losses from reference case in 2020

Visibility Benefits





Emissions Comparison

			NCC Study				2015				2017	
Series	Unit	2005	2020 No CPP	Scenario 2	No CPP-Scenario 2	CPP	No CPP	No CPP - CPP	Percent change	CPP	No CPP	No CPP - CPP
Coal generation	Thousand GWh					1,126	1,443	317		1,024	1,422	398
Gas generation	Thousand GWh					1,340	1,411	71		1,499	1,344	-155
Renewables generation	Thousand GWh					850	821	-29		1,114	1,031	-83
Total generation	Thousand GWh					4,110	4,467	357		4,442	4,603	161
Henry Hub Nat gas price	2016$/MMBtu					6.32	6.41	0.10		5.00	4.86	-0.14
CO2 emissions	Million short tons	2410	2045	1562	483	1,814	2,227	413	0	1,694	2,078	384
SO2 emissions	Thousand short tons	9563	1584	1152	432	1,034	1,314	280		934	1,357	423
NOx emissions	Thousand short tons	3592	1210	938	272	1,015	1,293	278		854	1,109	255
Note:	Renewables include hydro.											
Sources:	2015 RIA: https://19january2017snapshot.epa.gov/sites/production/files/2015-08/documents/cpp-final-rule-ria.pdf											
	2017 AEO: https://www.eia.gov/outlooks/aeo/tables_side.php											

PMD Avoided

- Our analysis (2013 AEO)
  - Upper bound = 0.013 deaths per ton SO2 averted
  - Central measure 3500
    - (0.008 deaths per ton SO2 averted)
  - 95% confidence interval 780 to 6100)
- Final CPP (2015 AEO)
  - 1500 to 3530
    - Upper bound = 0.011 deaths per ton SO2 averted
- Repeal (2017 AEO)
  - 1900 to 4500 (all concentrations)
    - Upper bound = 0.014 deaths per ton SO2 averted
    - Mid-point = 3200 (0.01 per ton SO2 averted)
  - 1800 to 2400 (zero below LML of 5.8)
    - Upper bound = 0.0075
  - 140 to 450 (zero below NAAQS)

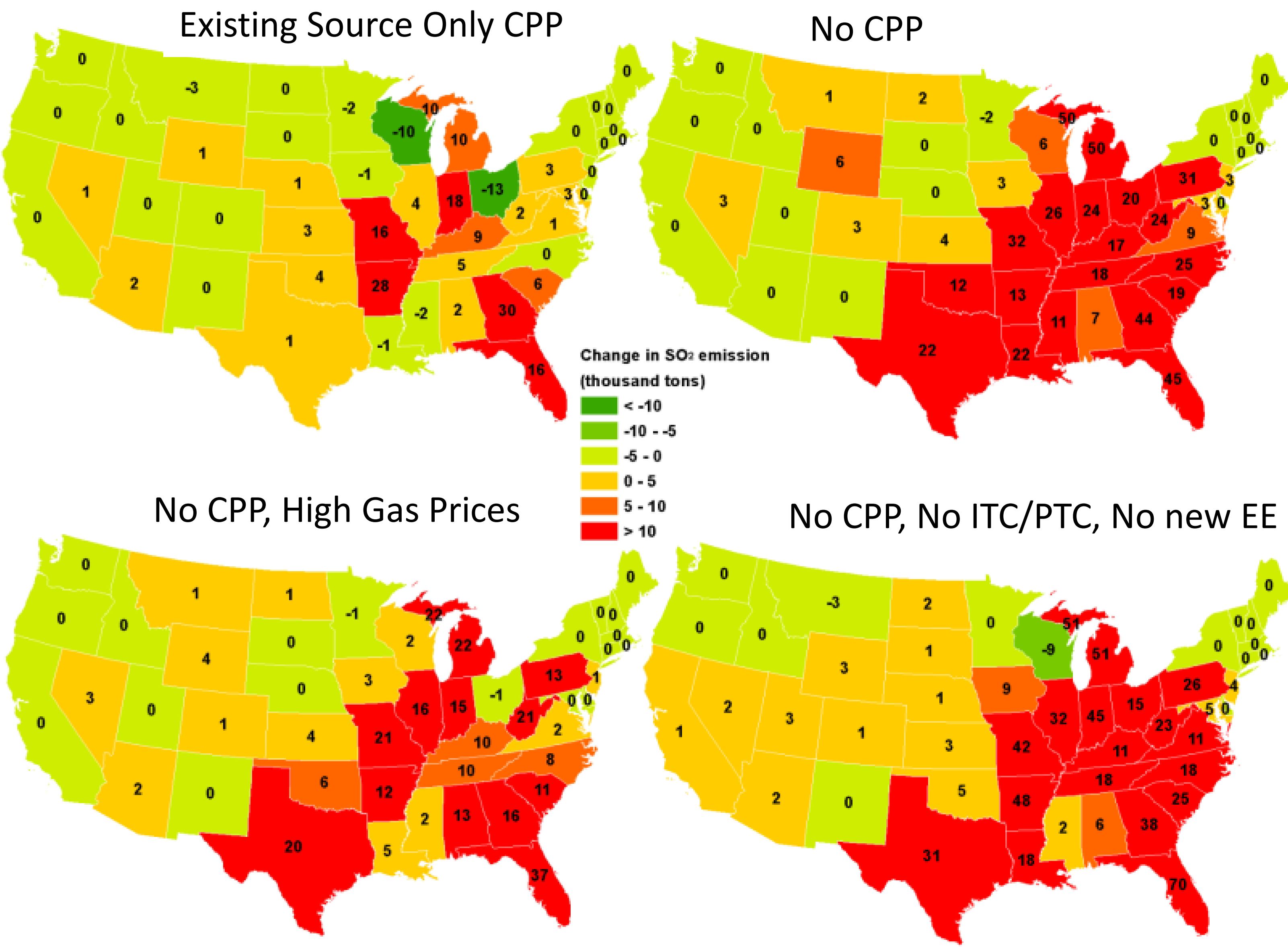
Change in projected NO_X emissions (in 2030) from CPP implementation scenarios to potential rollback scenarios (thousand short tons) (positive values indicate increased emission from the CPPs (i.e., rows) to the rollback (i.e., columns) scenarios)

