The Health and Environmental Benefits of Wind and Solar Energy in the United States, 2007-2015

Dev Millstein, Ryan Wiser, Mark Bolinger, Galen Barbose
Lawrence Berkeley National Laboratory

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Introduction:
Health and Environmental Benefits Estimation

Project Overview

- **Context:** Wind and solar provide public health and environmental benefits to the United States. However, not only do these benefits vary dramatically by region, they also vary over time. In the last decade, cumulative wind and solar power deployment has increased rapidly; at the same time, regulatory changes and fossil fuel price changes have led to steep cuts in overall power-sector emissions of pollutants such as SO_2, NO_x, and $PM_{2.5}$ as well as to reductions to CO_2 emission rates in certain regions.
- **Goal:** Evaluate how wind and solar health and environmental benefits have evolved from 2007 – 2015 both in absolute terms as well as on a dollar-benefit per kWh basis. Analyze how benefits differ regionally across the continental United States. Assess certain uncertainties in the magnitude of the benefits.

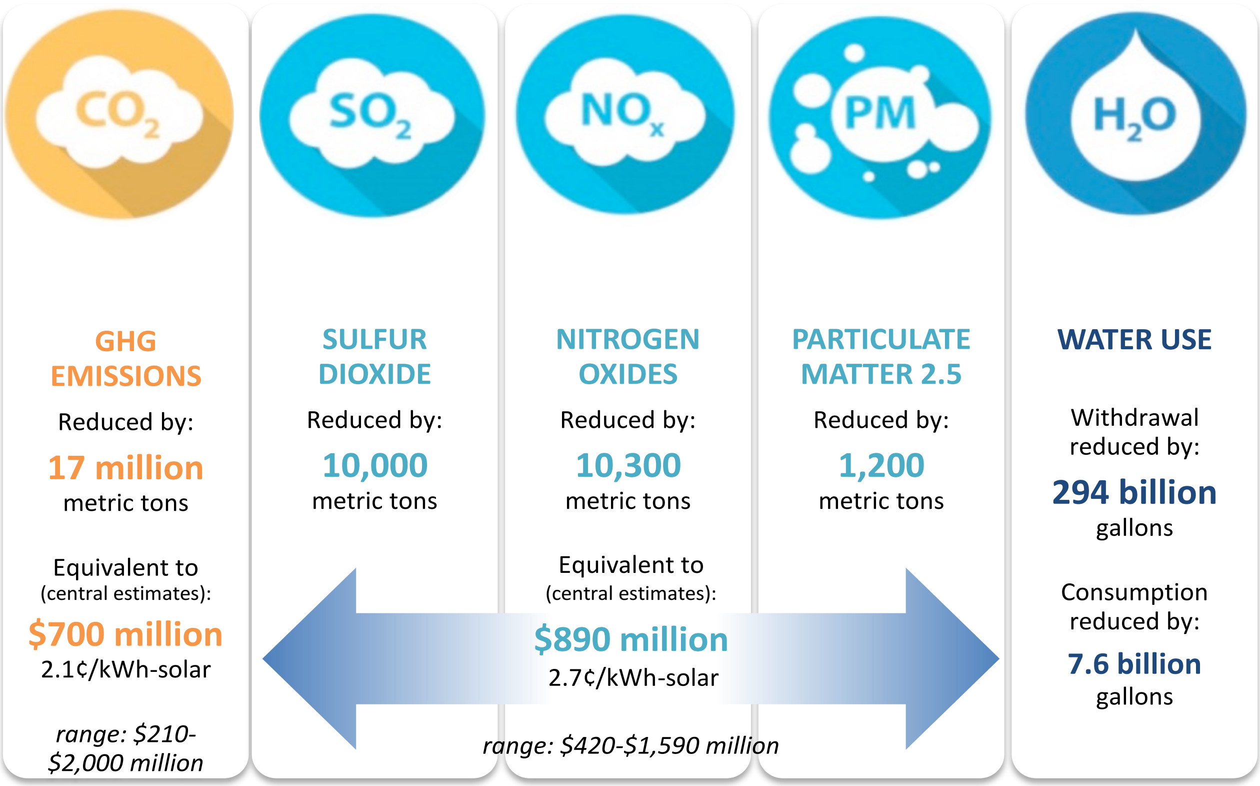
Project Approach

- Develop hourly generation estimates of (1) utility wind power; and (2) utility and distributed solar
  - Based on data collected by the EIA, within the DOE's *Wind Technology Market* report and LBNL's *Utility-Scale Solar* report, by GTM, and other sources
- Use EPA's AVERT and other sources to estimate avoided emissions of CO_2, SO_2, NO_x, and $PM_{2.5}$
- Use wide range of social cost of carbon estimates to monetize the CO_2 emission reductions
- Use a suite of air quality, exposure and health impact models to assess the air quality benefits
  - Both in terms of reduced incidence rates and monetary value

Literature Review

- A number of previous studies have touched on the broad themes of air quality and climate change impacts from the power sector and the related benefits of renewable power
  - Selected external references: Siler-Evans et al. (2013); NRC (2010); Driscoll et al. (2015)
  - DOE funded studies: Wind Vision, Hydropower Vision, On the Path to SunShot, RPS Benefits and Impacts
- However, past literature has often focused on a single time period or a limited set of regions, or instead focused on potential future benefits
- **No study has fully quantified the benefits that wind and solar power have already provided over the past decade**

Literature Review



Perhaps most related to the present work is our analysis of the benefits of solar energy in 2014 (left) that was developed for the *On the Path to SunShot* report: "The Environmental and Public Health Benefits of Achieving High Penetrations of Solar Energy in the United States."

The current analysis expands upon this DOE-funded SunShot work and the previous Wind Vision and RPS analyses, employing more sophisticated methods to estimate wind and solar generation and environmental and health impacts, covering 2007-2015.

Our Three-Step Approach

1. Determine the historical generation from utility wind, utility solar, and distributed solar

2. Determine the avoided combustion-based electricity generation due to wind and solar generation and the associated avoided carbon dioxide and air pollution emissions

3. Estimate avoided climate impacts (monetized value) and avoided health impacts (incidences and monetized value)

Caveats on Analysis Scope

- Focus is on health and environmental impacts associated with CO_2, SO_2, NO_x and $PM_{2.5}$; same set of benefits that academics, NRC, and EPA have often chosen to monetize
  - Not all environmental and health impacts are considered, e.g. water-use reductions and reductions of heavy metals such as mercury; wildlife and land use issues; etc.
  - Only combustion-related impacts considered; other life-cycle stages not included
- Costs are not considered, nor are other benefit and impact categories; solar and wind may not be the least-expensive means of achieving environmental and health benefits
- Cap-and-trade programs (for NO_x, SO_x, CO_2) are assumed to be non-binding, such that solar and wind reduce total emissions; this is accurate for most regions for much of this historical period
  - However, additional analysis of CAIR and other cap-and-trade programs may be needed to fully understand implications

1. Determine the Historical Generation from Utility Wind, Utility Solar, and Distributed Solar

Methods

Utility Wind Generation

- Monthly utility wind generation (MWh per month) is recorded by the U.S. EIA for each wind power plant
- For the purpose of calculating avoided fossil generation, wind power generation needed to be 'counted' in the region into which it was delivered
  - Every wind plant was screened and all regional power transfers were taken into account
    - Data sources: EIA Forms 860, 923; AWEA wind project data base; AWEA transfer data; FERC EQR data; DOE's Wind Technology Market Report data base
- AVERT default profiles then used to estimate hourly generation

Utility Solar Generation

- Monthly utility solar generation (MWh per month) is recorded by the U.S. EIA for each solar power plant
  - EIA 'utility' solar includes all plants, even net-metered plants, larger than 1 MW in capacity
  - Includes both CSP and PV projects
- Cross region transfers were accounted for in a similar manner to the wind projects
  - Data: EIA Forms 860, 923; FERC EQR data; LBNL Utility Scale Solar Report data base
- AVERT default profiles then used to estimate hourly generation

Distributed Solar Generation

- EIA data on distributed solar generation are available only starting in 2014; as such, generation had to be estimated based on records of installed capacity
- GTM provided utility and distributed solar capacity by state and for each quarter for the years 2010-2015
  - Data from Larry Sherwood and other data sources were used prior to 2010
- Total distributed capacity calculated as the sum of total GTM/Sherwood solar capacity minus EIA utility capacity
  - Necessary because EIA utility category includes the GTM utility category and a portion of GTM's non-residential category

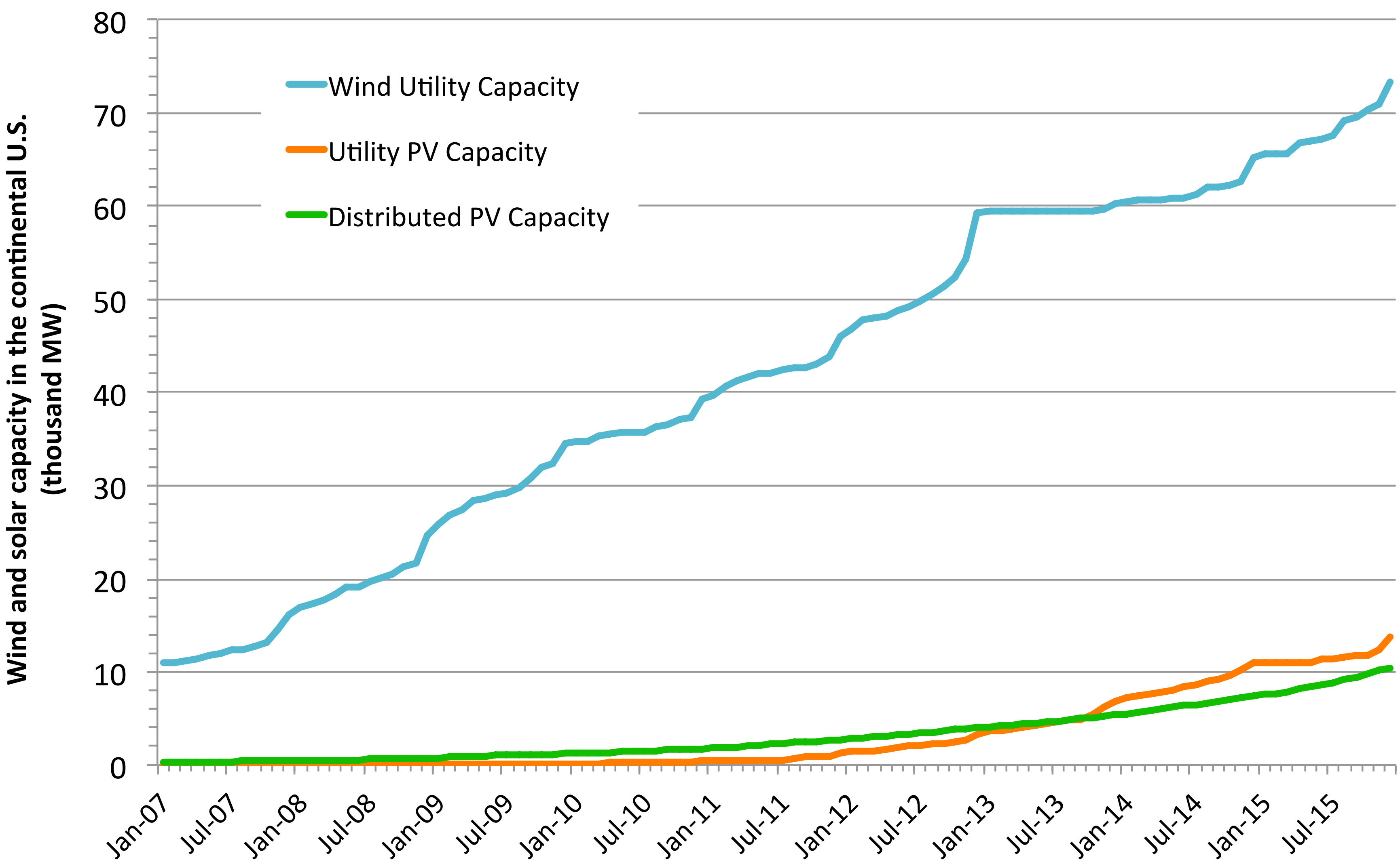
Distributed Solar Generation

- Monthly capacity was derived from quarterly capacity based on linear interpolation and a simple smoothing process to account for small differences in utility plant additions between EIA and GTM
- Monthly generation (MWh) estimates were then based on total monthly capacity
  - Regional monthly capacity factors were applied based on profiles within EPA's AVERT tool, derived from PV-Watts
- Monthly generation estimates compared to 2014-2015 EIA distributed solar estimates (also from PV-Watts)
- AVERT default profiles to estimate hourly generation

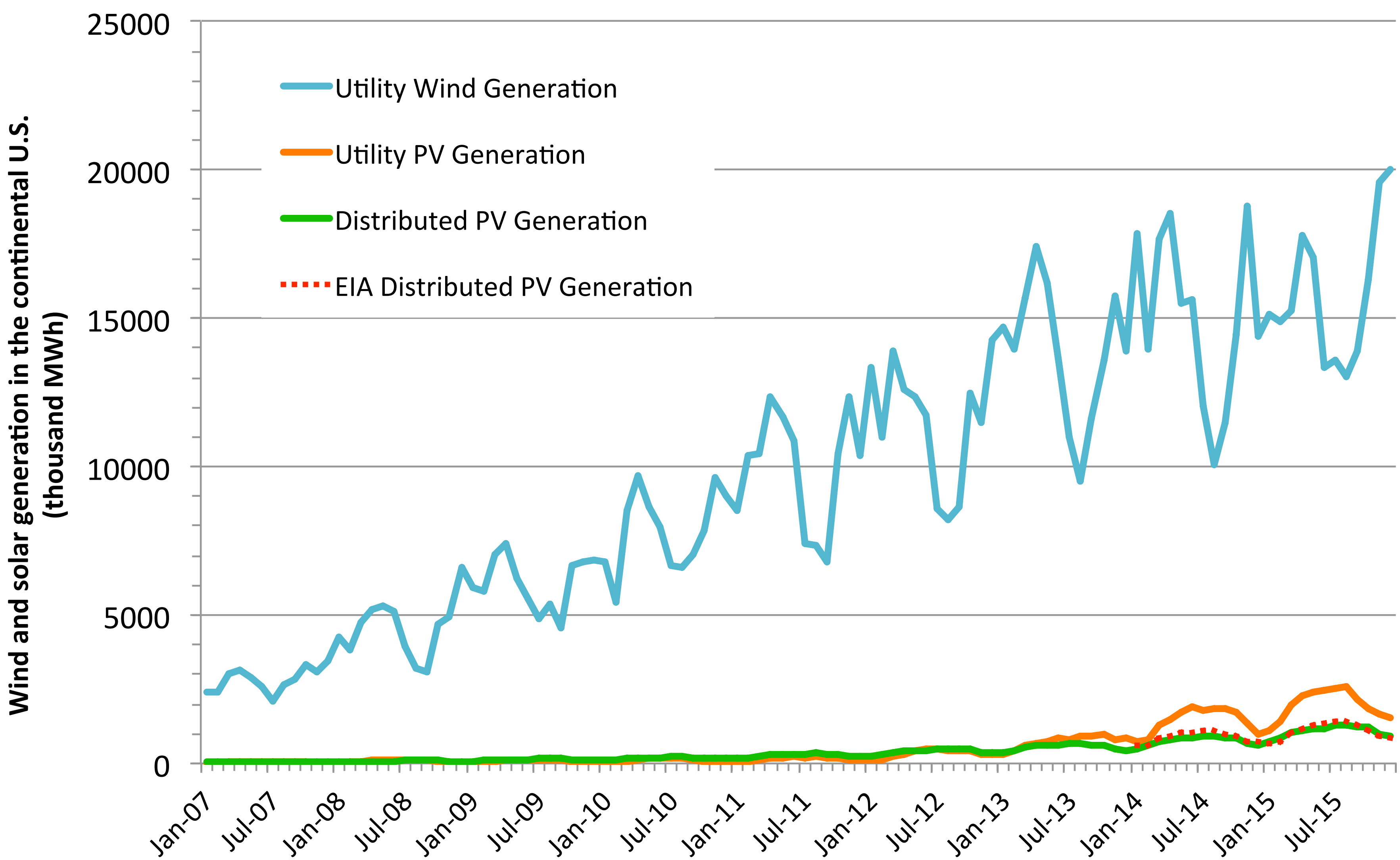
1. Determine the Historical Generation from Utility Wind, Utility Solar, and Distributed Solar

Results

Wind & Solar Capacity by Month



Wind & Solar Generation by Month



2. Determine the Avoided Combustion-Based Electricity Generation Due to Wind and Solar Generation and the Associated Avoided Carbon Dioxide and Air Pollution Emissions

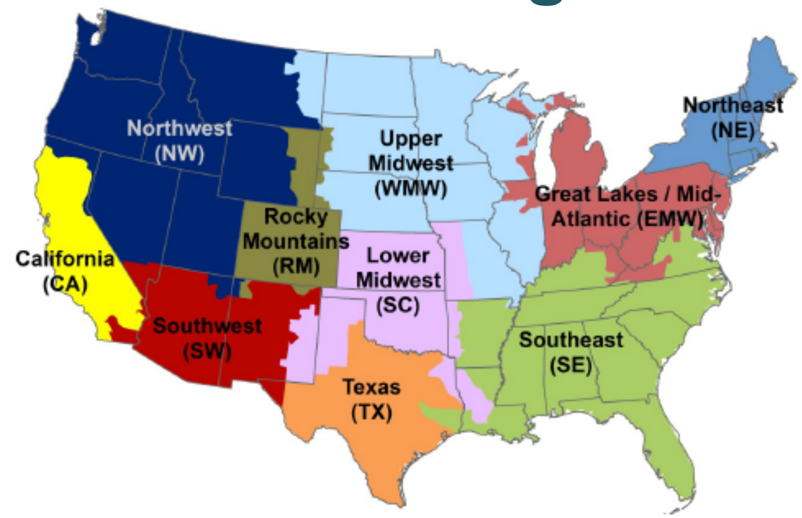
Methods

Determine Avoided Carbon Dioxide and Air Pollution Due to Wind and Solar Generation

EPA's AVERT Model

Study utilizes EPA AVERT model to estimate impact of wind and solar on the operation of the existing generation fleet in 2007 – 2015

AVERT Regions



Input:

Hourly renewable MWh generated in or delivered to each AVERT region

Output:

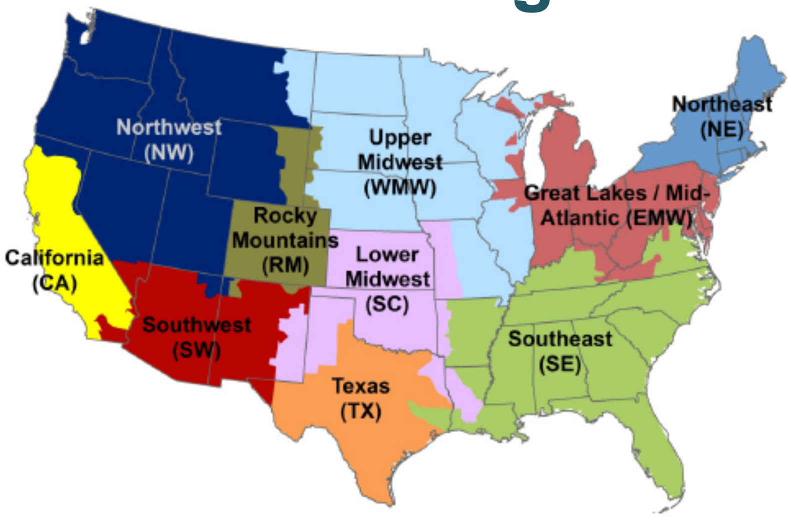
Plant-level changes in MWh, fuel, and emissions (NO_x, SO_2, CO_2) by unit

Determine Avoided Carbon Dioxide and Air Pollution Due to Wind and Solar Generation

EPA's AVERT Model

- AVERT characterizes how each power plant in each region responds to different load
- In other words: AVERT estimates which power plants would likely have been turned up if wind and solar power generation had not been available in each hour of each year
  - AVERT also estimates the air pollution emissions characteristics of those plants given the type of load seen at the specific hour