Reference Cases	Initials	CPP Existing sources only (PC06)	No CPP - Reference (G1)	No CPP – High gas (G1c)	No CPP, No ITC/PTC, no incremental EE (RC0)
		1081	1063	1174	1300
CPP mass based (banking) (G4f)	866	215	197	308	434
CPP with increased stringency (G5a)	472	609	592	703	829

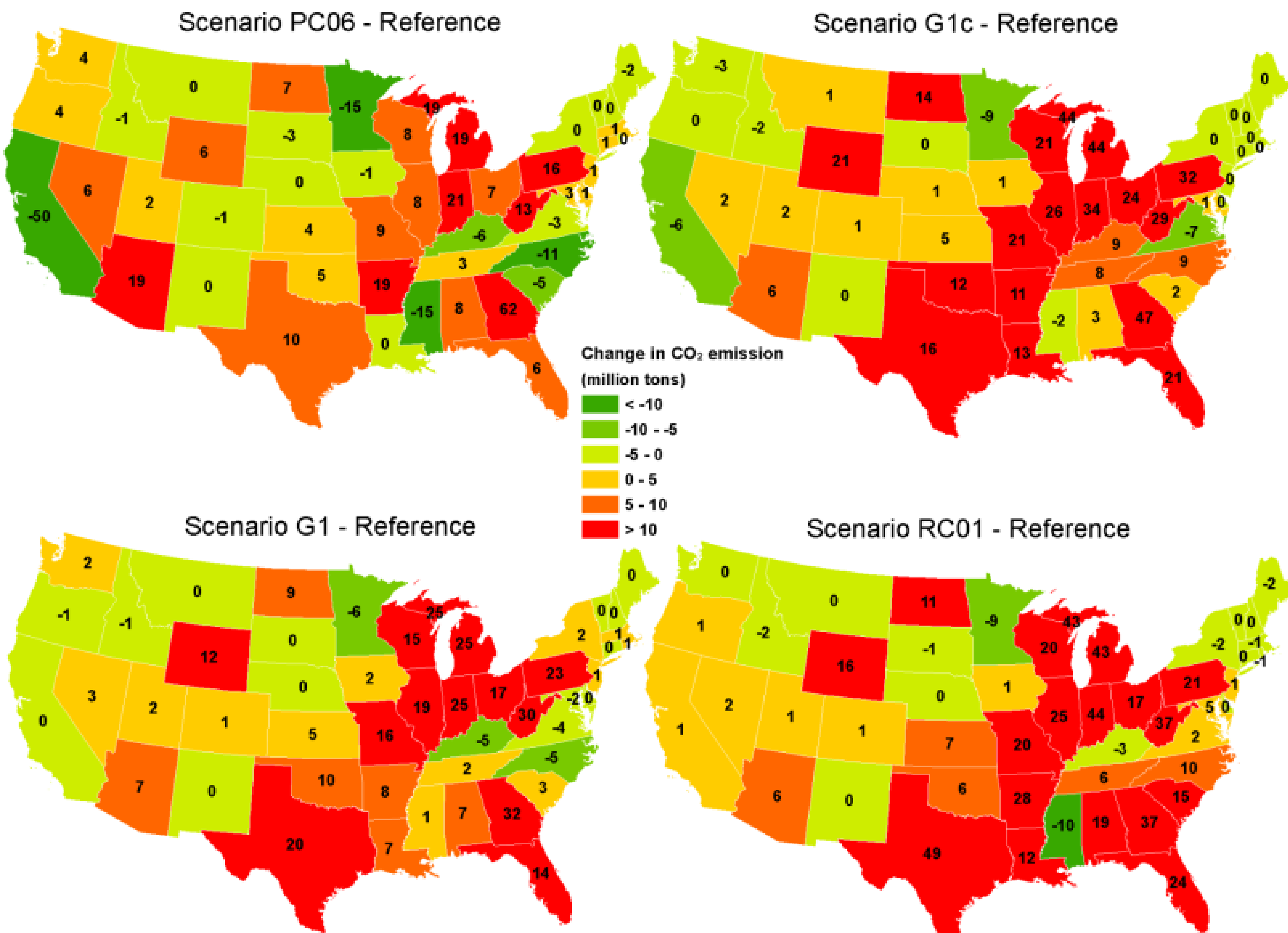
Change in projected SO_2 emissions (in 2030) from CPP implementation scenarios to potential rollback scenarios (thousand short tons) (positive values indicate increased emission from the CPPs (i.e., rows) to the rollback (i.e., columns) scenarios)

		CPP Existing sources only (PC06)	No CPP - Reference (G1)	No CPP – High gas (G1c)	No CPP, No ITC/PTC, no incremental EE (RC01)
Reference cases	Initials	1108	1254	1479	1533
CPP mass based (banking) (G4f)	976	132 (12%)	278 (22%)	503 (34%)	557 (36%)
CPP with increased stringency (G5a)	395	713	859	1084	1138

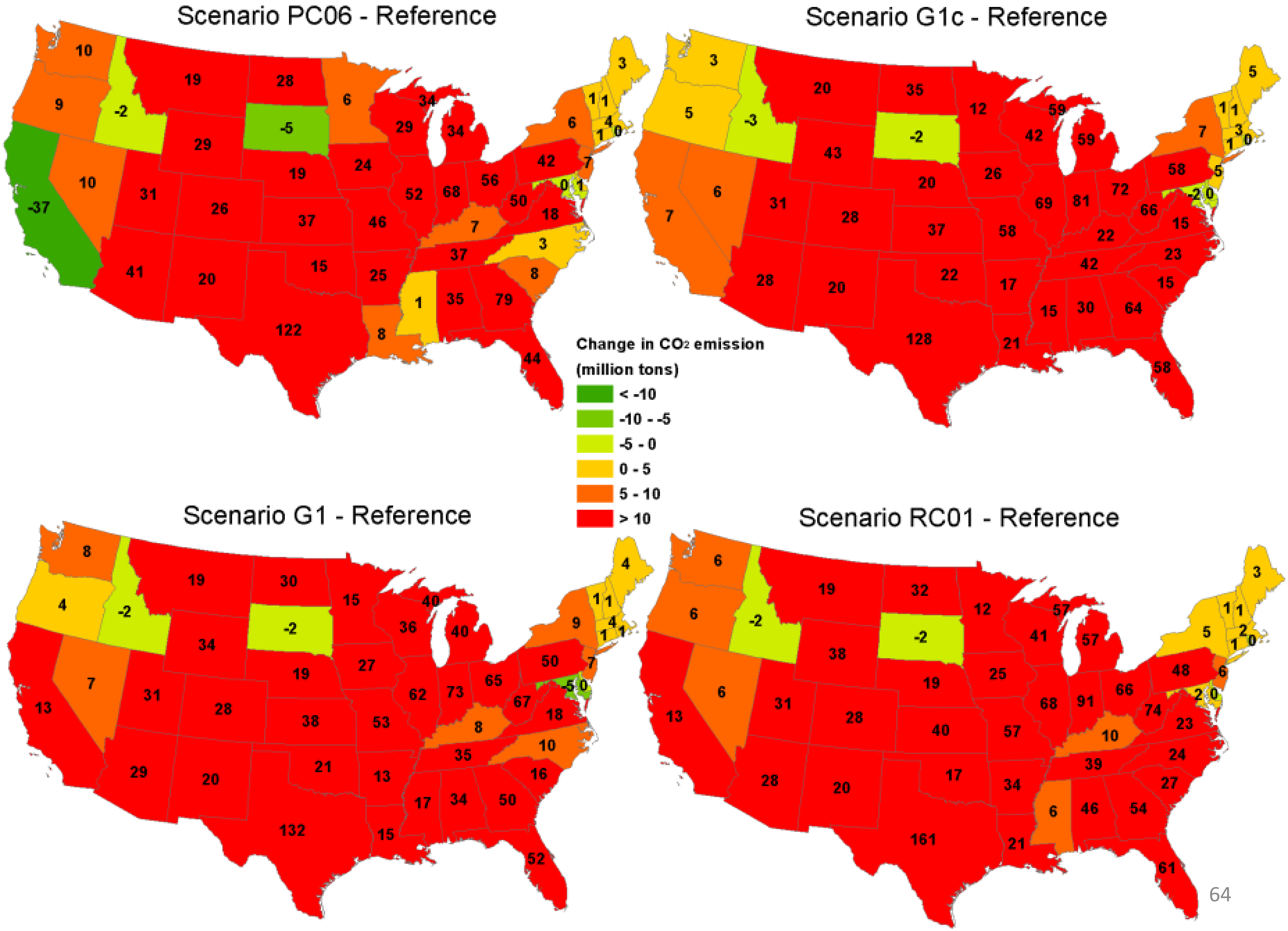
Change in SO_2 Emissions in 2030
Four Rollback Cases Compared to Clean Power Plan



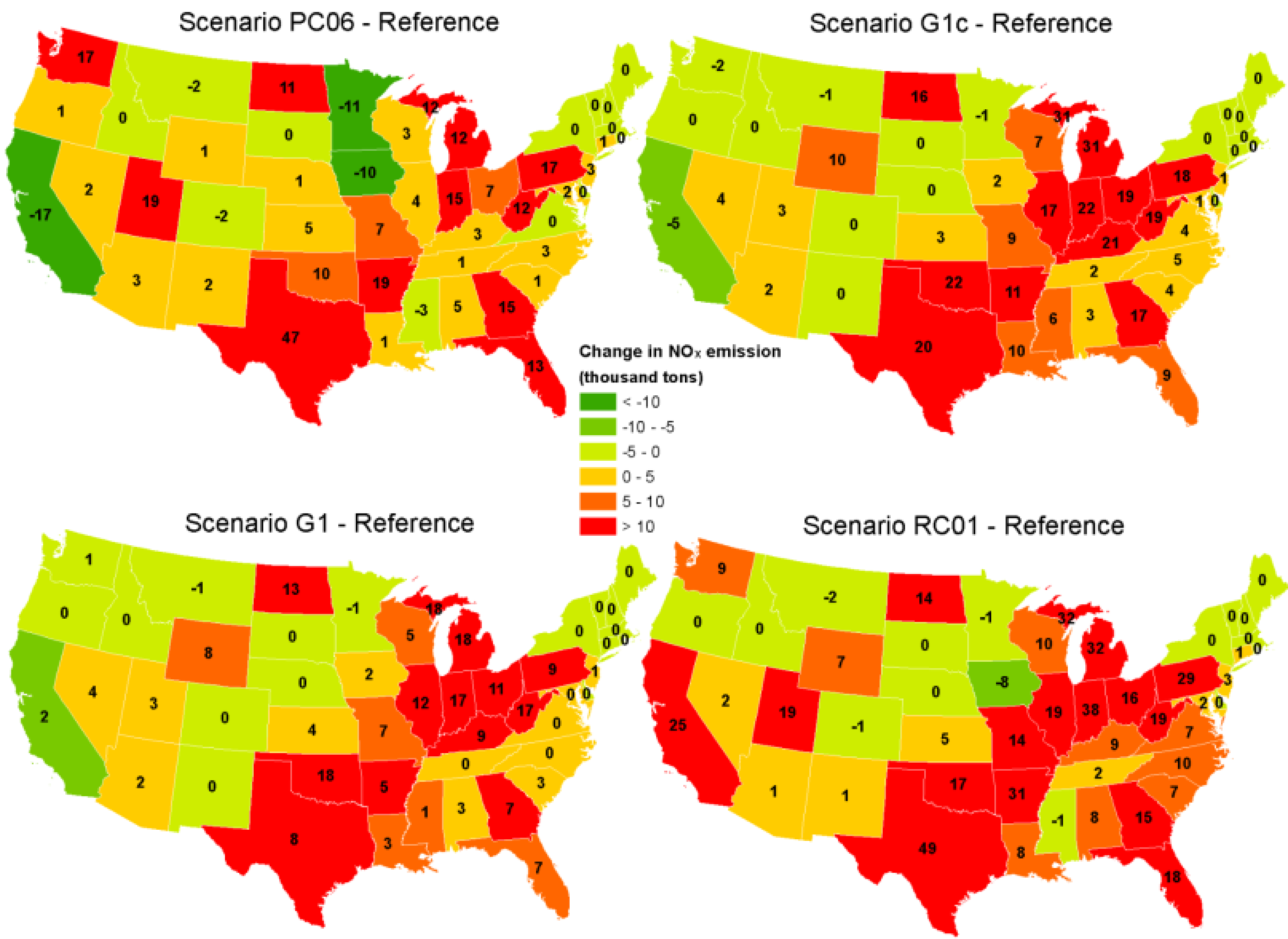
Change in projected CO_2 emissions for four projected scenarios compared to the reference in 2030 (million short tons)