AVERT Regions



Possible limitations to use of AVERT: (1) intermediate approach in terms of complexity and accuracy; (2) presumes cap-and-trade programs are non-binding; (3) insensitive to location within AVERT regions and does not fully consider cross-region interactions; (4) only treats marginal changes

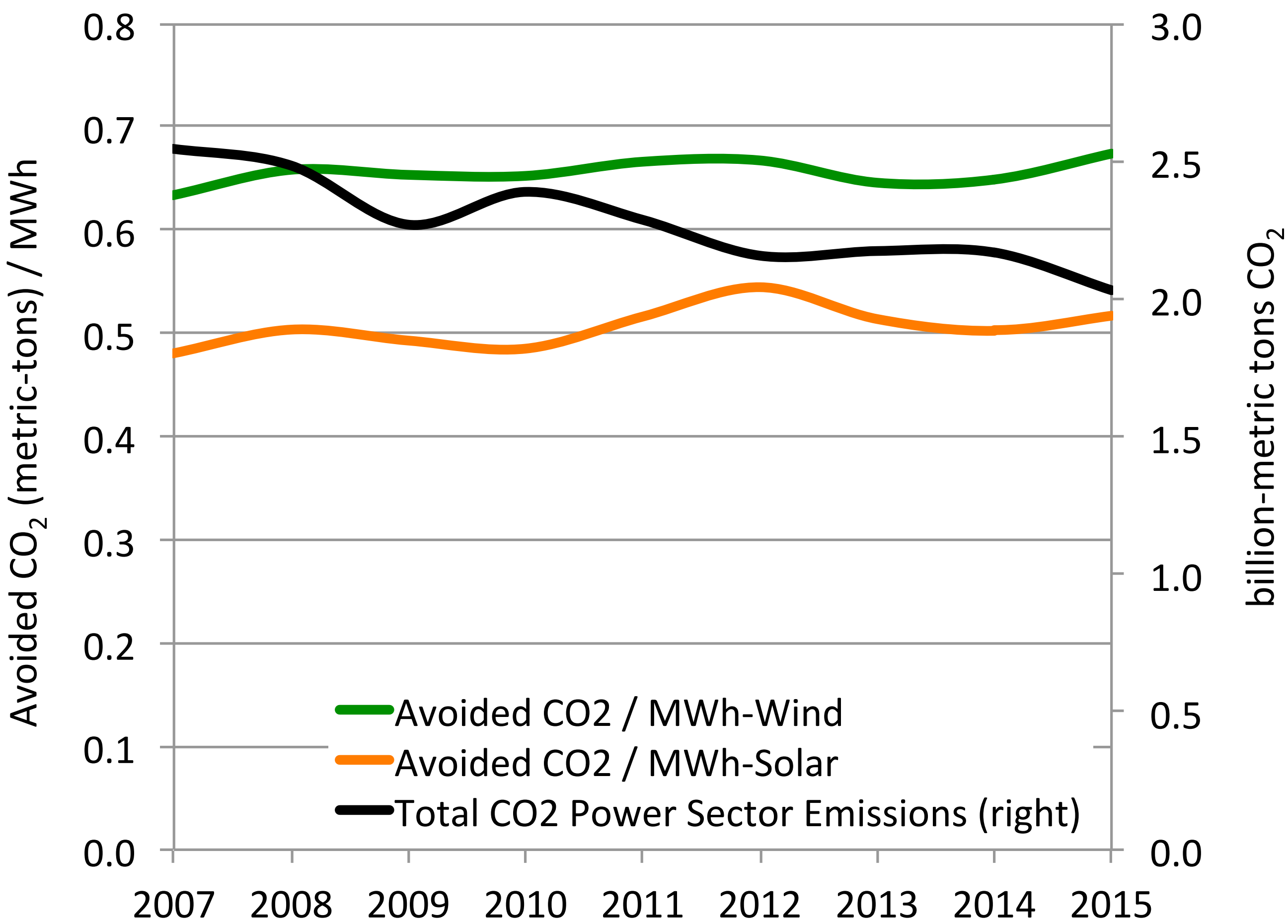
Determine Avoided Carbon Dioxide and Air Pollution Due to Wind and Solar Generation

- CO_2, NO_x, and SO_2 emissions provided by AVERT
  - Emission reductions are based on combustion-only estimates and do not include full life-cycle impacts
- $PM_{2.5}$ emissions estimated as a function of generation reduction (MWh) by plant type and state (as calculated by AVERT) and state-level $PM_{2.5}$ emission factors (g/MWh)
- Emissions estimates do not fully account for changes to power plant ramping and cycling, although studies indicate these impacts are relatively minor and will not fundamentally alter the results presented here
  - Oates and Jaramillo (2013); Valentino et al. (2012); Lew et al. (2013)

2. Determine the Avoided Combustion-Based Electricity Generation Due to Wind and Solar Generation and the Associated Avoided Carbon Dioxide and Air Pollution Emissions

Results

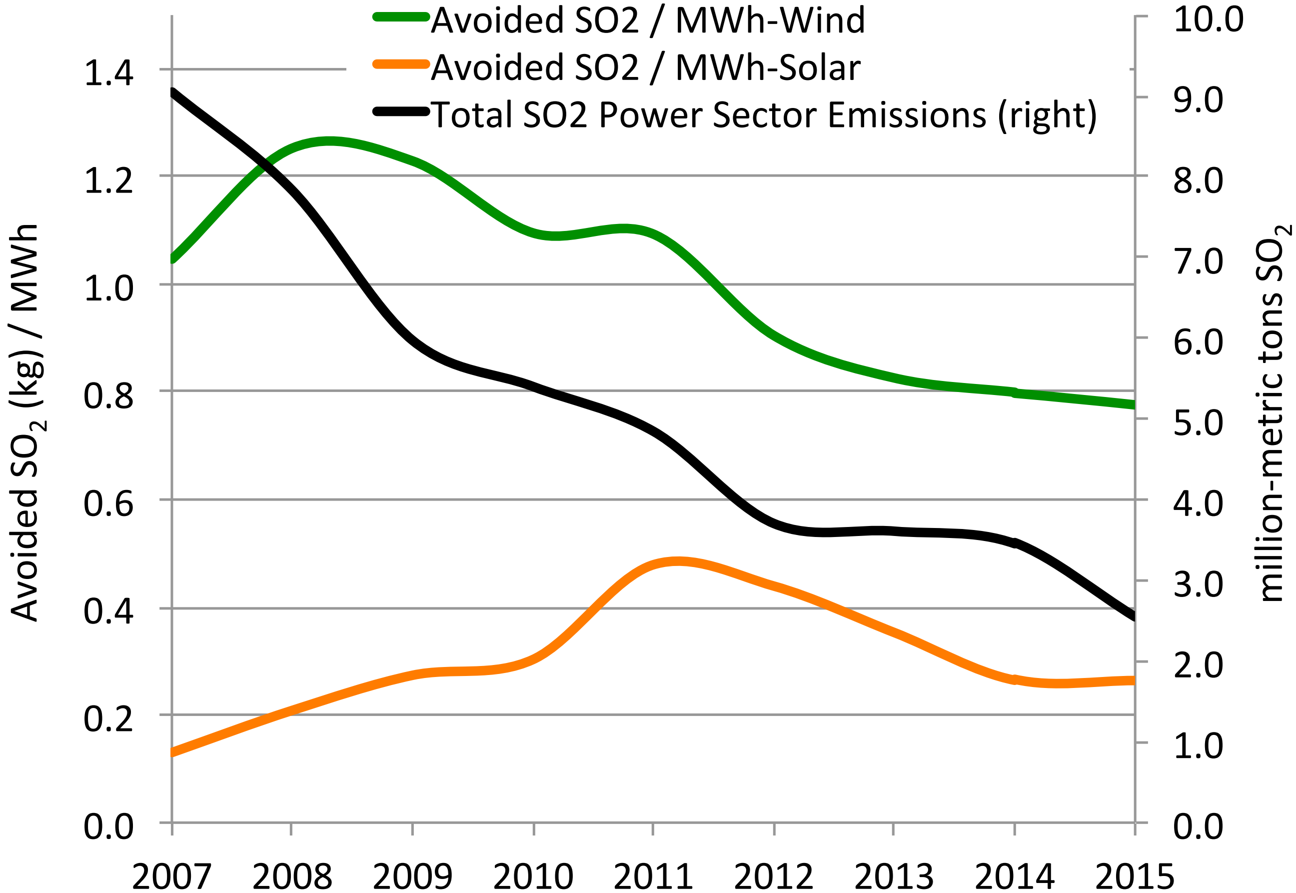
Avoided CO_2 per MWh from Wind & Solar has been Relatively Constant Over Time



- Figure shows national averages and total; regional variations not depicted here

Given location and temporal output profile, wind generation has historically offset more carbon per MWh than solar; emissions offset rates have been relatively constant over time despite drop in total power-sector emissions

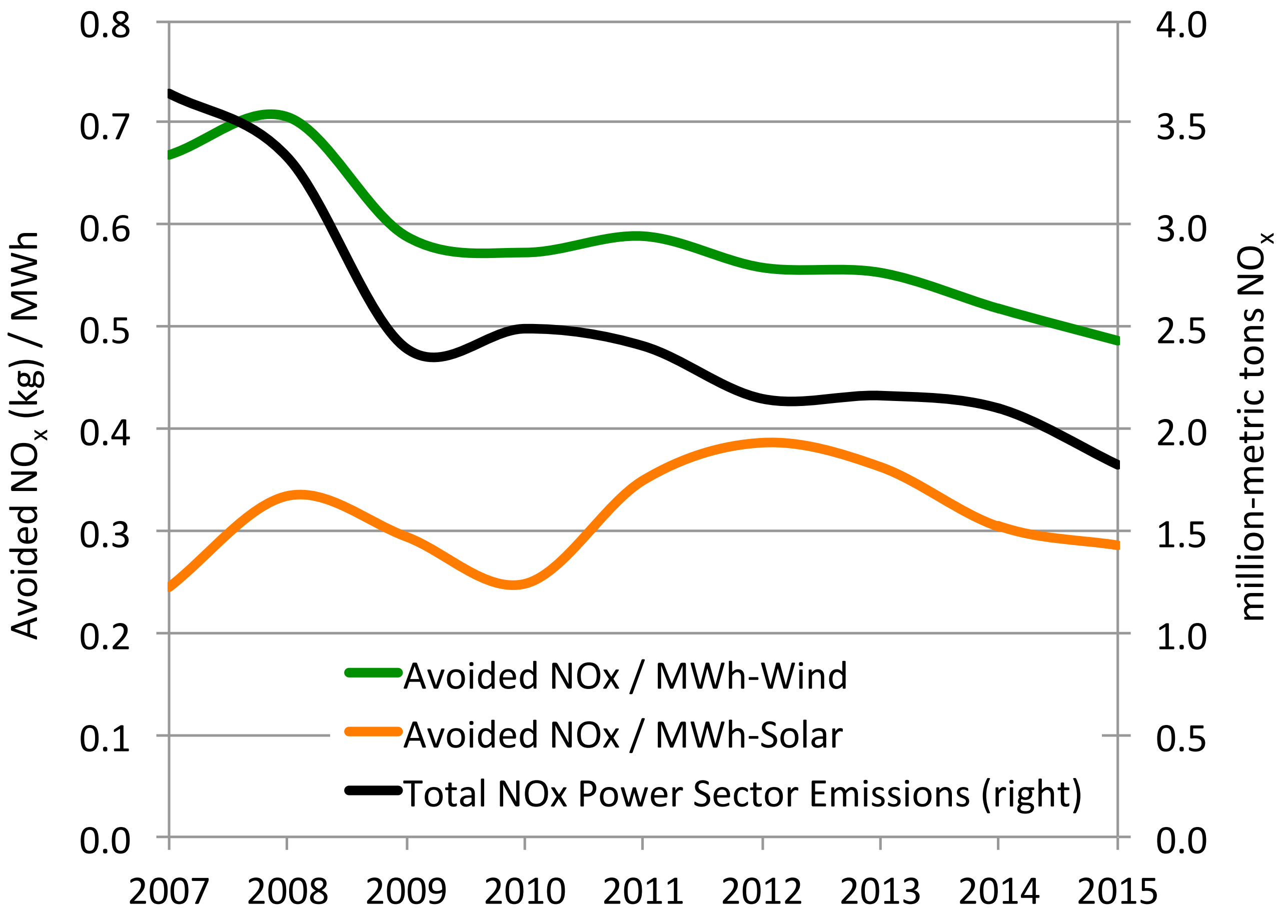
Reductions in Power-Sector SO_2 Lead to a Reduced Rate of Avoided SO_2 from Wind



- Figure shows national averages and total; regional variations not depicted here

Solar power does not show same decline in the rate of avoided SO_2 due to its expansion over time into regions outside of California and the Southwest; wind generation has historically offset more SO_2 per MWh

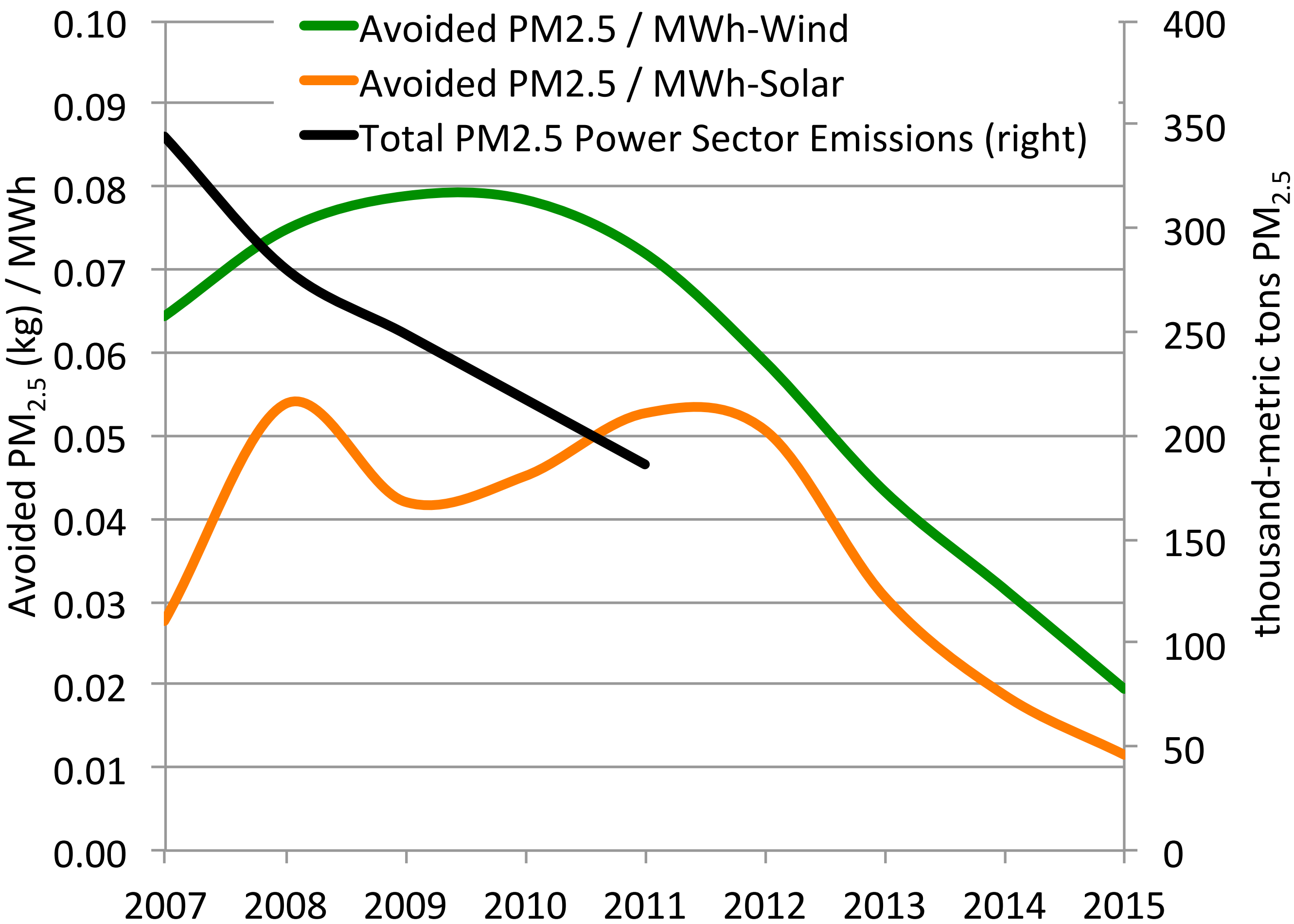
Reductions in Power-Sector NO_x Lead to a Reduced Rate of Avoided NO_x from Wind



- Figure shows national averages and total; regional variations not depicted here

Solar power does not show same decline in the rate of avoided NO_x due to its expansion over time into regions outside of California and the Southwest; wind generation has historically offset more NO_x per MWh

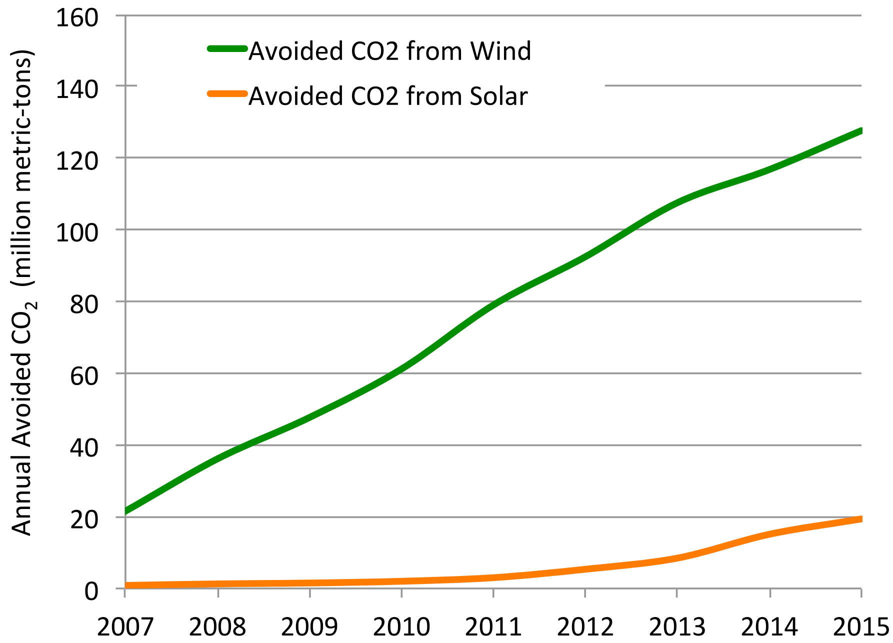
Avoided $PM_{2.5}$ Emissions Rate for Wind and Solar Follow a Decreasing trend after 2010



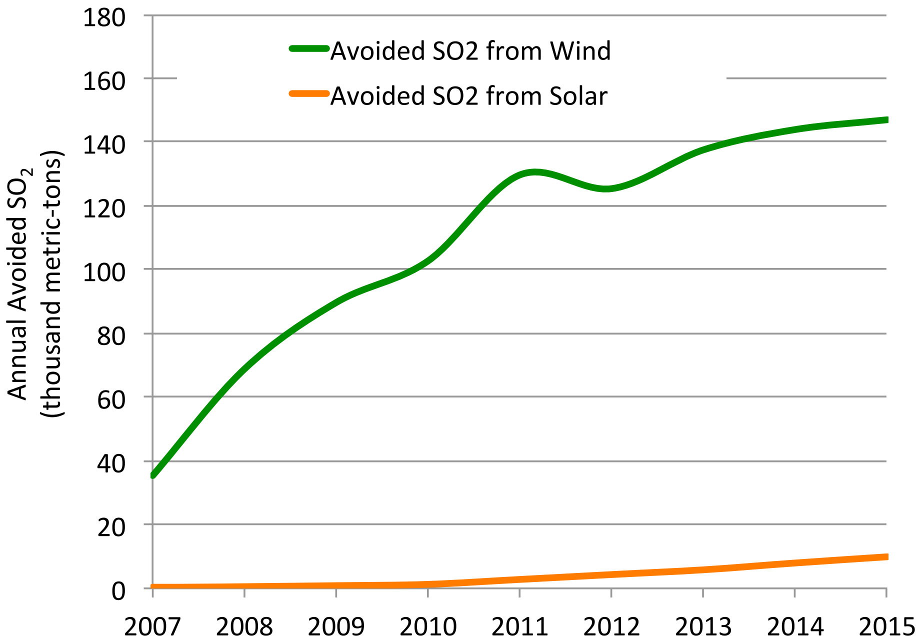
- Figure shows national averages and total; regional variations not depicted here
- Total $PM_{2.5}$ power sector emissions are based on the EPA National Emissions Inventory, with the most recent finalized data from 2011

Annual Total Emissions Avoided from Wind and Solar Power

CO_2



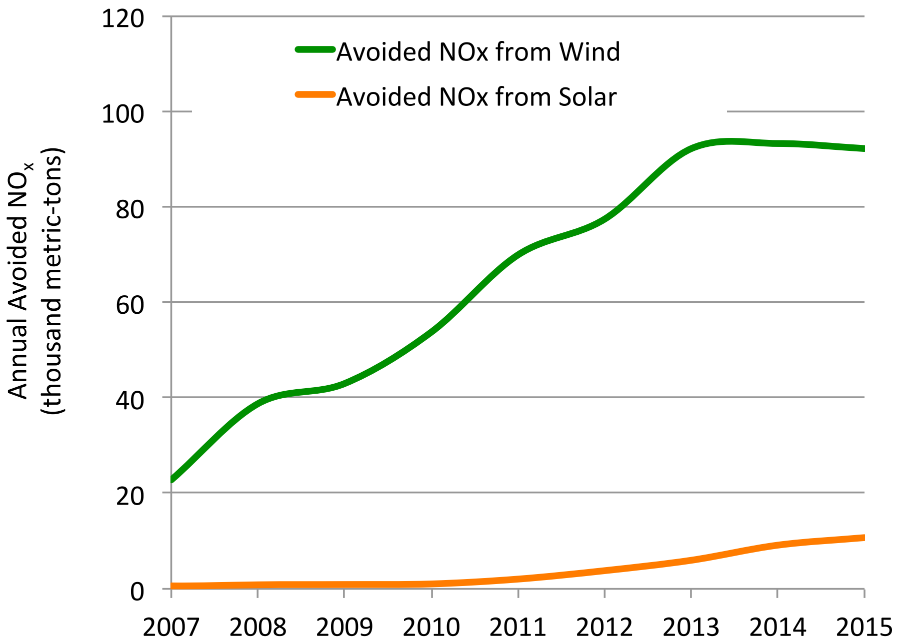
SO_2



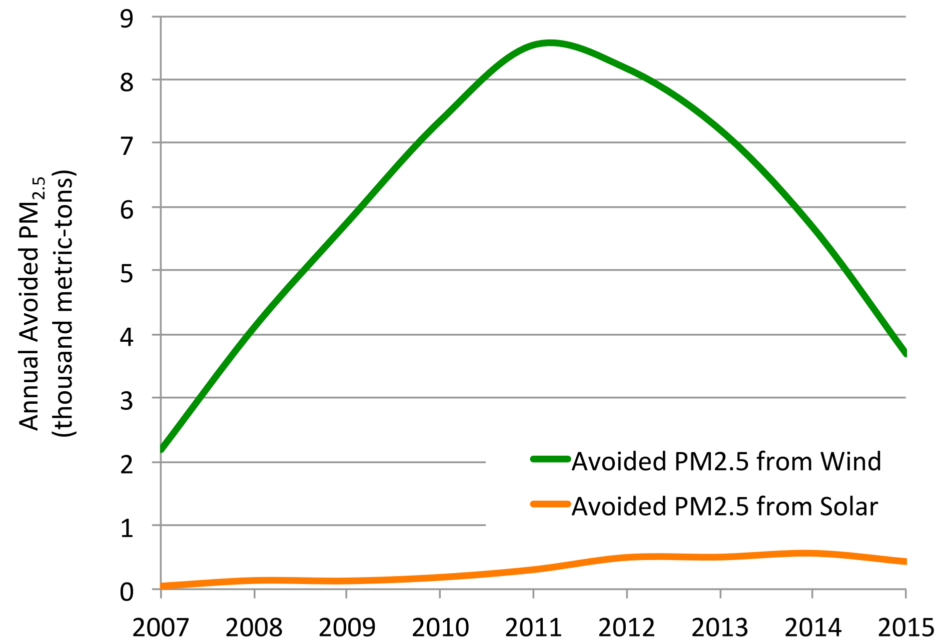
Although the average SO_2 emission rate from coal plants was reduced throughout the time period, the overall growth rate in wind and solar power generation leads to higher total avoided emissions

Annual Total Emissions Avoided from Wind and Solar Power

NO_x



$PM_{2.5}$



Avoided $PM_{2.5}$ emissions were estimated as a post-processing step to AVERT based on limited available data regarding $PM_{2.5}$ emission rates. Emission rates in 2015 are ~1/5th those of 2010 (following Cai et al. 2012, 2013). Emission rates prior to 2010 were held at 2010 levels. Both of these are conservative assumptions (avoided $PM_{2.5}$ emissions might be higher). While SO_2 and NO_x emissions are directly measured at the stack of every large power plant, $PM_{2.5}$ emission rates are based on detailed engineering estimates.

3. Estimate Avoided Climate Impacts (monetized value) and Avoided Health Impacts (incidences and monetized value)

Methods

Estimating Avoided Climate Impacts from CO_2

- Monetized CO_2 benefits based on a meta-analysis of 'Social Cost of Carbon' (SCC) estimates (e.g., Tol 2008; 2011; 2013)
  - SCC includes global impacts on agricultural productivity, human health, property damages, and ecosystem services
- Central value: ranges from $34 – $41 per $MTCO_2$ from 2007–2015
  - Central value based on median value from Tol (2013) meta-analysis
  - Similar to U.S. Interagency Working Group (IWG) "central value" SCC
- To capture significant uncertainty in and variation across SCC estimates, a lower estimate based on work by Havranek et al. (2015) is applied, as is a higher estimate based on van den Bergh and Botzen (2014)
  - Lower and higher estimates span very wide range: $0.0 and $125 per $MTCO_2$ (in 2010)
  - These values roughly bracket the meta-analysis from Tol (2013) with zero and 125 $ per $MTCO_2$ equaling approximately the 25th and 85th percentile of all estimates
- Appendix C shows results calculated with the Interagency Working Group (IWG) SCC, used recently in U.S. regulatory proceedings

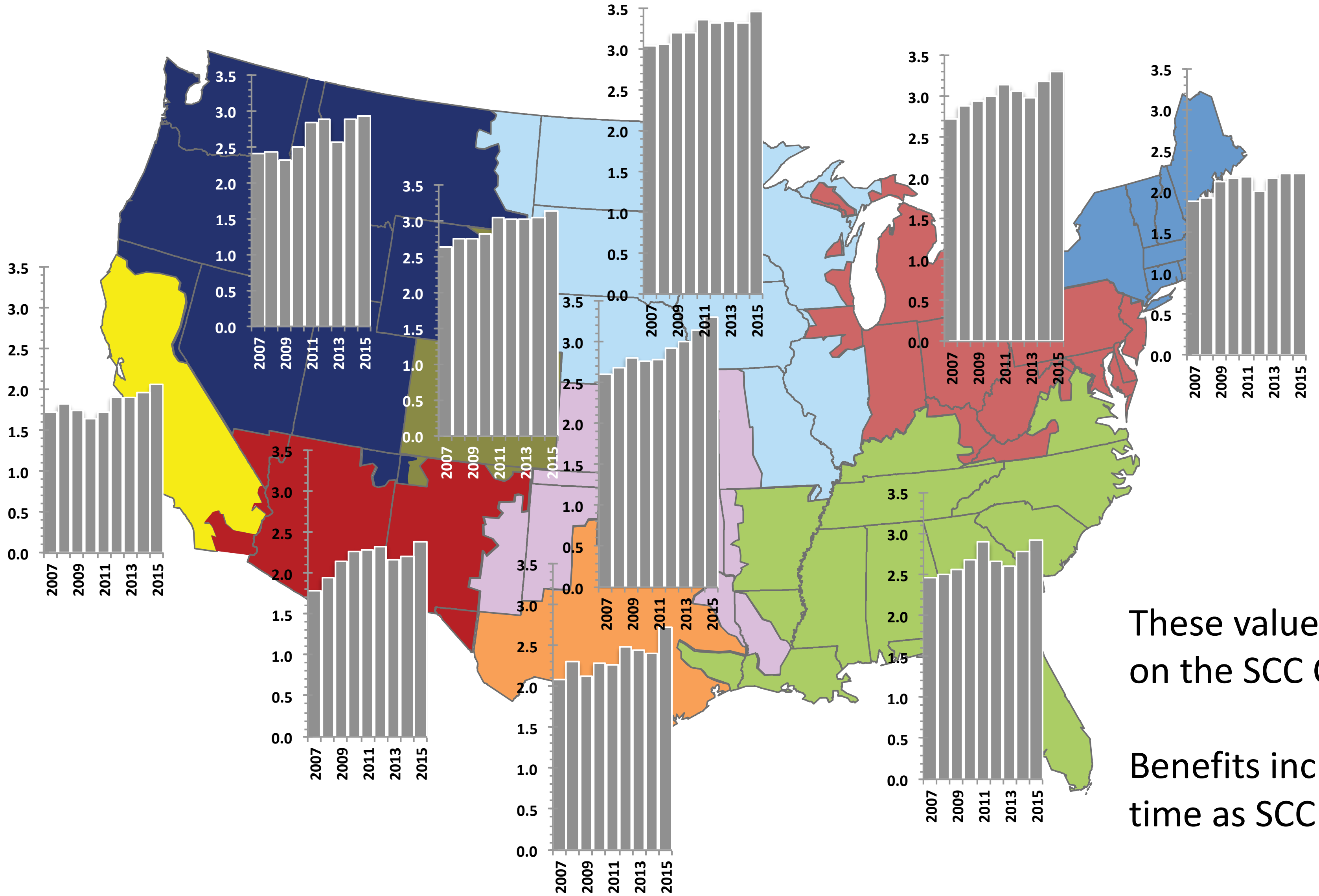
Estimating Avoided Health Impacts from SO_2, NO_x, and $PM_{2.5}$

- Monetized air quality benefits with multiple methods
  - EPA benefit-per-ton impact analysis (low and high values)*‡
  - EPA COBRA model (low and high values)*
  - EASIUR model (low and high values)*
  - APEEP model version 2 (AP2)*‡
- Each approach covers pollution transport, transformation, exposure, and impact→ but each does so differently, covering varying impact pathways
- Models account for *particulate matter and ‡ozone exposure
- EPA and EASIUR "low" and "high" estimates are based on range in literature on impact of pollution on health outcomes
- Central value is reported based on simple average of all estimates

3. Estimate Avoided Climate Impacts (monetized value) and Avoided Health Impacts (incidences and monetized value)

Results

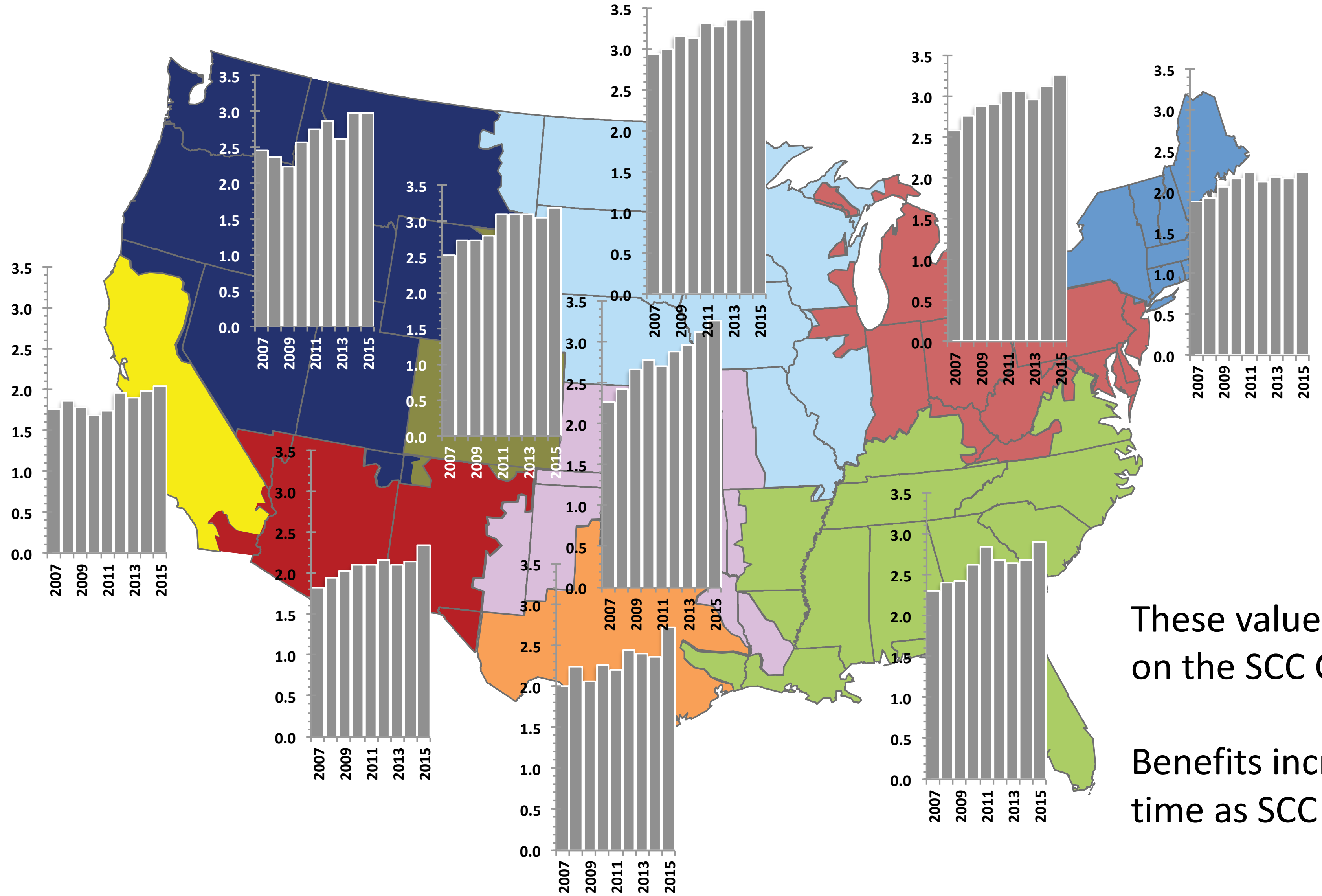
CO_2 Avoided Climate Impacts (¢/kWh-Wind): Higher in Regions with Greater Coal Offset



These values are based on the SCC Central Value

Benefits increase over time as SCC increases

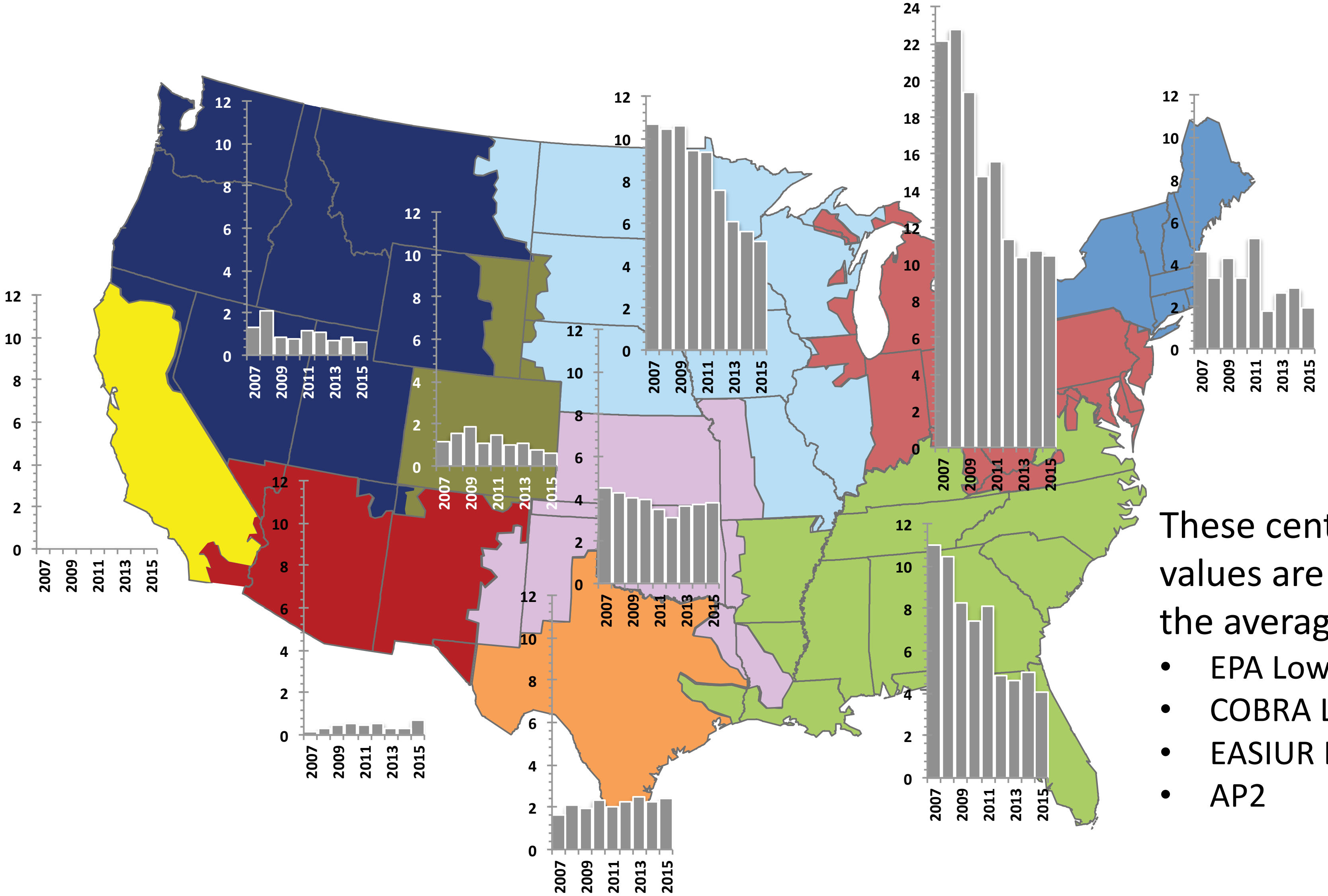
CO_2 Avoided Climate Impacts (¢/kWh-Solar): Regional Results Very Similar to Wind