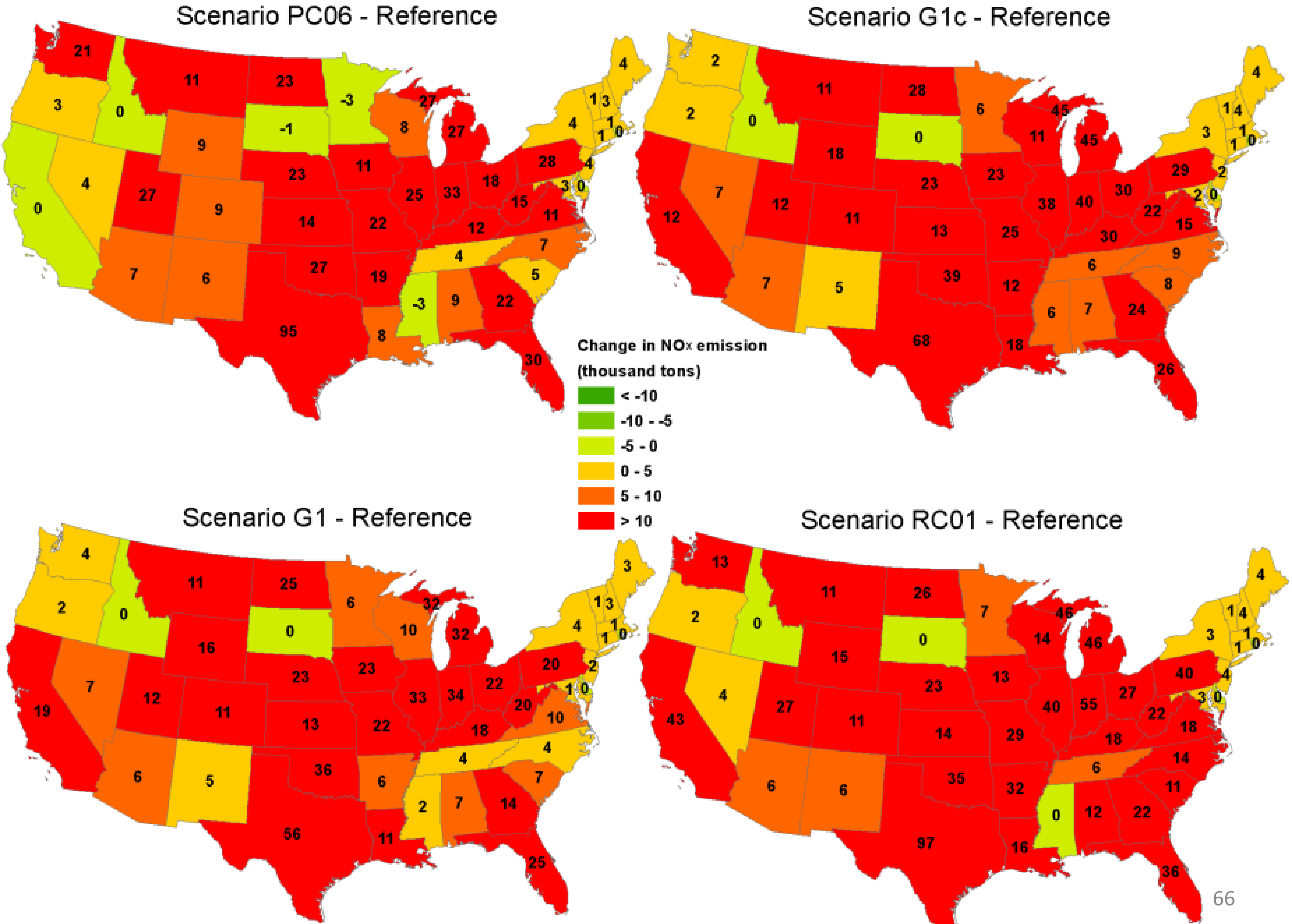
Change in projected CO_2 emissions for four projected scenarios compared to the reference (G5a) in 2030 (million short tons)



Change in projected NO_x emissions for four projected scenarios compared to CPP reference in 2030 (thousand short tons)