These values are based on the SCC Central Value

Benefits increase over time as SCC increases

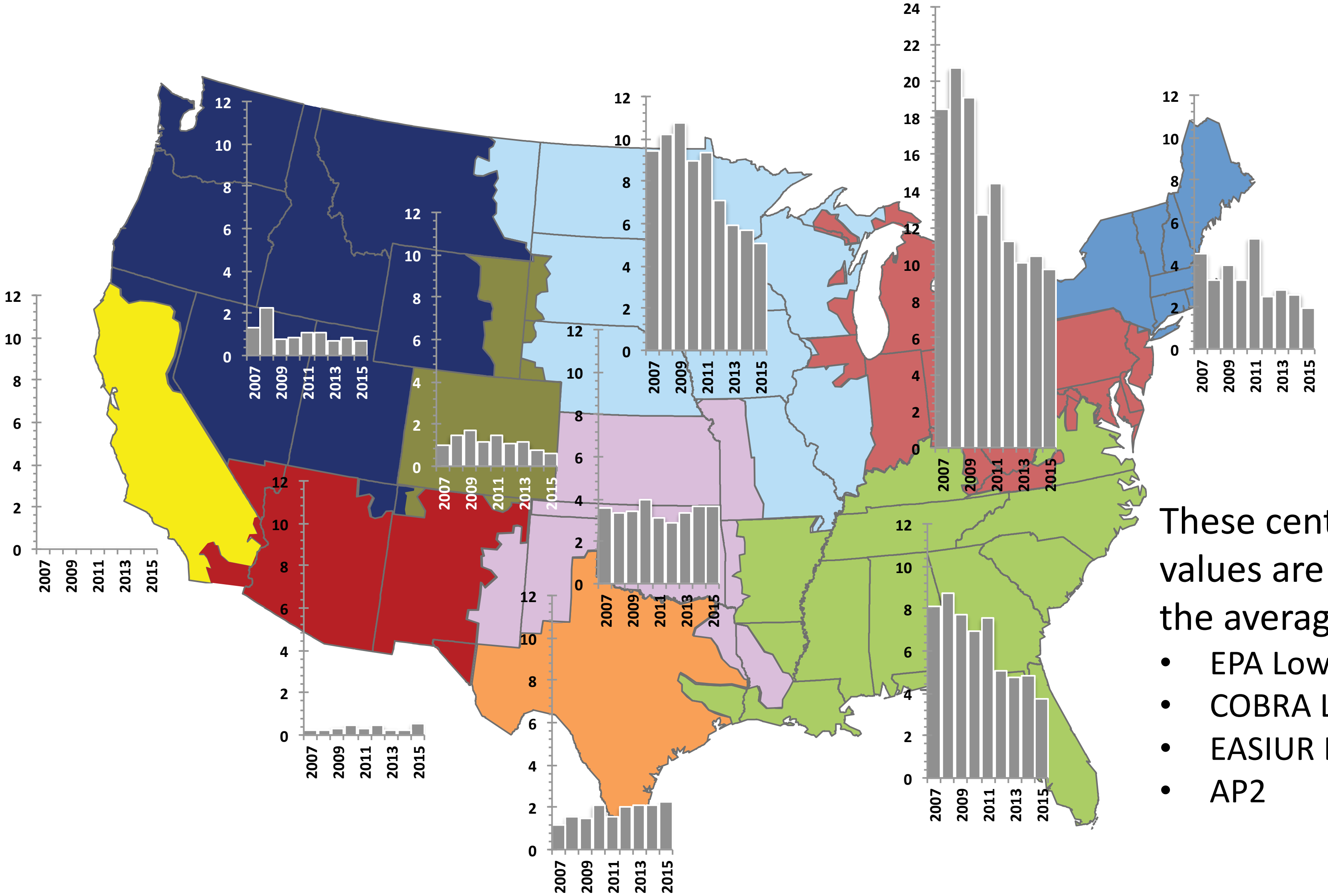
SO_2 Avoided Health Impacts (¢/kWh-Wind): Regional Variations, Decrease with Time



These central estimate values are based on the average of:

- EPA Low and High
- COBRA Low and High
- EASIUR Low and High
- AP2

SO_2 Avoided Health Impacts (¢/kWh-Solar): Slightly Lower than Wind in Some Regions



These central estimate values are based on the average of:

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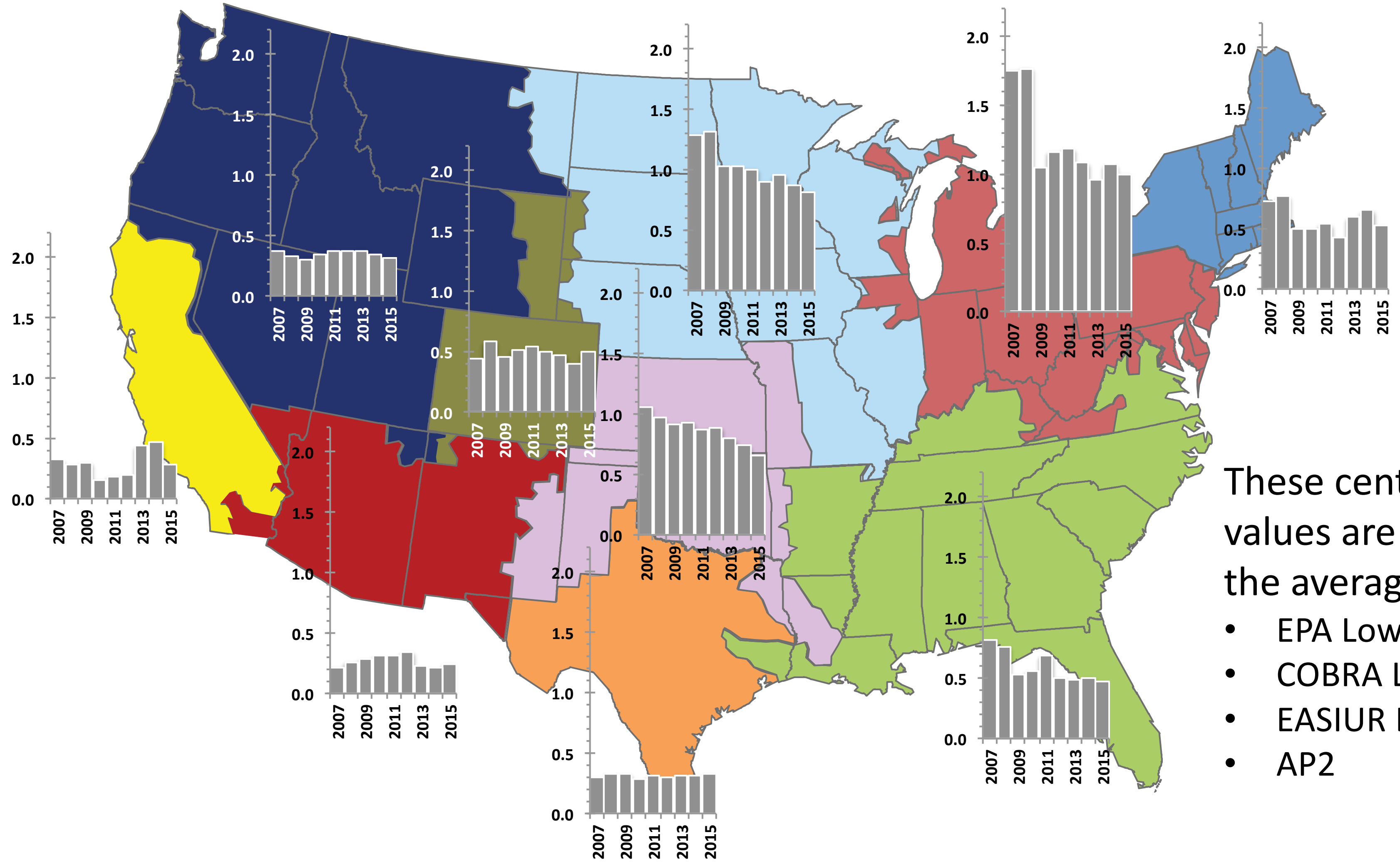
- EASIUR Low and High
- AP2

NO_x Avoided Health Impacts (¢/kWh-Wind): Lower and Less Regional Variation than SO_2



These central estimate values are based on the average of:

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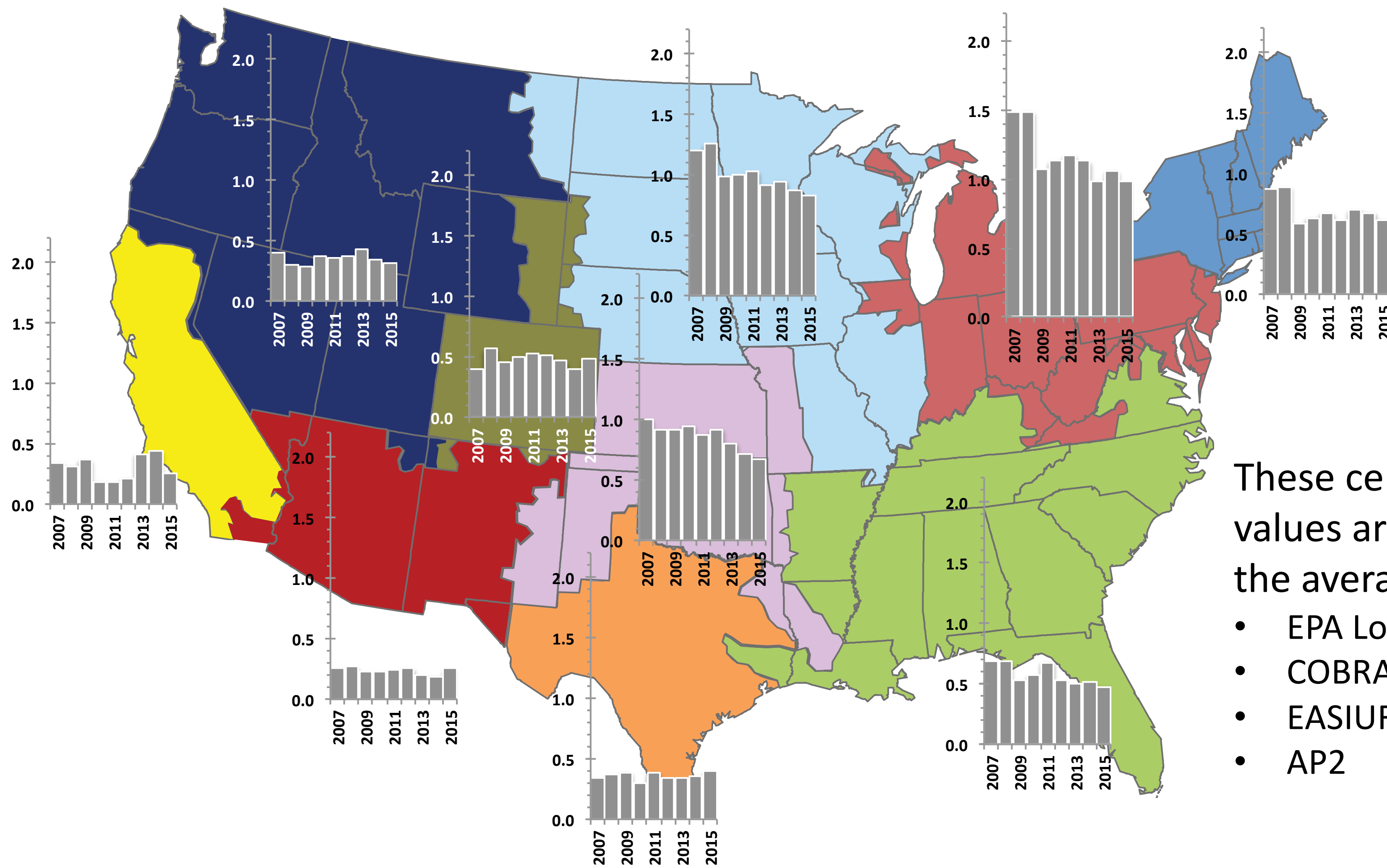
- COBRA Low and High
- EASIUR Low and High
- AP2

NO_x Avoided Health Impacts (¢/kWh-Solar): Results Similar to Wind



These central estimate values are based on the average of:

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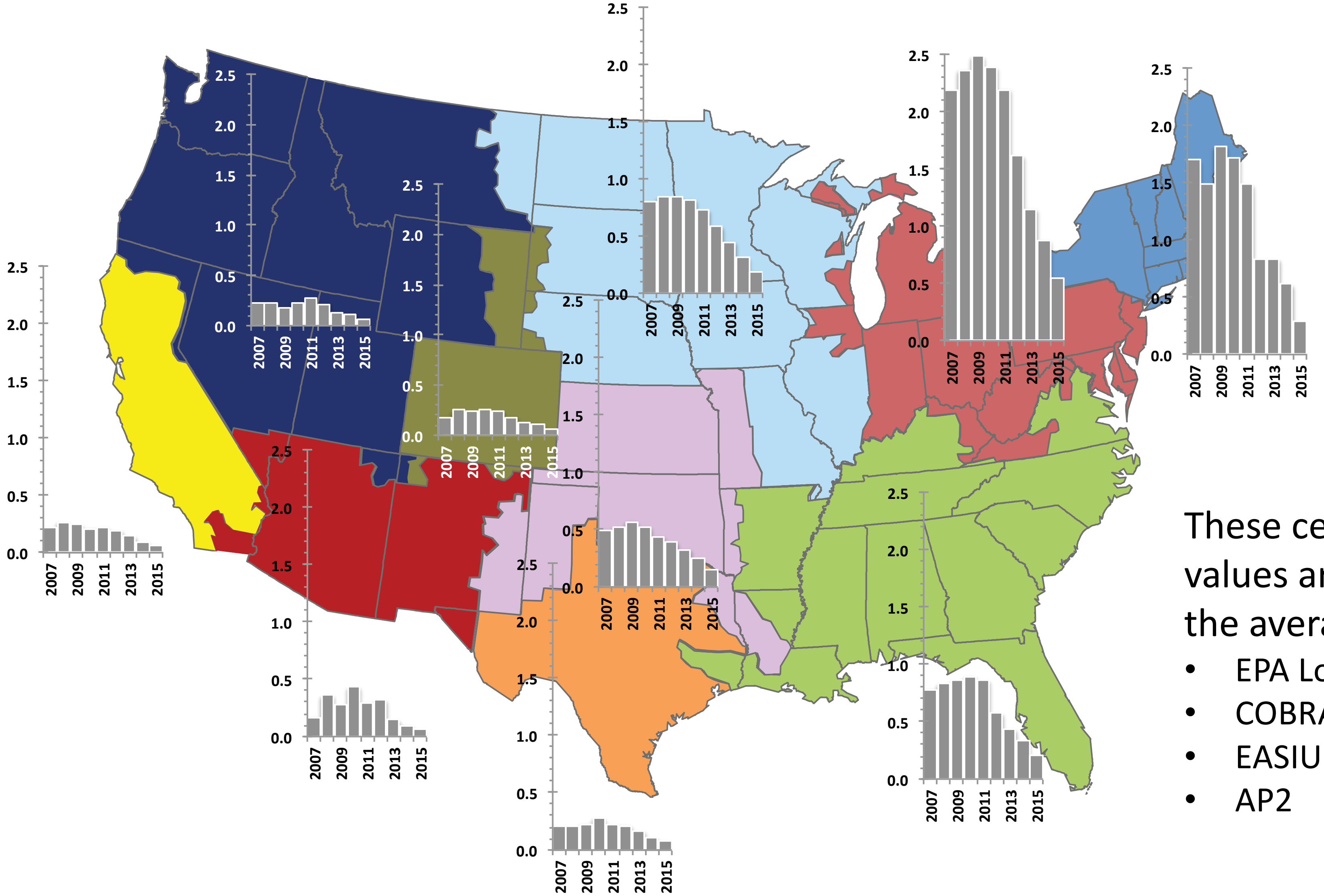
- COBRA Low and High
- EASIUR Low and High
- AP2

$PM_{2.5}$ Avoided Health Impacts (¢/kWh-Wind): Regional Variations, Decrease with Time



These central estimate values are based on the average of:

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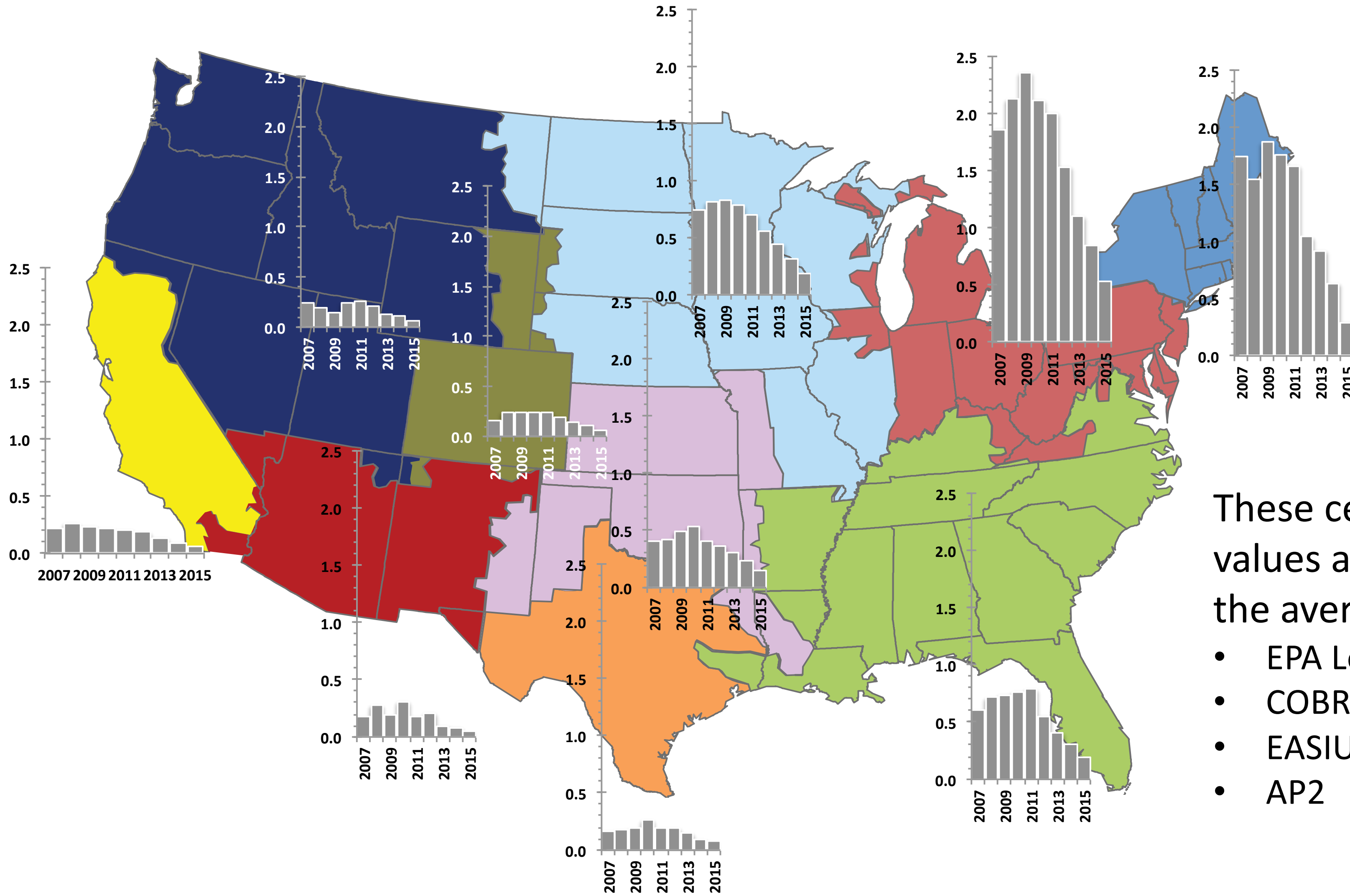
PM$_{2.5}$ Avoided Health Impacts (¢/kWh-Solar): Slightly Lower than Wind in Some Regions

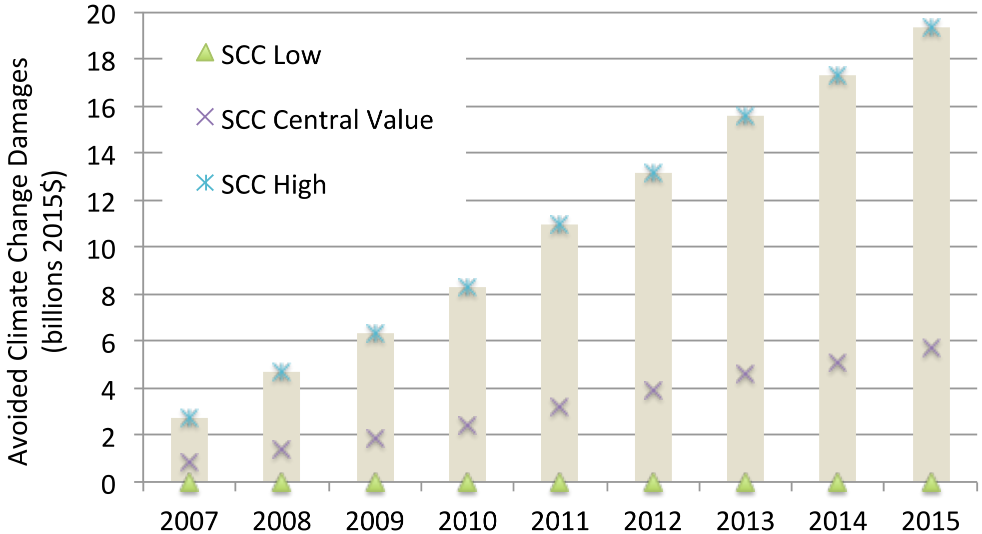


These central estimate values are based on the average of:

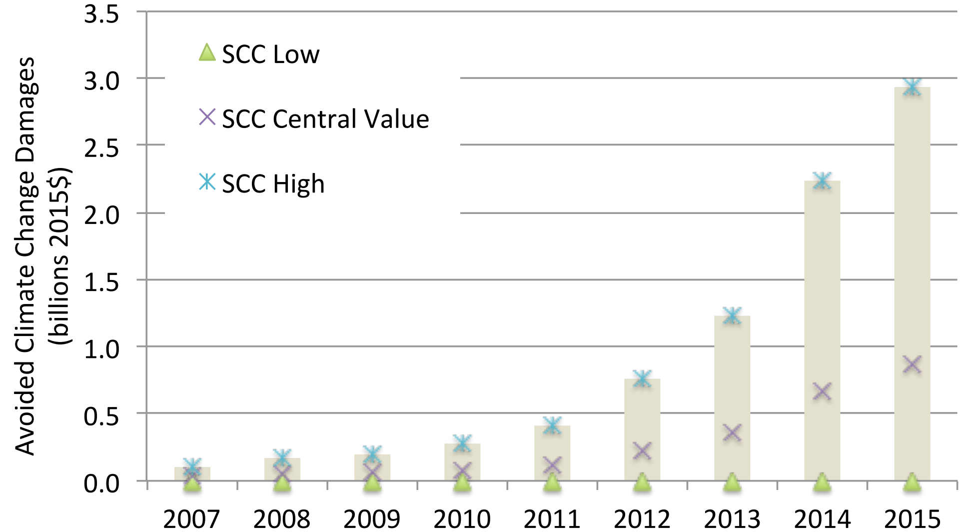
- EPA Low and High
- COBRA Low and High
- EASIUR Low and High
- AP2

National Avoided Climate Damages: Literature Based SCC, Large Uncertainty

Wind

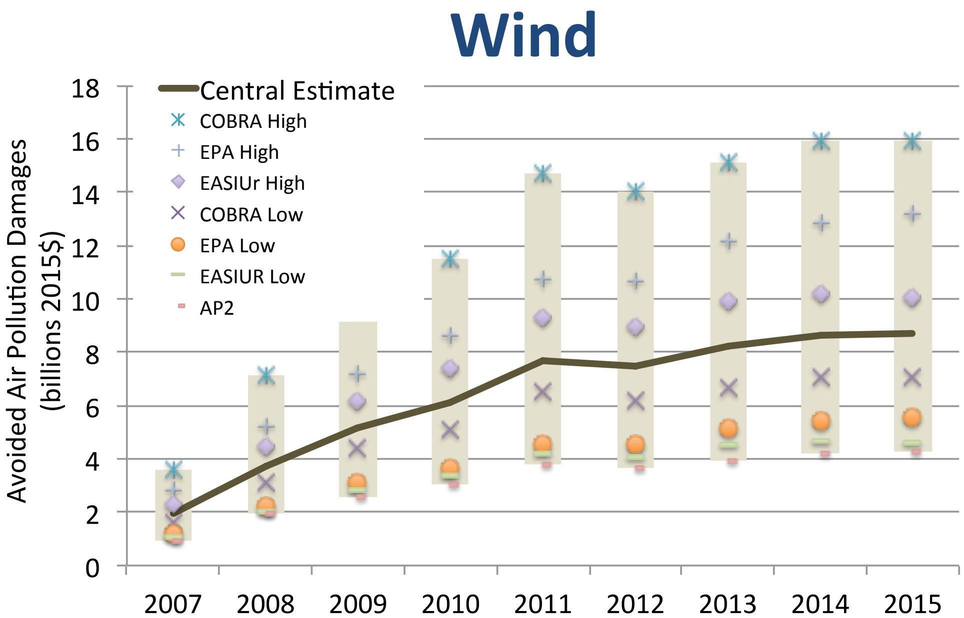


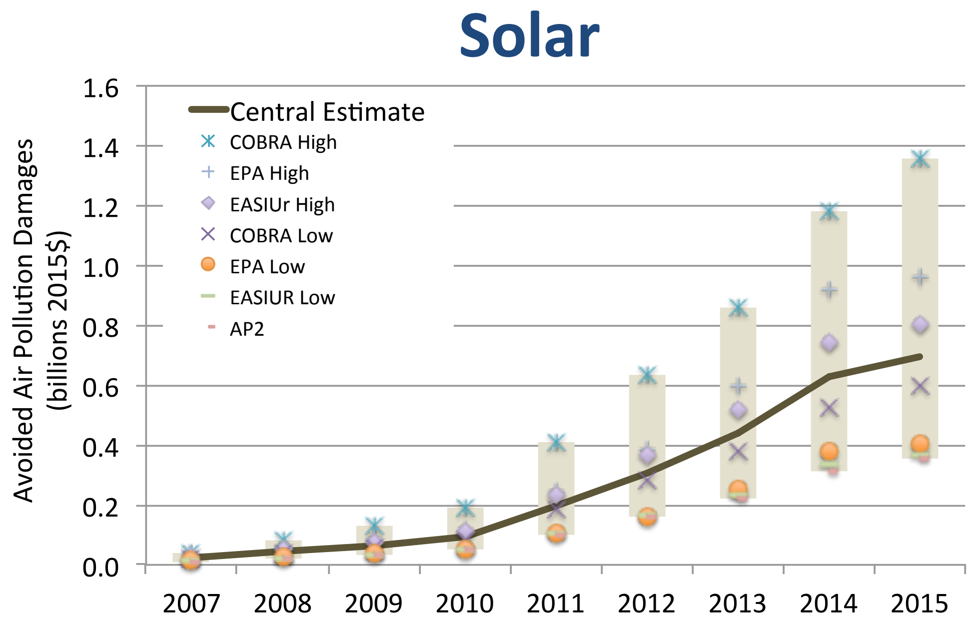
Solar



	2007 - 2015				2015			
	Total Benefits (Billions 2015$)		Avg. Marginal Benefits (¢/kWh)		Total Benefits (Billions 2015$)		Avg. Marginal Benefits (¢/kWh)	
	Central	Range	Central	Range	Central	Range	Central	Range
Wind	29.0	0.0 – 98.5	2.8	0.0 – 9.4	5.7	0.0 – 19.3	3.0	0.0 – 10.2
Solar	2.5	0.0 – 8.3	2.2	0.0 – 7.5	0.9	0.0 – 2.9	2.3	0.0 – 7.8

National Avoided Air Pollution Damages: Significant Uncertainty in Magnitude



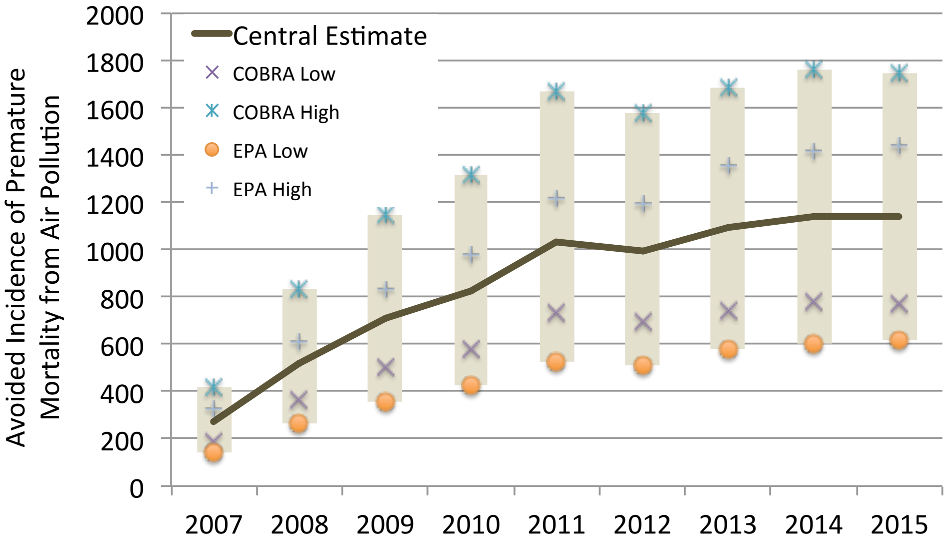


The central estimate is the simple average of the suite of other estimates

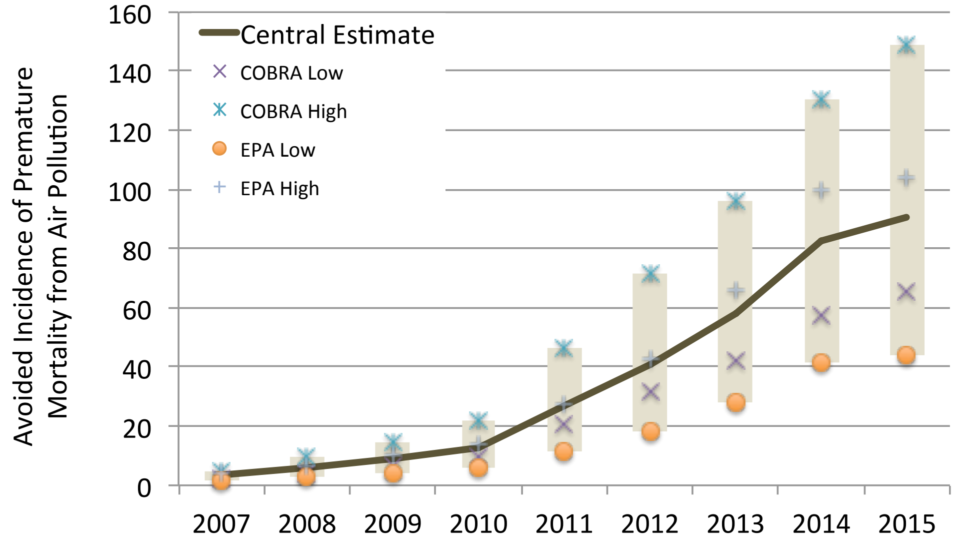
	2007 - 2015				2015			
	Total Benefits (Billions 2015$)		Avg. Marginal Benefits (¢/kWh)		Total Benefits (Billions 2015$)		Avg. Marginal Benefits (¢/kWh)	
	Central	Range	Central	Range	Central	Range	Central	Range
Wind	57.6	28.4 – 107.9	5.5	2.7 – 10.3	8.7	4.3 – 15.9	4.6	2.3 – 8.4
Solar	2.5	1.3 – 4.9	2.2	1.1 – 4.4	0.7	0.4 – 1.4	1.8	1.0 – 3.6

National Avoided Air Pollution Mortalities

Wind



Solar



The central estimate is the simple average of the suite of other estimates

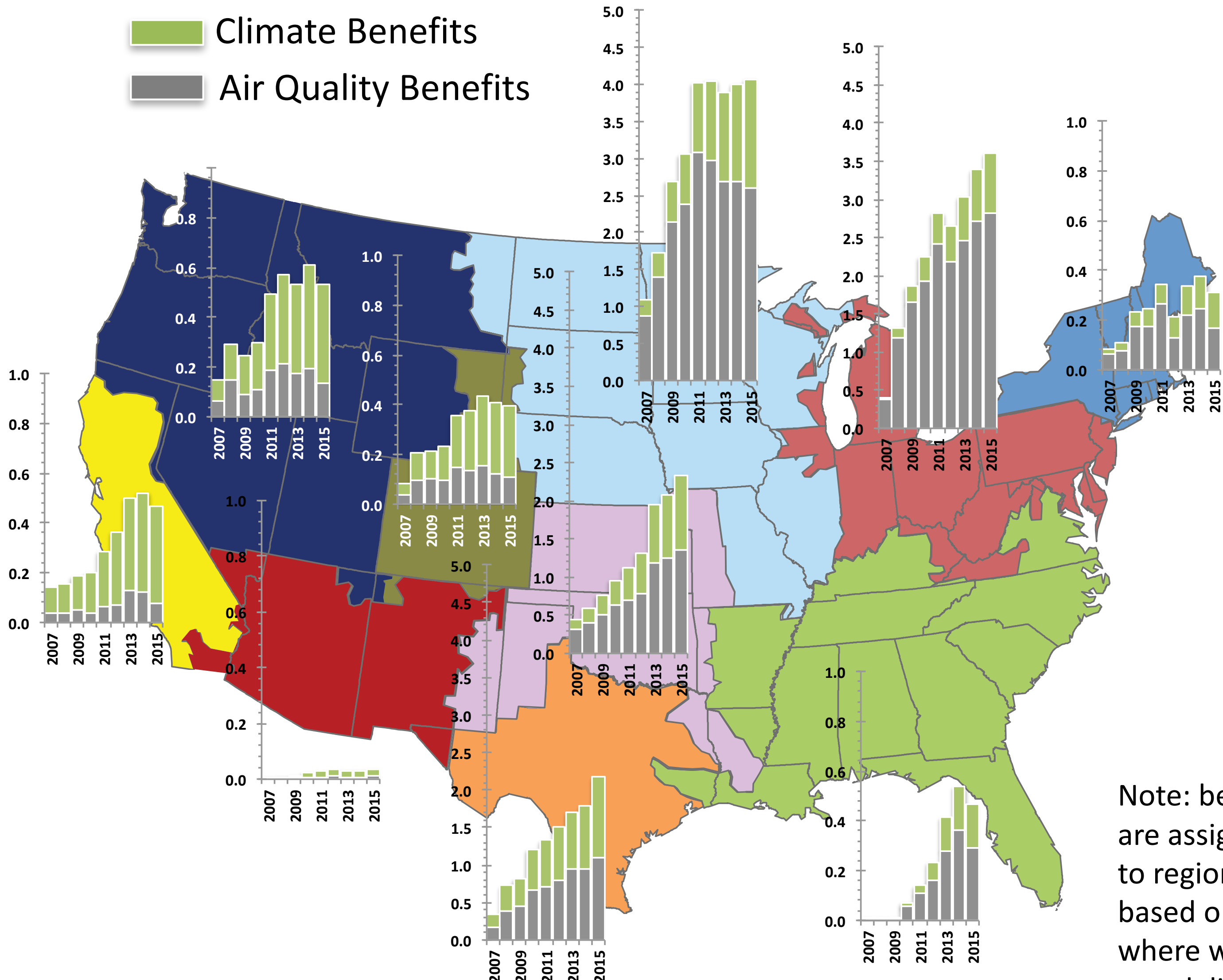
	2017 - 2015		2015	
	Total Benefits (Avoided Mortalities)		Total Benefits (Avoided Mortalities)	
	Central	Range	Central	Range
Wind	7,700	4,000 – 12,200	1,100	600 – 1,700
Solar	300	200 – 500	90	40 – 150

Total Regional Avoided Climate & Air Pollution Damages: Wind ($ Billion, central case)

The largest wind power benefits accrued in the Mid-West, Great Lakes/Mid-Atlantic, Central, and Texas regions. Note the larger scale for those regions compared others.

In some regions, climate benefits dominate; in others health-related air pollution benefits are the dominant driver of total benefits.

All regions benefit from wind, including the Southeast – mostly from imported wind generation.



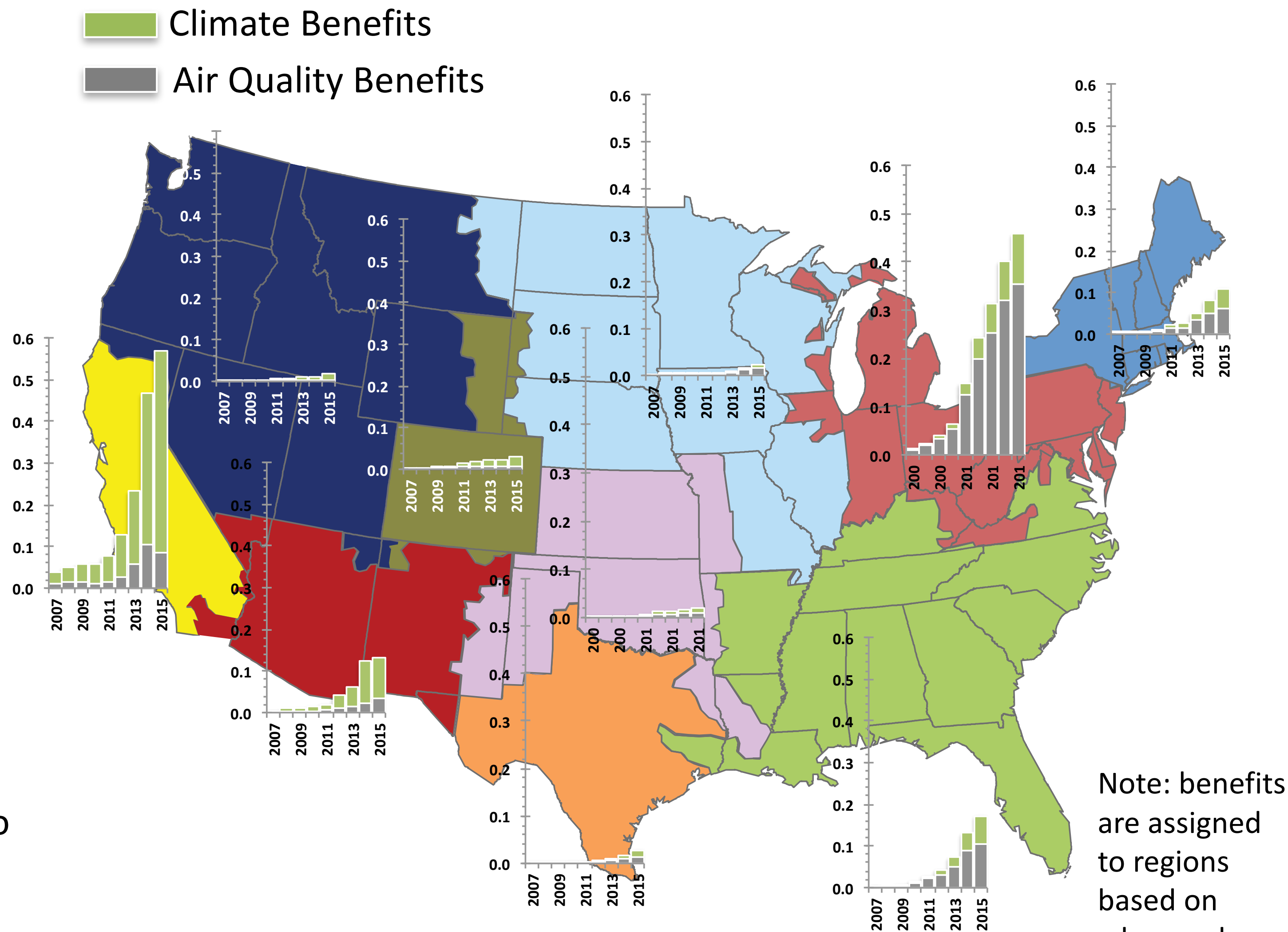
Note: benefits are assigned to regions based on where wind was delivered

Total Regional Avoided Climate & Air Pollution Damages: Solar ($ Billion, central case)

Largest benefits accrued in the Great Lakes/Mid-Atlantic and California regions.

California benefits are mostly in the form of climate benefits while the majority of benefits in the Great Lakes/Mid-Atlantic come from air quality.

Benefits are increasing rapidly over time with growth in solar. But total benefits are lower than wind partly because of lower solar output, but also because solar deployment has focused on areas with more gas and less coal.