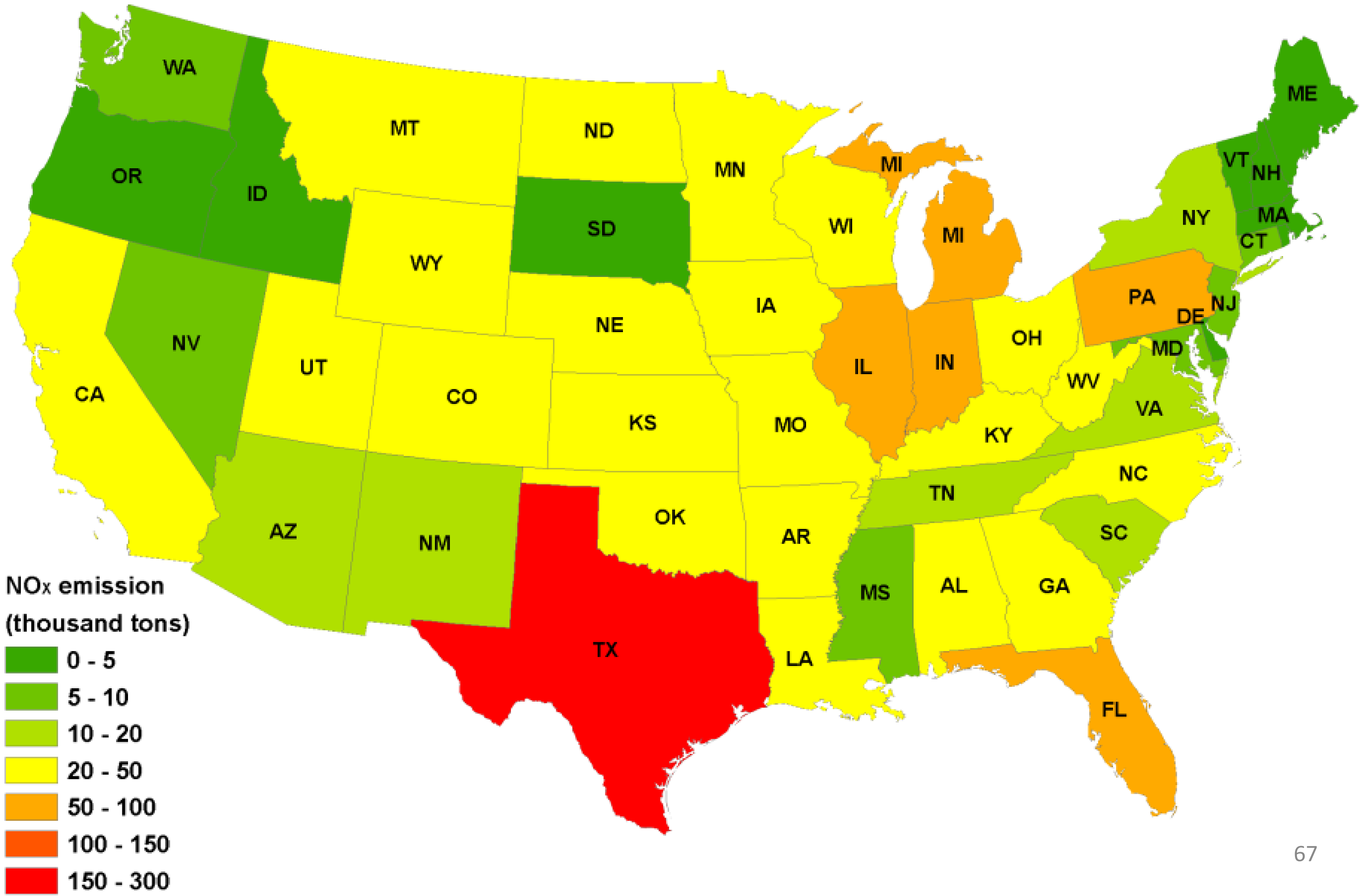


Change in projected NO_X emissions for four projected scenarios compared to the Increasde Stringency reference (G5a) in 2030 (thousand short tons)