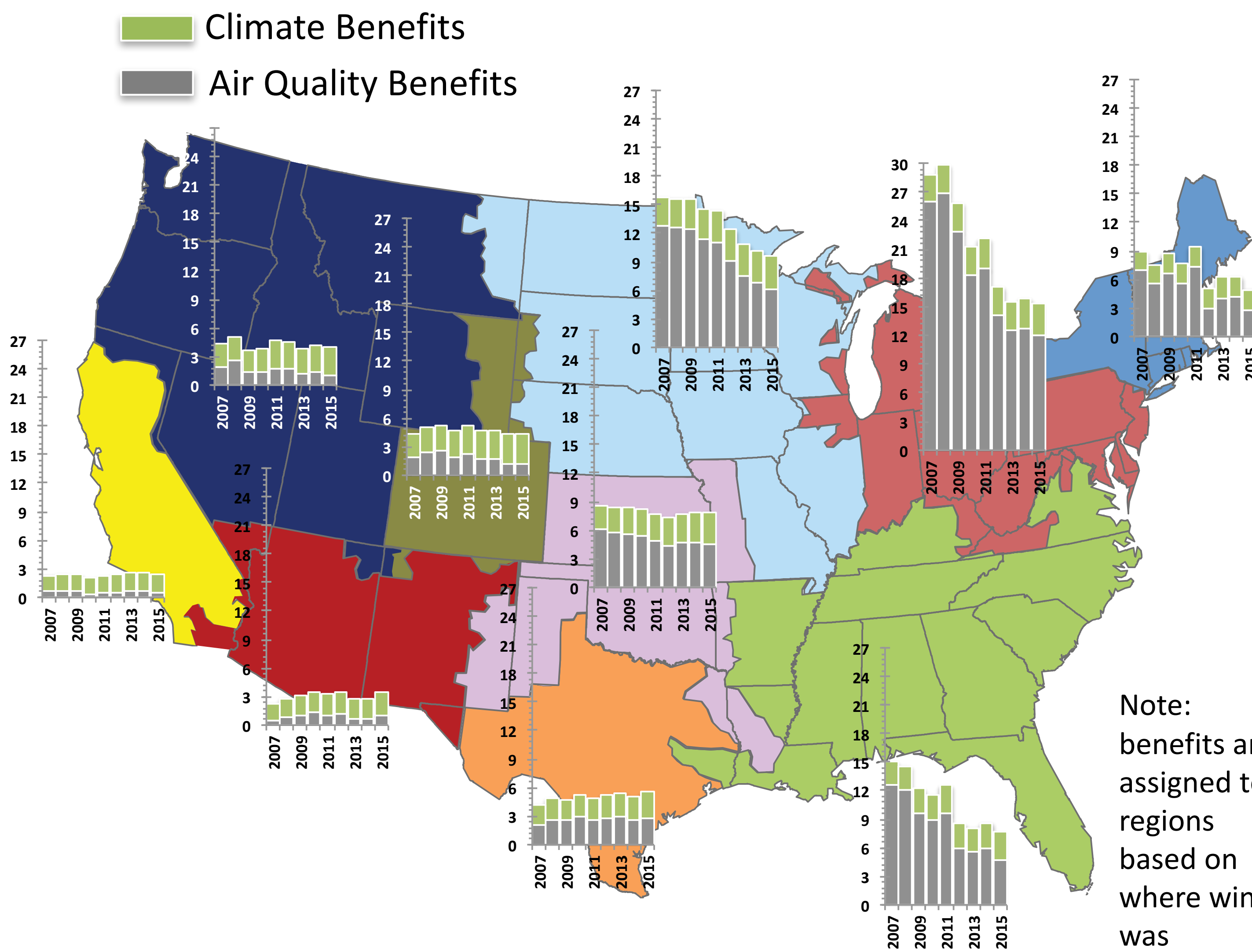


Note: benefits are assigned to regions based on where solar was delivered

Marginal Regional Avoided Climate & Air Pollution Damages: Wind (¢/kWh-Wind, central case)

The largest marginal wind power benefits accrued in the Mid-West and Great Lakes/Mid-Atlantic regions, dominated by air quality improvements; those marginal benefits have decreased with time but remain very high.

Although there are some regional differences in marginal climate benefits, these differences are small compared to the regional differences in marginal air quality benefits.



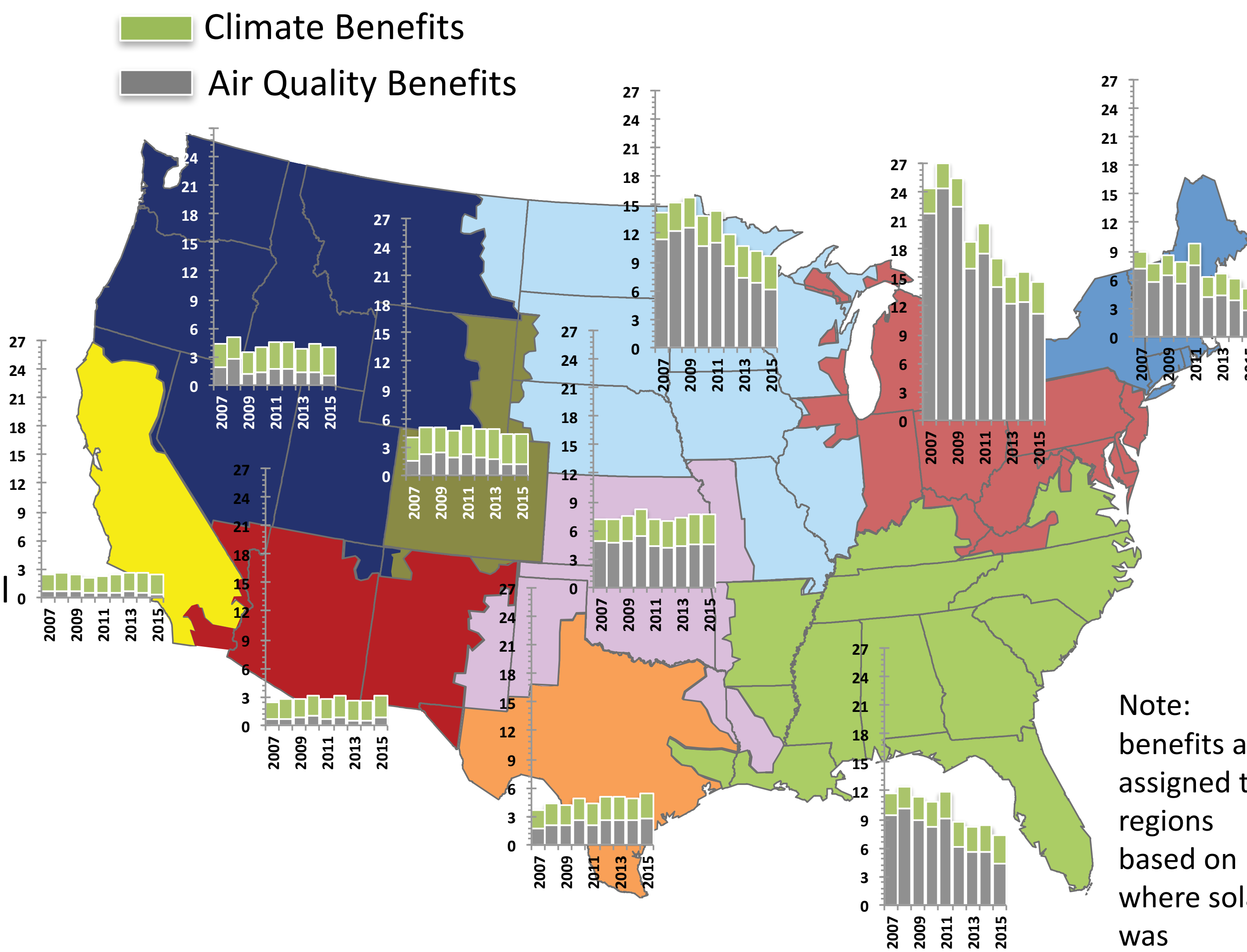
Note: benefits are assigned to regions based on where wind was delivered

Marginal Regional Avoided Climate & Air Pollution Damages: Solar (¢/kWh-Solar, central case)

The largest marginal solar power benefits accrued in the Mid-West and Great Lakes/Mid-Atlantic regions, dominated by air quality; marginal benefits have decreased with time but remain very high.

Although there are some regional differences in marginal climate benefits, these differences are small compared to the regional differences in marginal air quality benefits.

Overall the marginal benefits of solar are relatively similar to those of wind.



Note: benefits are assigned to regions based on where solar was delivered

Conclusions

Conclusions: Total Benefits 2007 - 2015

Wind

- Climate Savings: **$29 Billion** (range 0.0-98.5); **2.8 ¢/kWh** (range 0.0 – 8.3)
- Air Pollution Savings: **$58 Billion** (range 28-108); **5.5 ¢/kWh** (range 2.7 – 10.3)
- Avoided Premature Mortalities: **7,700** (range 4,000 – 12,200)

Solar

- Climate Savings: **$2.5 Billion** (range 0.0 – 8.3); **2.2 ¢/kWh** (range 0.0 – 7.5)
- Air Pollution Savings: **$2.5 Billion** (range 1.3 – 4.9); **2.2 ¢/kWh** (range 1.1 – 4.4)
- Avoided Premature Mortalities: **300** (range 200 – 500)

Total benefits from wind exceed solar in large measure because of greater historical generation levels; marginal ¢/kWh benefits are also greater for wind, due largely to the fact that wind has historically been deployed in more coal-heavy regions

Conclusions: Total Benefits in 2015 Alone

Wind

- Climate Savings: **$5.7 Billion** (range 0-19); **3.0 ¢/kWh** (range 0.0 – 10.2)
- Air Pollution Savings: **$8.7 Billion** (range 4-16); **4.6 ¢/kWh** (range 2.3 – 8.4)
- Avoided Premature Mortalities: **1,100** (range 600 – 1,700)

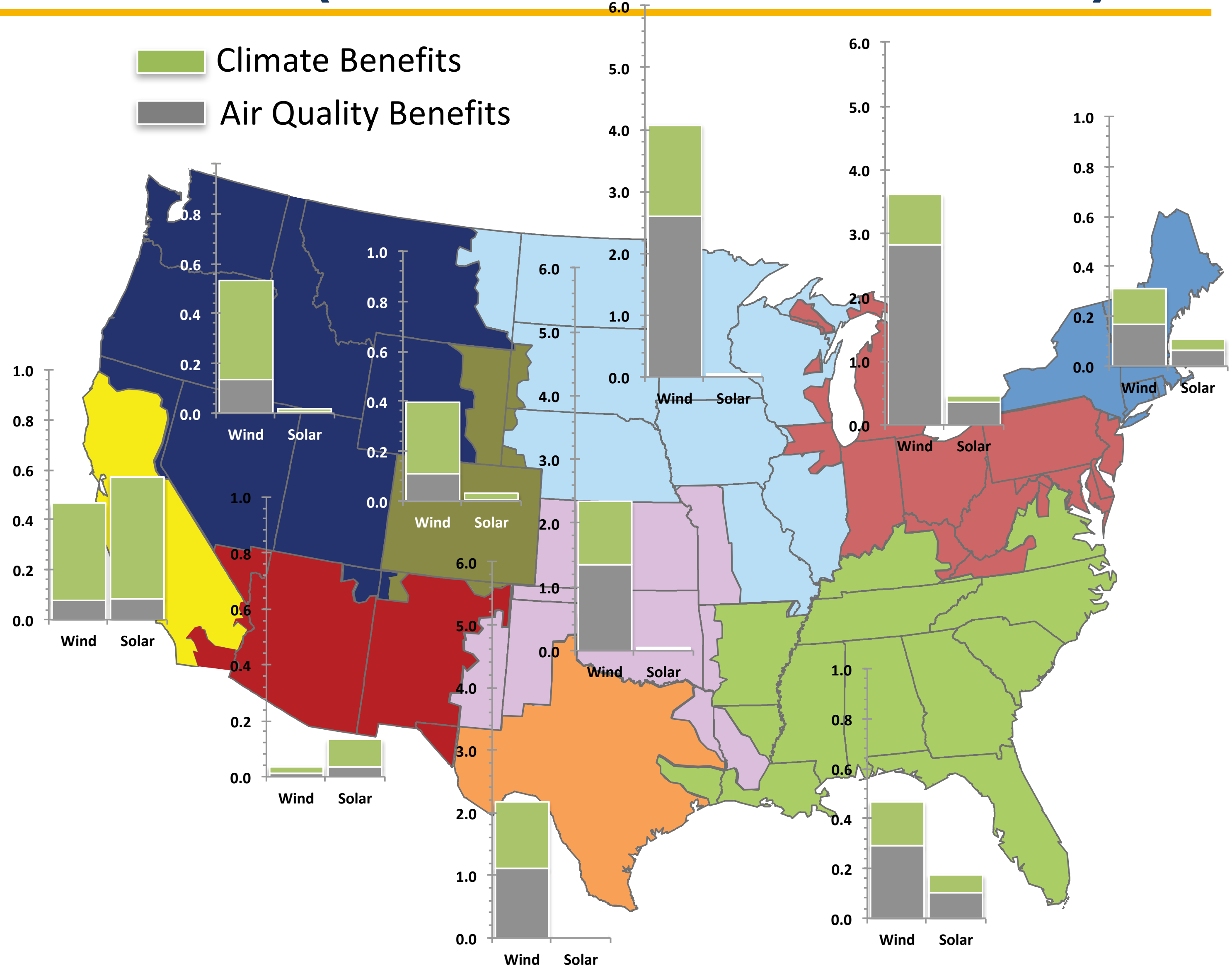
Solar

- Climate Savings: **$0.9 Billion** (range 0.0 – 2.9); **2.3 ¢/kWh** (range 0.0 – 7.8)
- Air Pollution Savings: **$0.7 Billion** (range 0.4 – 1.4); **1.8 ¢/kWh** (range 1.0 – 3.6)
- Avoided Premature Mortalities: **90** (range 40 – 150)

Total benefits from wind exceed solar in large measure because of greater 2015 generation; marginal ¢/kWh benefits are also greater for wind, due largely to the fact that wind has historically been deployed in more coal-heavy regions

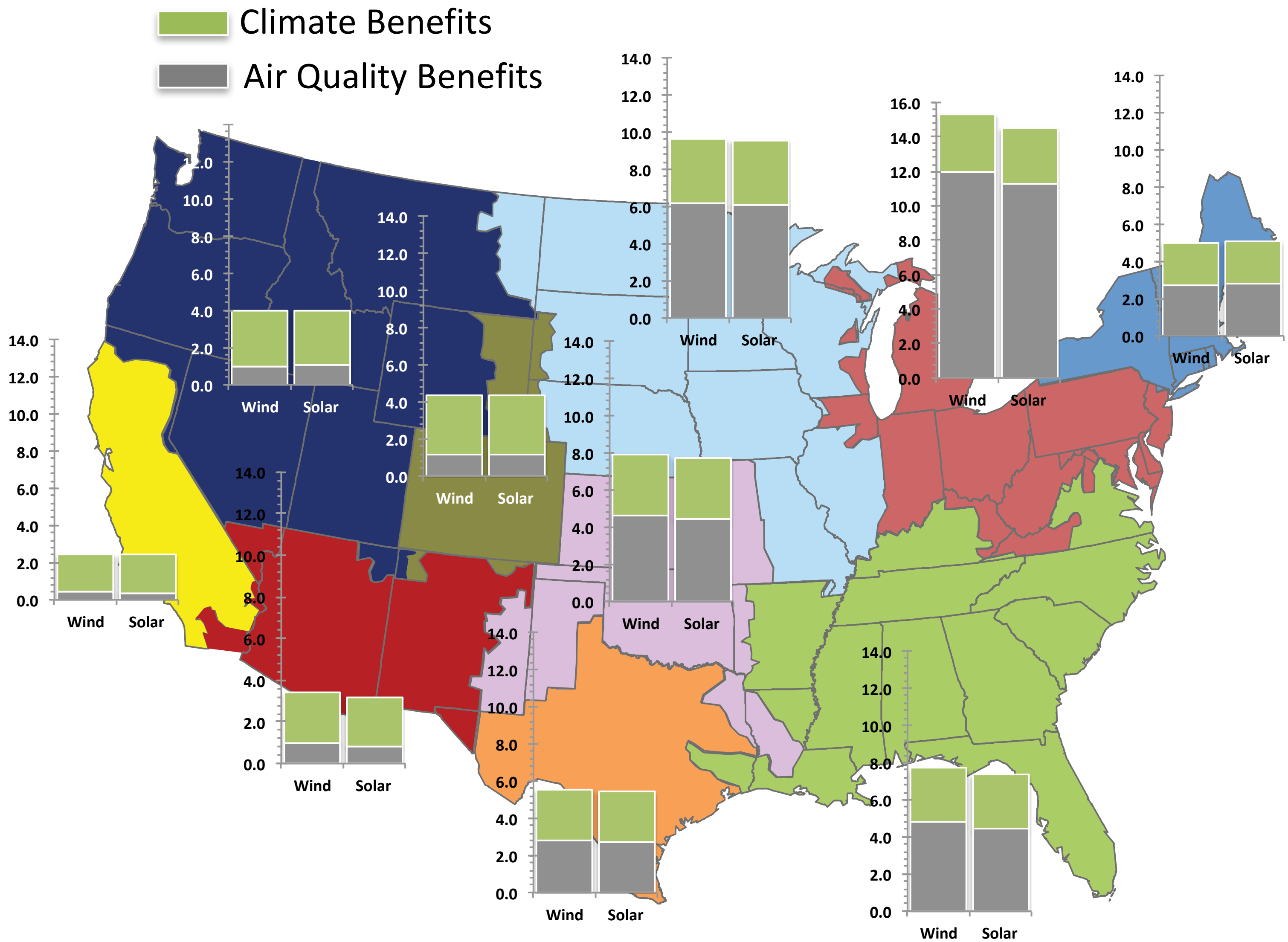
Conclusions: Regional Variations in Benefits in 2015 (Billion $, central case)

Solar power produced greater benefits than wind power in 2015 in the Southwest and California, with the reverse being true in the rest of the country.



Conclusions: Regional Variations in Benefits in 2015 (¢/kWh, central case)

Marginal climate and air quality benefits were near parity between solar and wind in 2015.



A Few Relevant Comparisons

- Wind and solar may not be the least-expensive means of achieving these benefits, and costs, impacts, and other benefits deserve full consideration
- Central value national air pollution and climate benefits in 2015 estimated at 7.6 ¢/kWh (wind) and 4.1 ¢/kWh (solar), but with significant variation over time and geography, and with wide range of estimates given underlying uncertainties
- Compares to:
  - Recent renewable energy certificate prices for wind as high as 5 ¢/kWh in New England, 2 ¢/kWh in Mid-Atlantic, less than 0.5 ¢/kWh in most other regions
  - For solar "carve-outs" in RPS programs, REC prices can be as high as 50 ¢/kWh, but often much lower
  - Recent wind power purchase agreement prices of ~2-3 ¢/kWh, and solar purchase agreement prices of 3-6 ¢/kWh (note, these prices include federal tax incentives)
  - Wind production tax credit of 2.3 ¢/kWh, 10-yrs; solar 30% investment tax credit

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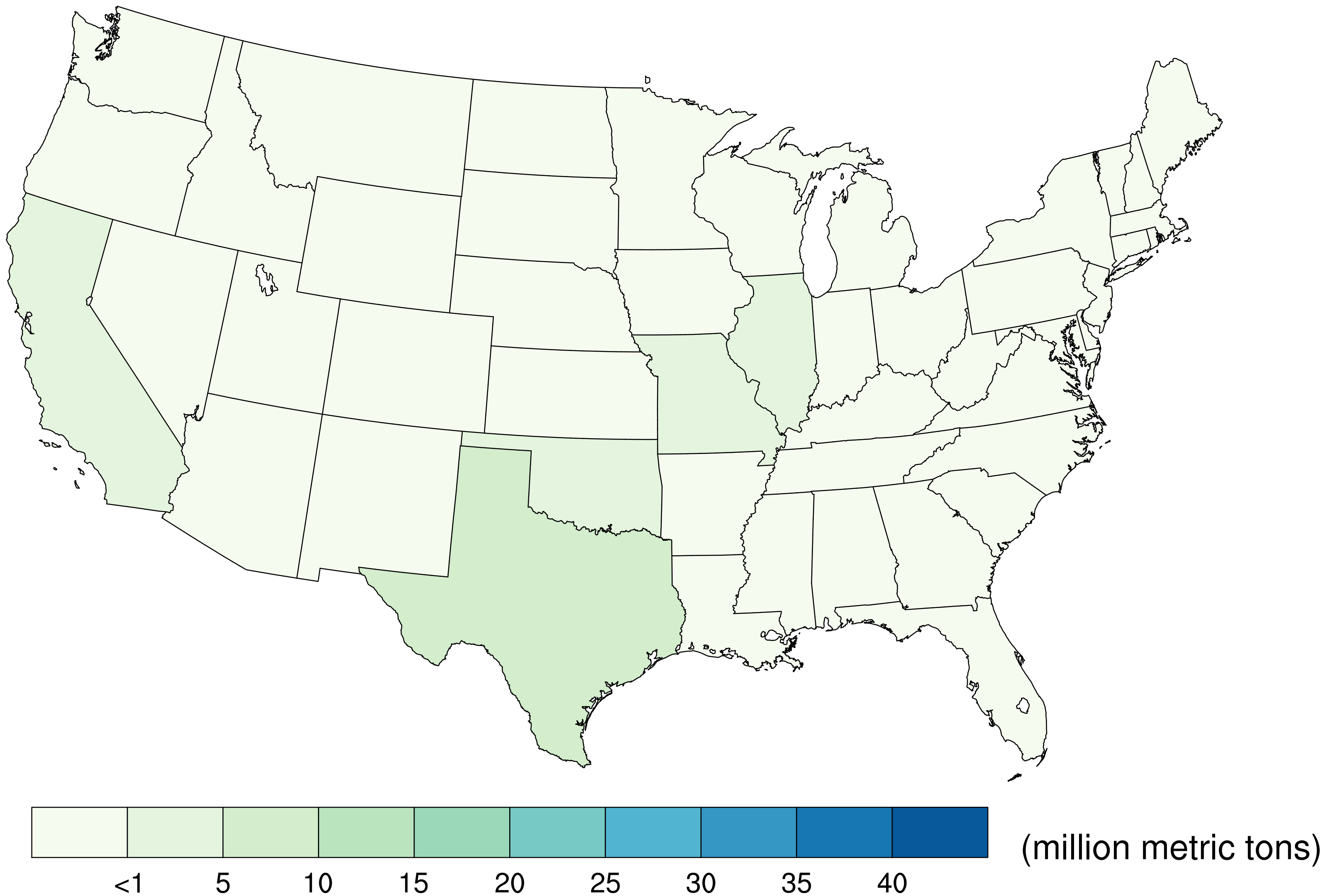
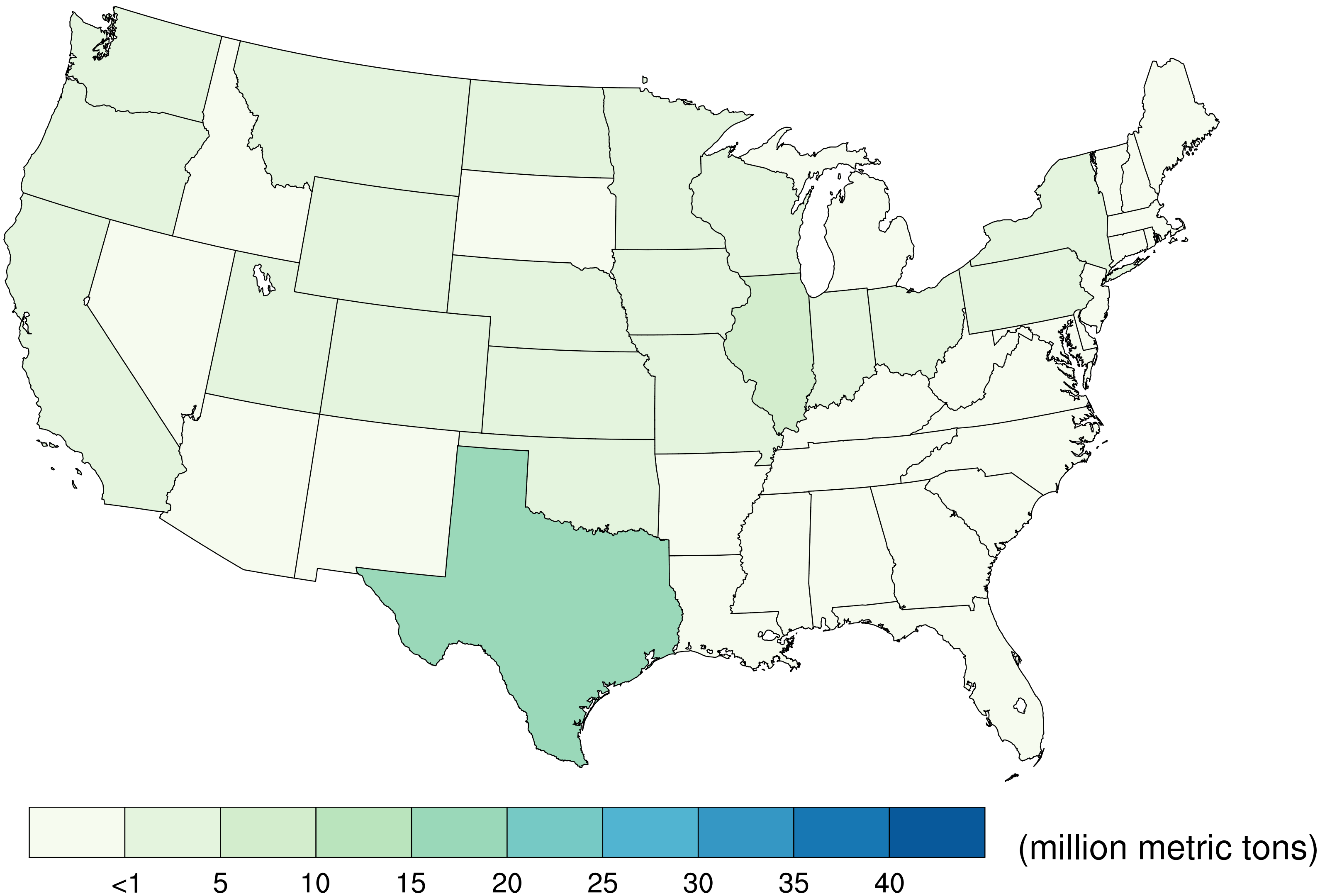
Appendix A: Wind Power -- Avoided Emissions by State