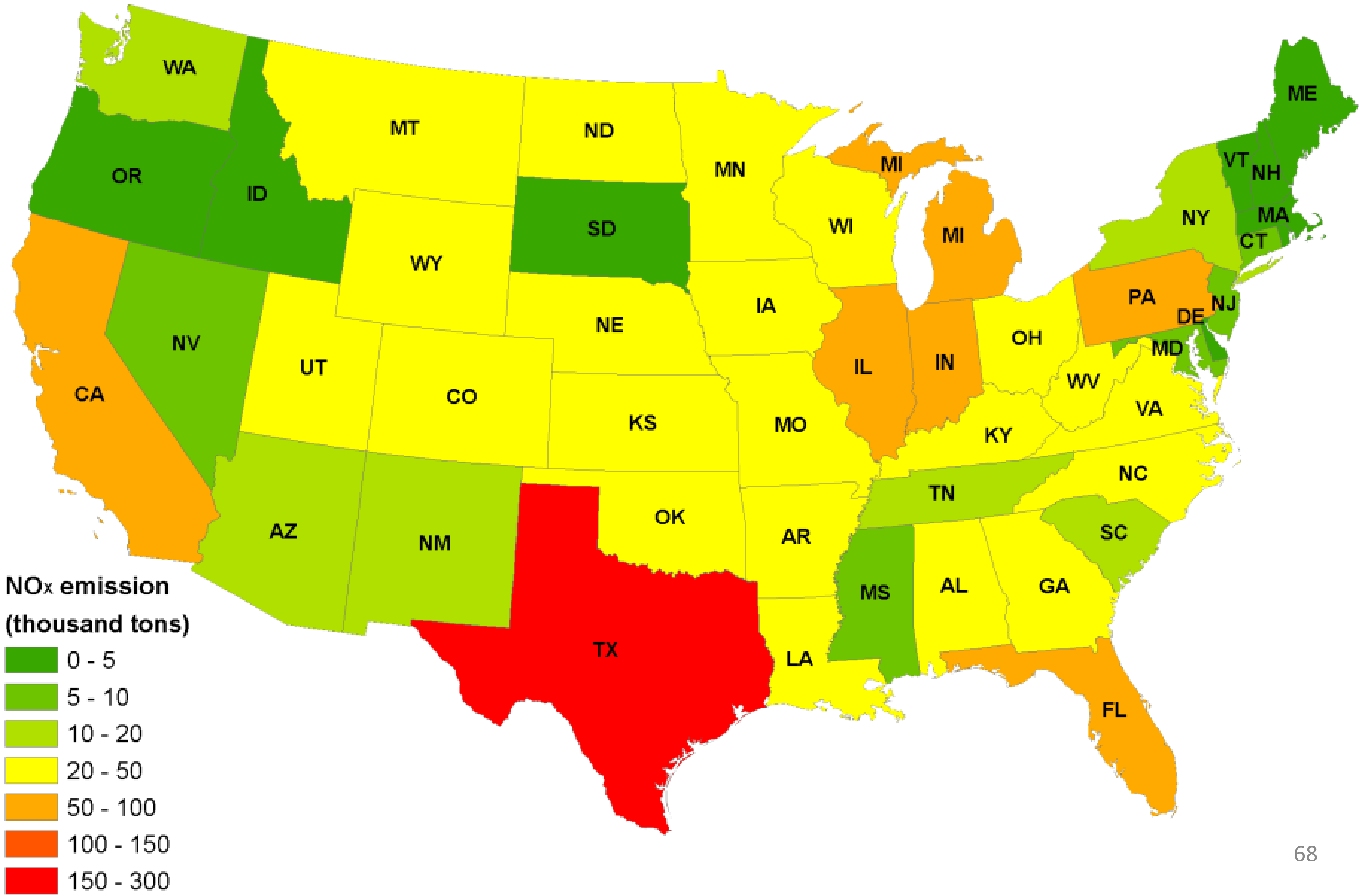
Projected NO_x emissions in 2030

G4f emission scenario for states joined the USClimate Alliance
and RC01 emission scenario for other states



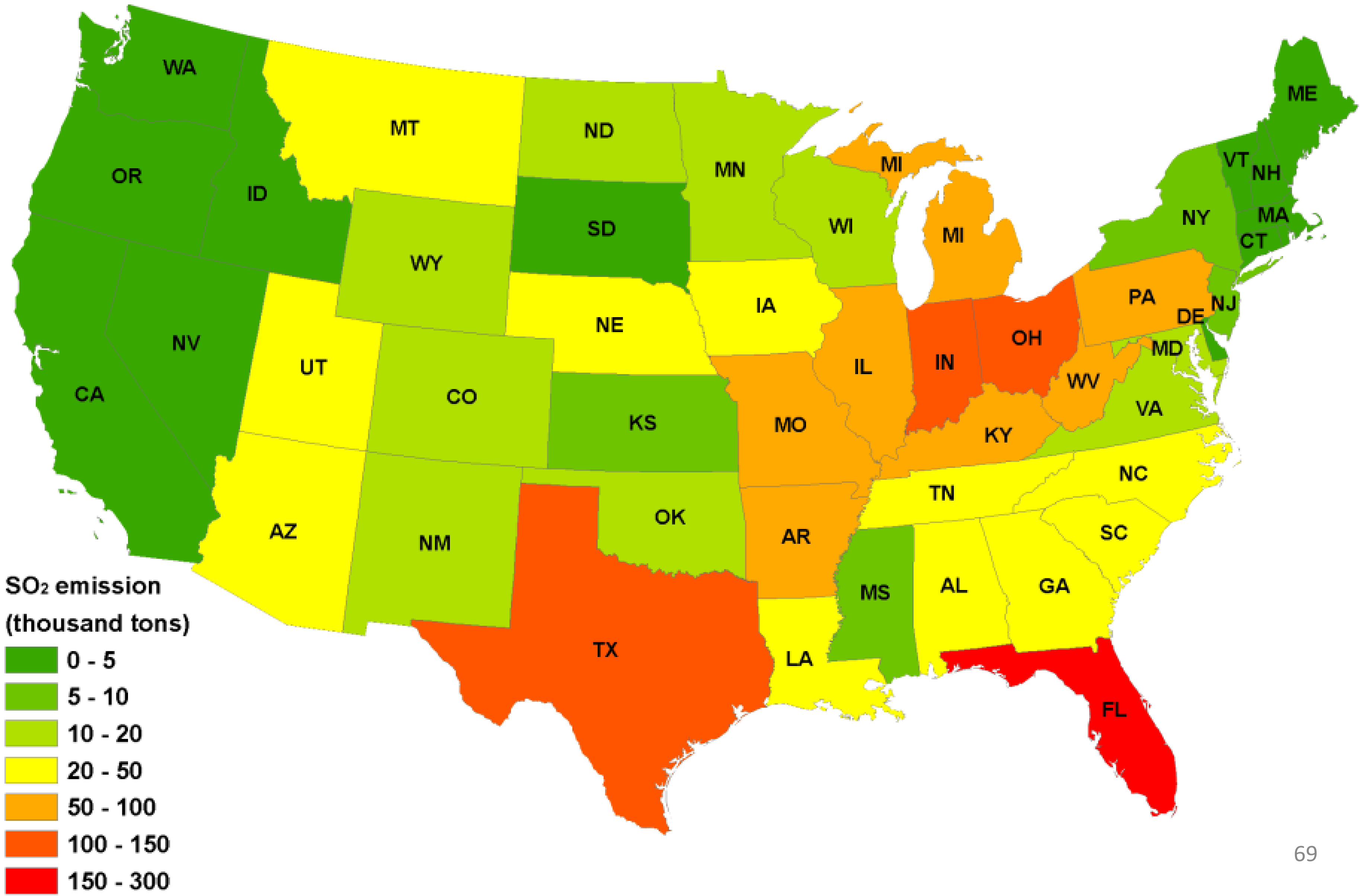
Projected NO_x emissions in 2030

RC01 emission scenario for all states



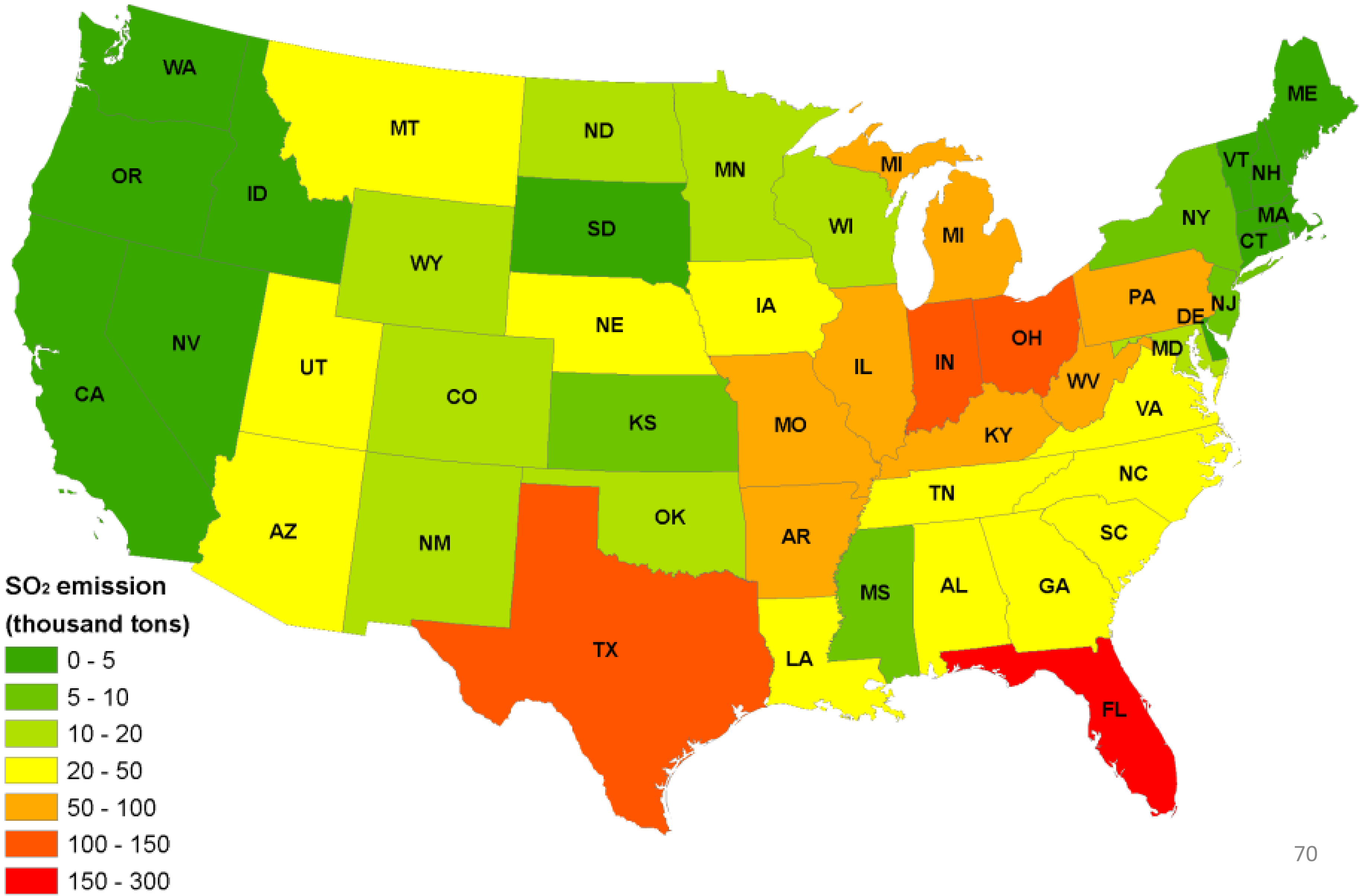
Projected SO_2 emissions in 2030

G4f emission scenario for states joined the USClimate Alliance
and RC01 emission scenario for other states



Projected SO_2 emissions in 2030

RC01 emission scenario for all states



From 2017 RIA

- We seek comment from the public on how best to use empirical data to quantitatively characterize the increasing uncertainty in PM2.5 co-benefits that accrue to populations who live in areas with lower ambient concentrations.

2015 RIA

Table ES-7. Combined Estimates of Climate Benefits and Health Co-Benefits for Rate-Based Approach (billions of 2011$)*

SC-CO₂ Discount Rate and Statistic**	Climate Benefits Only	Climate Benefits plus Health Co-benefits (Discount Rate Applied to Health Co-benefits)					
		3%			7%		
In 2020	69	million short tons CO_2					
5%	$0.80	$1.5	to	$2.6	$1.4	to	$2.5
3%	$2.8	$3.5	to	$4.6	$3.5	to	$4.5
2.5%	$4.1	$4.9	to	$6.0	$4.8	to	$5.9
3% (95th percentile)	$8.2	$8.9	to	$10	$8.9	to	$9.9
In 2025	232	million short tons CO_2					
5%	$3.1	$11	to	$21	$9.9	to	$19
3%	$10	$18	to	$28	$17	to	$26
2.5%	$15	$23	to	$33	$22	to	$31
3% (95th percentile)	$31	$38	to	$49	$38	to	$47
In 2030	415	million short tons CO_2					
5%	$6.4	$21	to	$40	$19	to	$37
3%	$20	$34	to	$54	$33	to	$51
2.5%	$29	$43	to	$63	$42	to	$60
3% (95th percentile)	$61	$75	to	$95	$74	to	$92

Final CPP in Repeal RIA

Table 1-2. Forgone Climate and Air Pollutant Emission Reductions under the Proposed Repeal of the Clean Power Plan, Rate-Based and Mass-Based Illustrative Plan Approaches[1]

	CO_2 (million short tons)	SO_2 (thousand short tons)	Annual NO_X (thousand short tons)
Rate-based			
2020	69	14	50
2025	232	178	165
2030	415	318	282
Mass-based			
2020	82	54	60
2025	264	185	203
2030	413	280	278

Source: Integrated Planning Model, 2015. Emissions change may not sum due to rounding.

[1] Forgone CO_2 emission reductions are used to estimate the forgone climate benefits of repealing the CPP. SO_2, and NO_X reductions are relevant for estimating the forgone air quality health co-benefits of the repealing the CPP.

2017 Repeal RIA

Table 1-11. Combined Estimates of Forgone Climate Benefits and Health Co-benefits, based on the 2017 Annual Energy Outlook (billions of 2011$)

Year	Discount Rate	Forgone Domestic Climate Benefits	Forgone Health Co-benefits	Total Forgone Benefits
2020	3%	$0.1	($0.5) to ($0.3)	($0.5) to ($0.2)
	7%	$0.0	($0.5) to ($0.2)	($0.5) to ($0.2)
2025	3%	$1.3	$7.7 to $18.3	$9.0 to $19.6
	7%	$0.2	$7.0 to $16.7	$7.2 to $16.9
2030	3%	$2.5	$18.1 to $42.4	$20.6 to $44.9
	7%	$0.4	$16.4 to $38.5	$16.8 to $39.0

Notes: All forgone benefit estimates are rounded to one decimal point and may not sum due to independent rounding. The forgone climate benefit estimates in this summary table reflect domestic impacts from CO_2 emission changes and do not account for changes in non-CO_2 GHG emissions. Forgone co-benefits were calculated using a benefit-per-ton estimate corresponding to each of three regions of the U.S. Forgone ozone co-benefits are modeled to occur in analysis year and so are constant across discount rates. The forgone health co-benefits reflect the sum of the forgone $PM_{2.5}$ and ozone co-benefits and reflect the range based on adult mortality functions (e.g., from Krewski et al. (2009) with Bell et al. (2004) to Lepeule et al. (2012) with Levy et al. (2005)). The forgone monetized health co-benefits do not account for forgone emissions of directly emitted $PM_{2.5}$, direct exposure to NO_X, SO_2, and hazardous air pollutants; ecosystem effects; or visibility impairment. See Section 5 and the Appendix of this RIA for more information about these estimates and for more information regarding the uncertainty in these estimates.

2015 FINAL RIA

Table ES-10. Monetized Benefits, Compliance Costs, and Net Benefits under the Mass-based Illustrative Plan Approach (billions of 2011$) [a]

	Mass-Based Approach					
	2020		2025		2030	
Climate Benefits [b]						
5% discount rate	$0.94		$3.6		$6.4	
3% discount rate	$3.3		$12		$20	
2.5% discount rate	$4.9		$17		$29	
95th percentile at 3% discount rate	$9.7		$35		$60	
	Air Quality Co-benefits Discount Rate					
	3%	7%	3%	7%	3%	7%
Air Quality Health Co-benefits [c]	$2.0 to $4.8	$1.8 to $4.4	$7.1 to $17	$6.5 to $16	$12 to $28	$11 to $26
Compliance Costs [d]	$1.4		$3.0		$5.1	
Net Benefits [e]	$3.9 to $6.7	$3.7 to $6.3	$16 to $26	$15 to $24	$26 to $43	$25 to $40
Non-Monetized Benefits	Non-monetized climate benefits Reductions in exposure to ambient NO_2 and SO_2 Reductions in mercury deposition Ecosystem benefits associated with reductions in emissions of NO_X, SO_2, PM, and mercury Visibility improvement					

Repeal RIA

Table 1-8. Monetized Forgone Benefits, Avoided Compliance Costs, and Net Benefits, assuming that Forgone PM2.5 Related Benefits Fall to Zero Below the Annual $PM_{2.5}$ National Ambient Air Quality Standard (billions of 2011$) [a]

	Rate-Based Approach		Mass-Based Approach	
	Discount Rate		Discount Rate	
	3%	7%	3%	7%
2020				
Cost: Forgone Benefits [b]	$1.7 to $2.1	$1.4 to $1.8	$1.8 to $2.4	$1.5 to $2.0
Benefit: Avoided Compliance Costs	$3.7	$4.2	$2.6	$3.1
Net Benefits	$1.5 to $2.0	$2.4 to $2.8	$0.2 to $0.8	$1.1 to $1.7
2025				
Cost: Forgone Benefits [b]	$11.4 to $13.3	$10.2 to $12.1	$12.4 to $14.6	$11.1 to $13.2
Benefit: Avoided Compliance Costs	$10.2	$14.1	$13.0	$16.9
Net Benefits	($3.1) to ($1.1)	$2.1 to $4.0	($1.6) to $0.6	$3.7 to $5.9
2030				
Cost: Forgone Benefits [b]	$23.0 to $26.5	$20.7 to $24.1	$23.3 to $26.6	$21.0 to $24.2
Benefit: Avoided Compliance Costs	$27.2	$33.3	$24.5	$30.6
Net Benefits	$0.7 to $4.2	$9.2 to $12.7	($2.1) to $1.2	$6.4 to $9.6