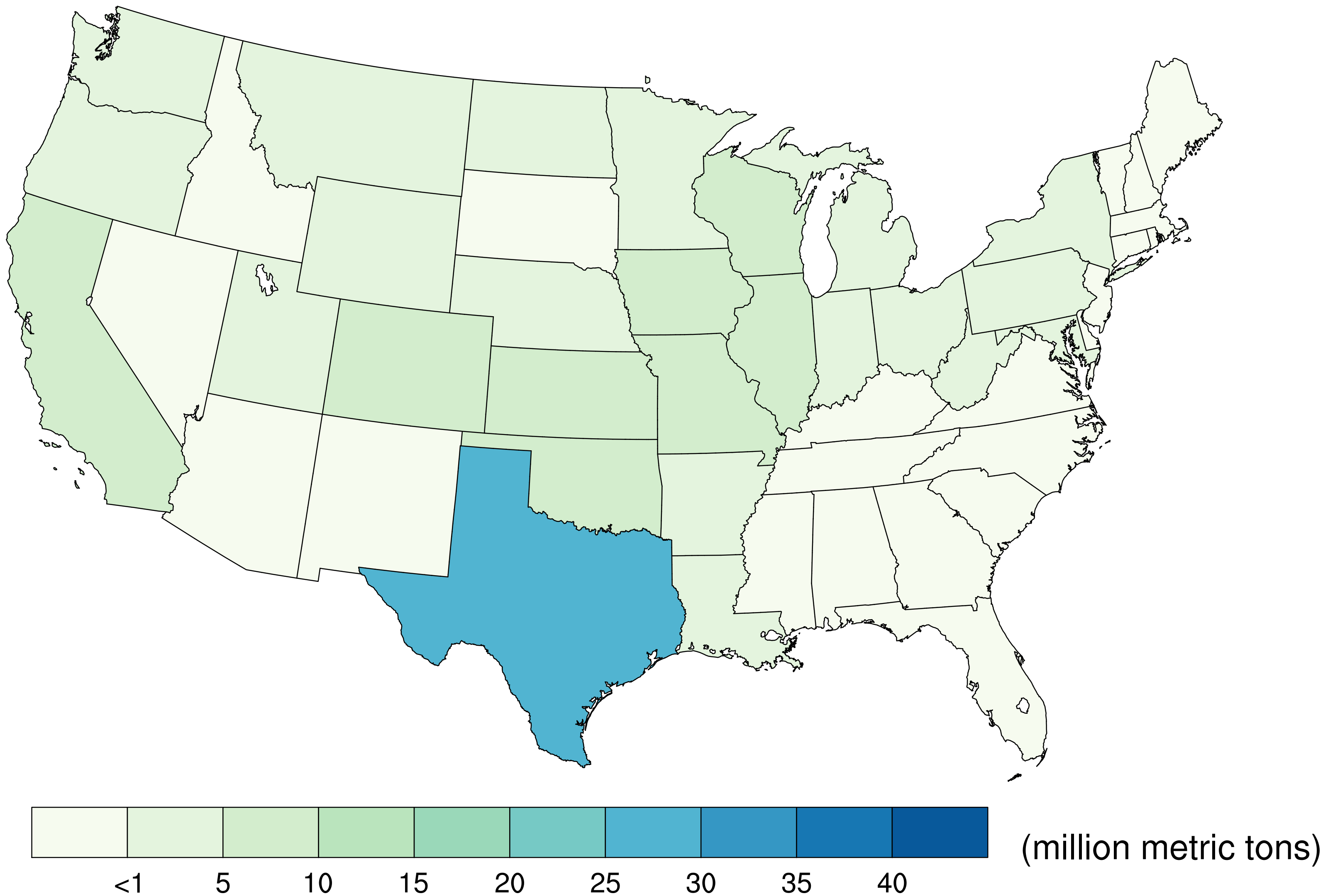
2007 CO_2 Avoided Emissions from Wind



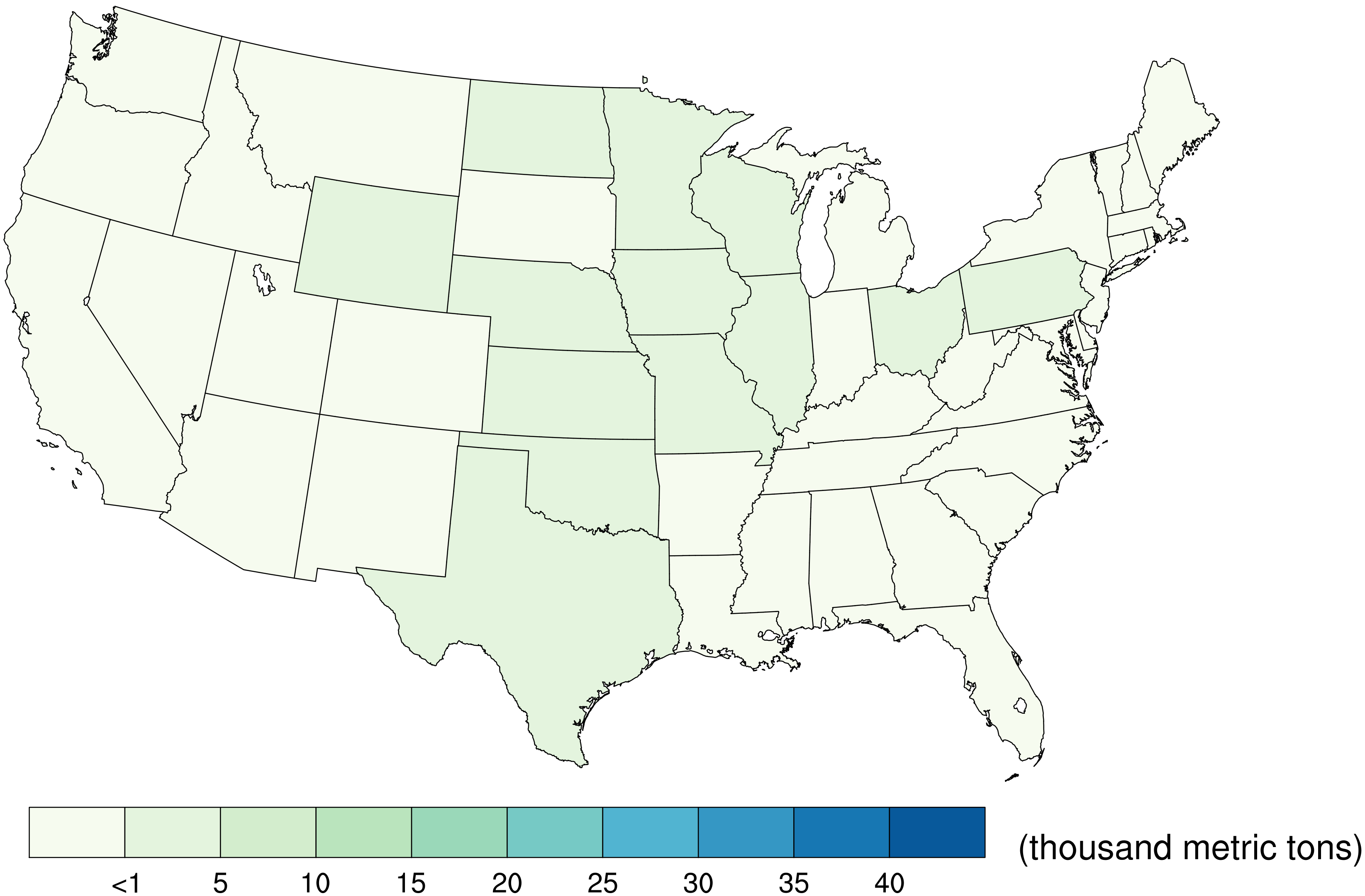
2011 CO_2 Avoided Emissions from Wind



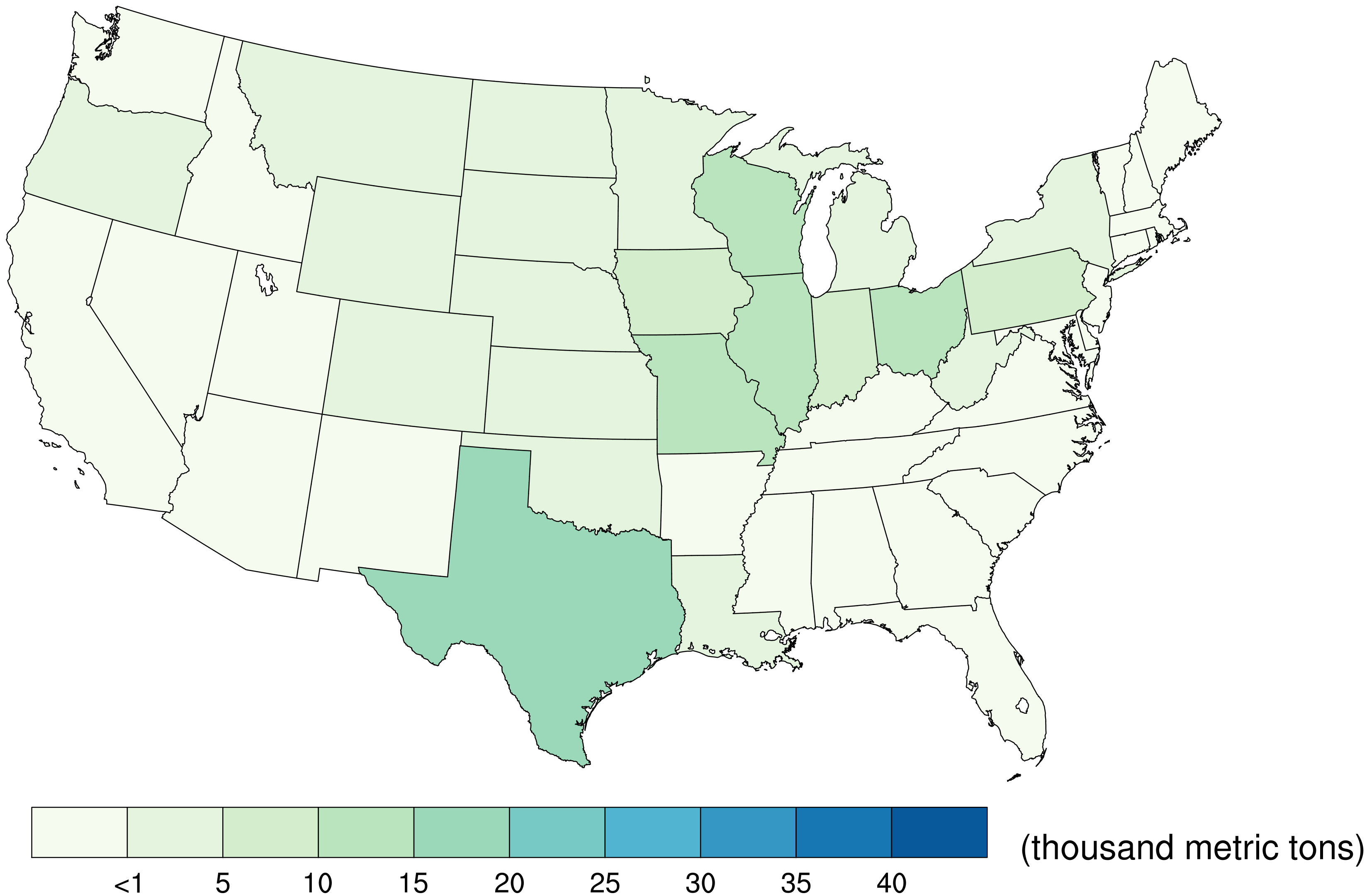
2015 CO_2 Avoided Emissions from Wind



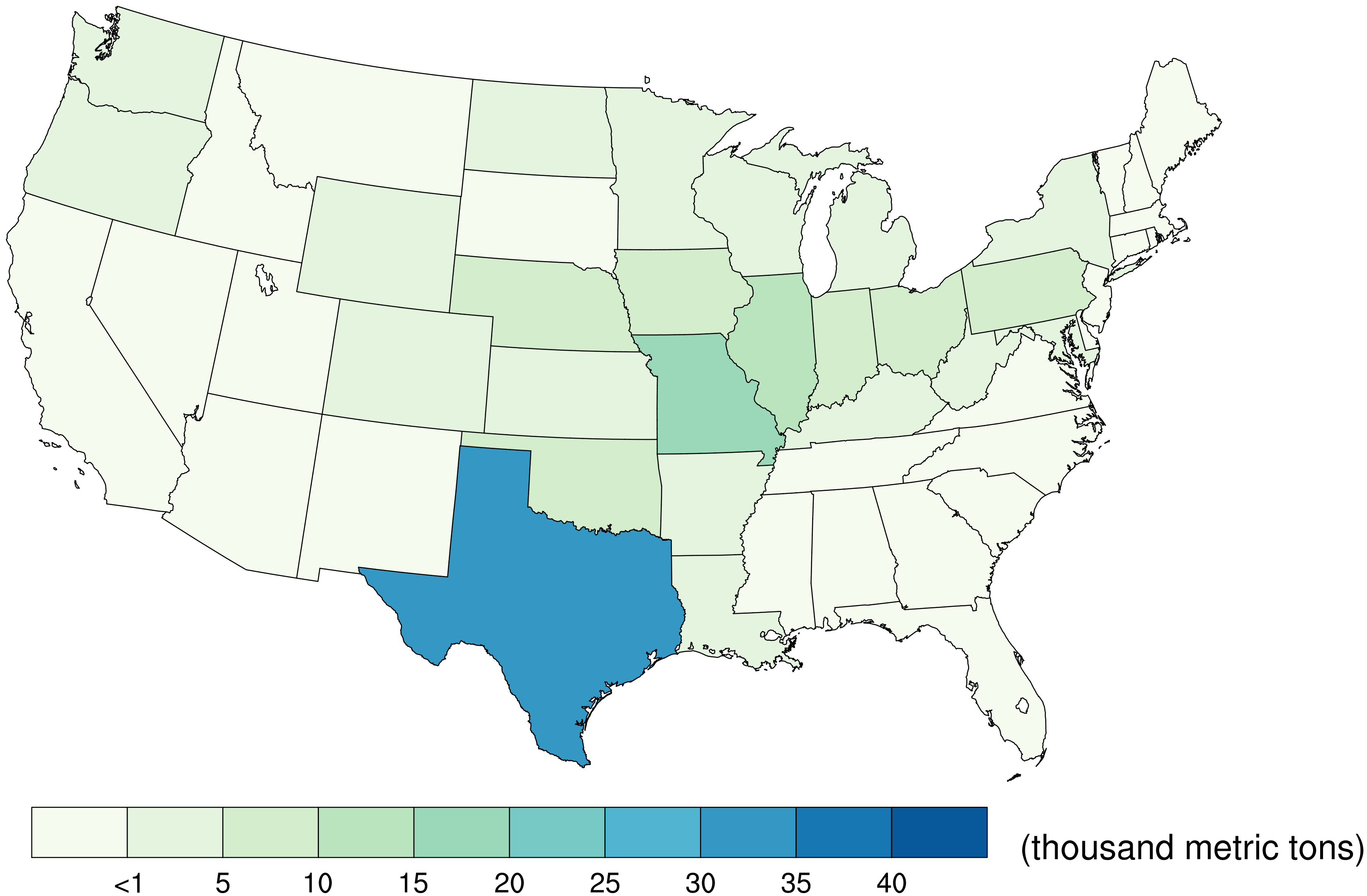
2007 SO_2 Avoided Emissions from Wind



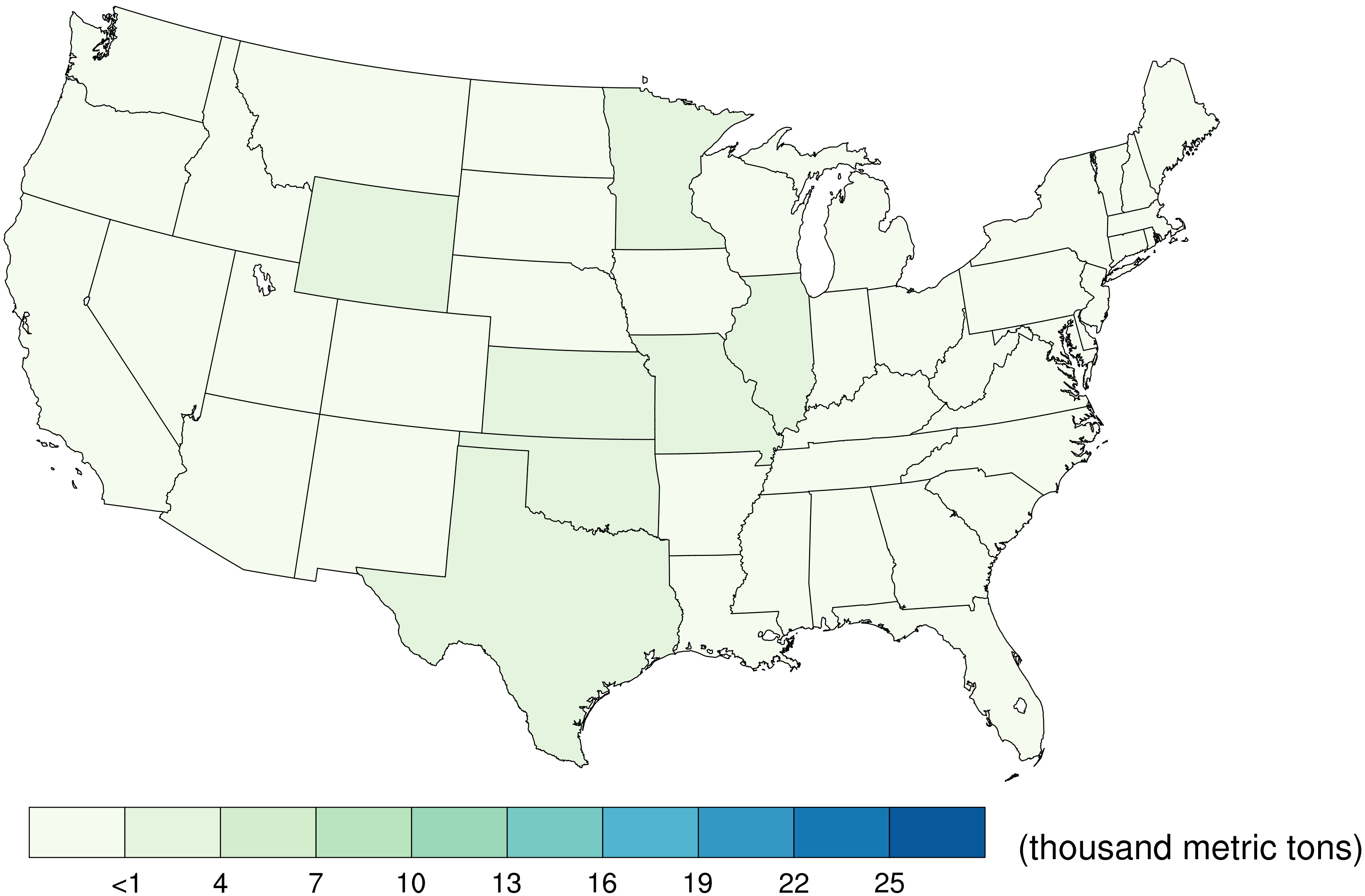
2011 SO_2 Avoided Emissions from Wind



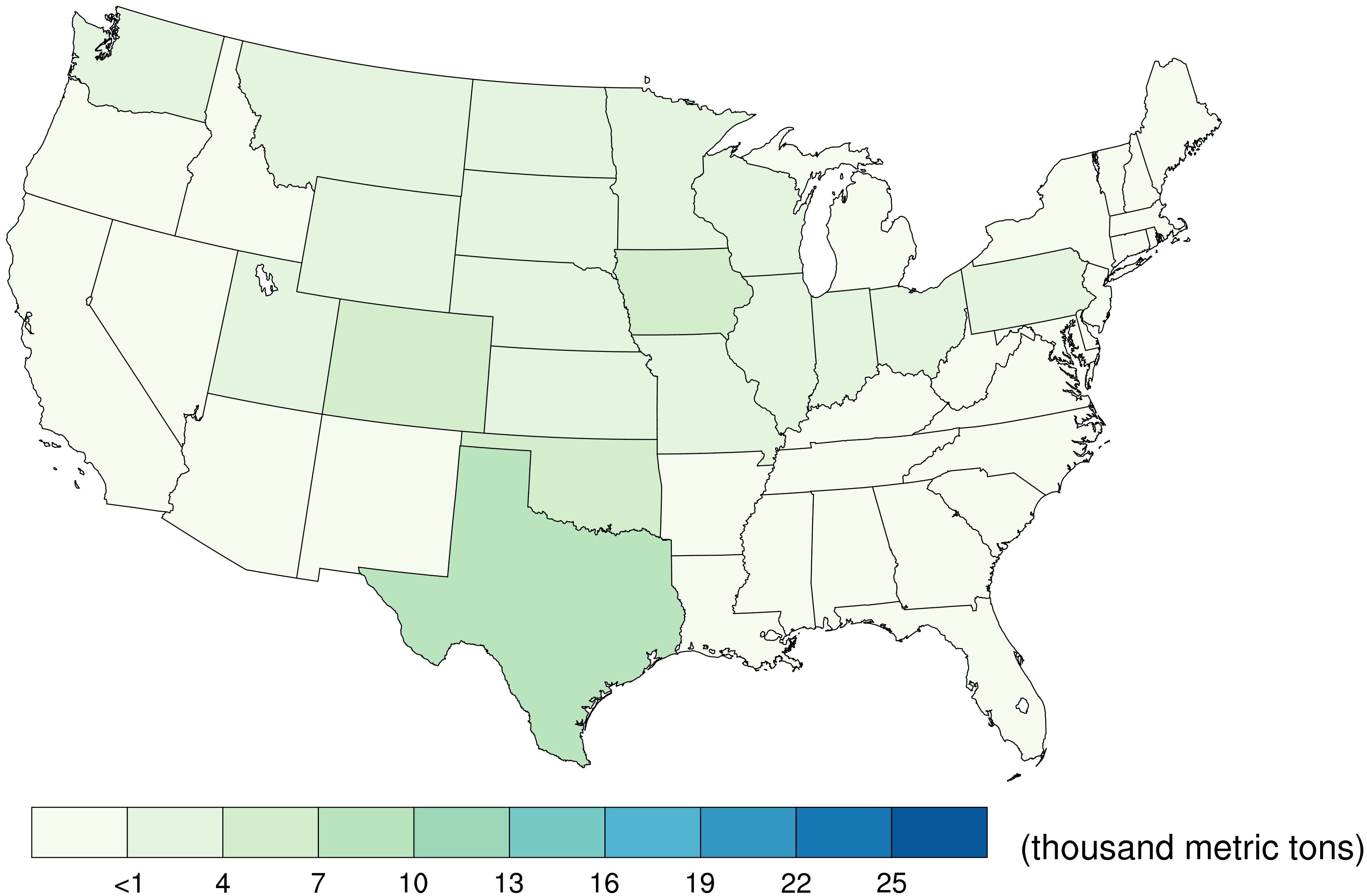
2015 SO_2 Avoided Emissions from Wind



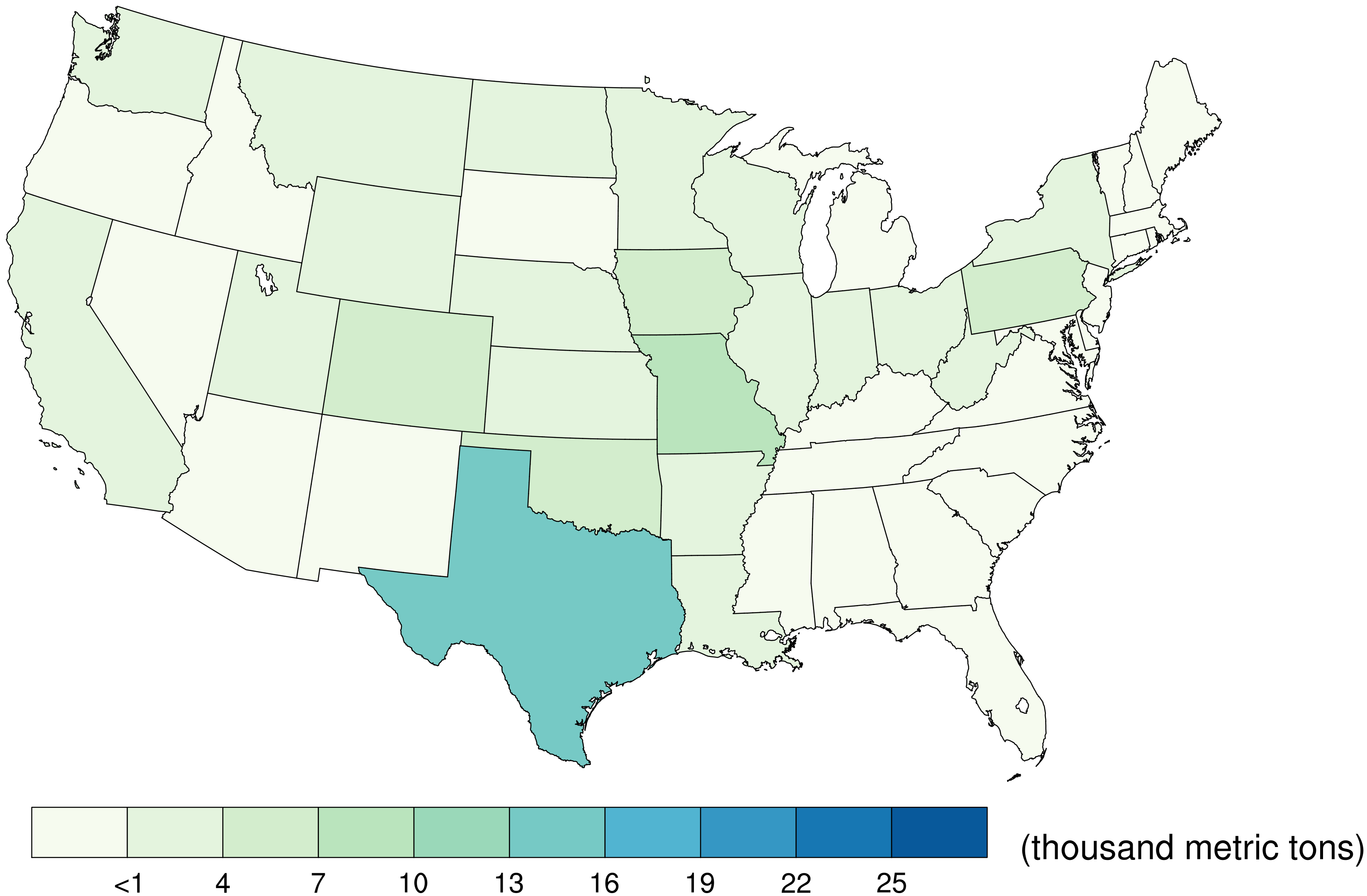
2007 NO_x Avoided Emissions from Wind



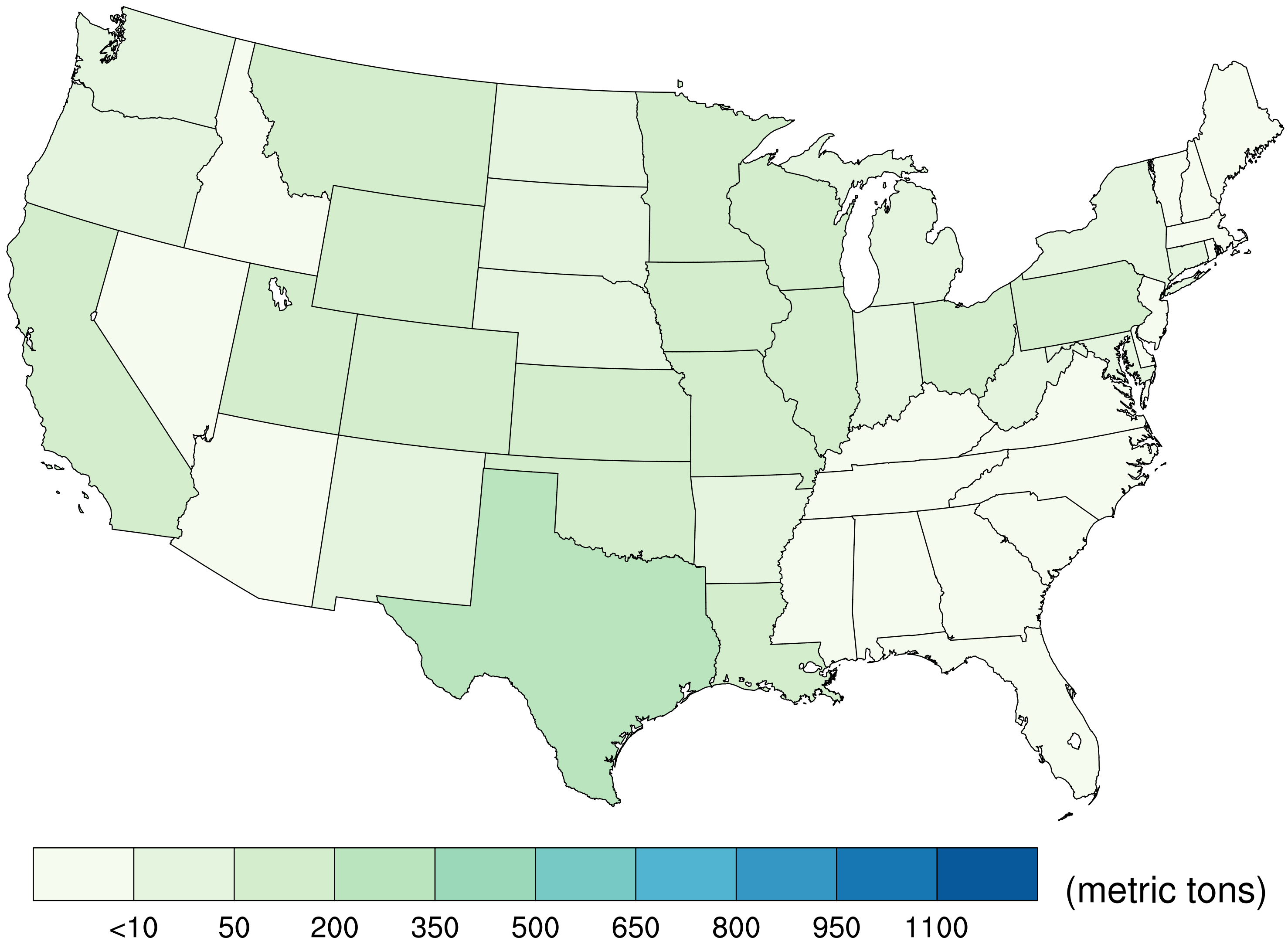
2011 NO_x Avoided Emissions from Wind



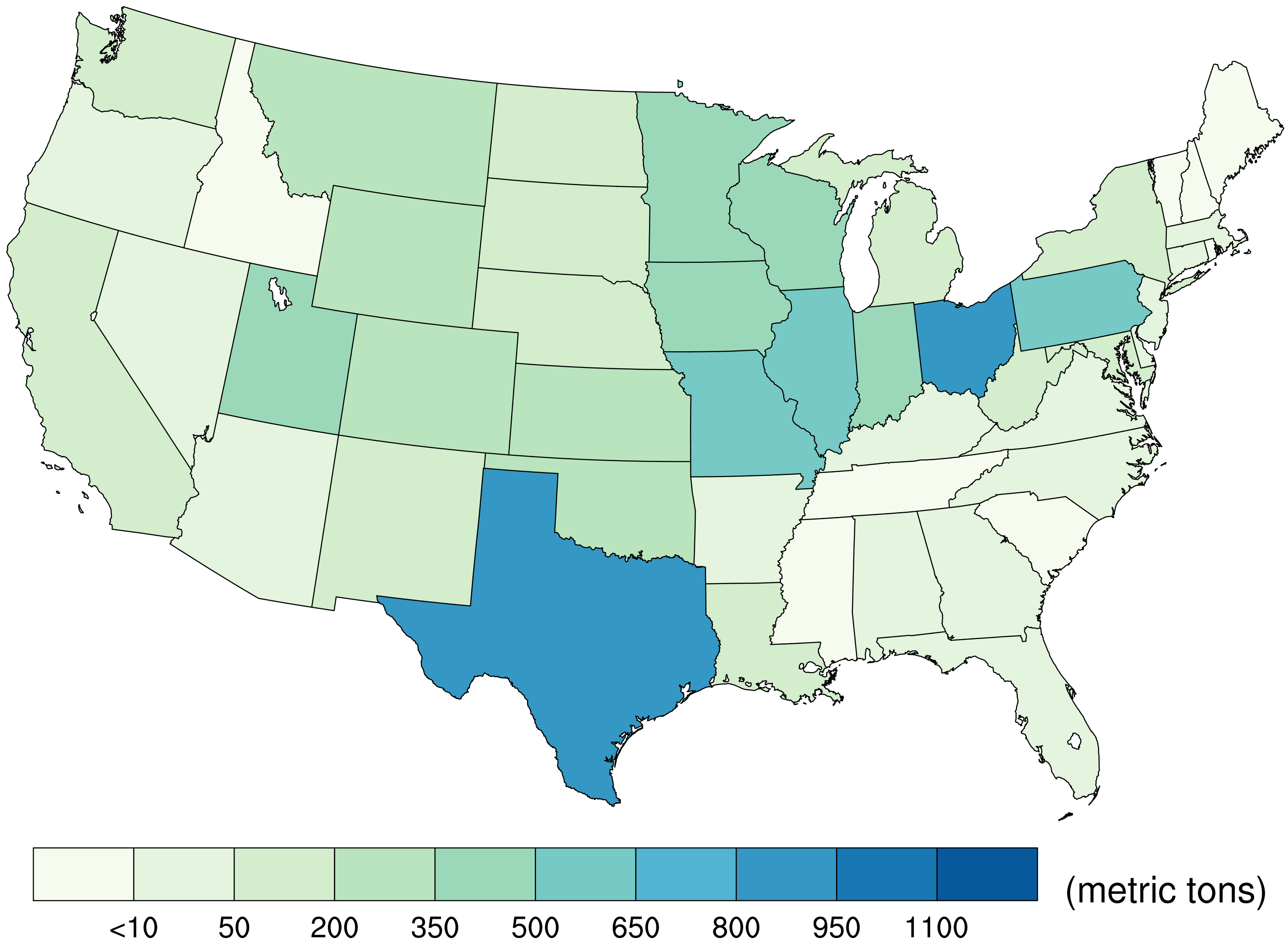
2015 NO_x Avoided Emissions from Wind



2007 $PM_{2.5}$ Avoided Emissions from Wind



2011 $PM_{2.5}$ Avoided Emissions from Wind



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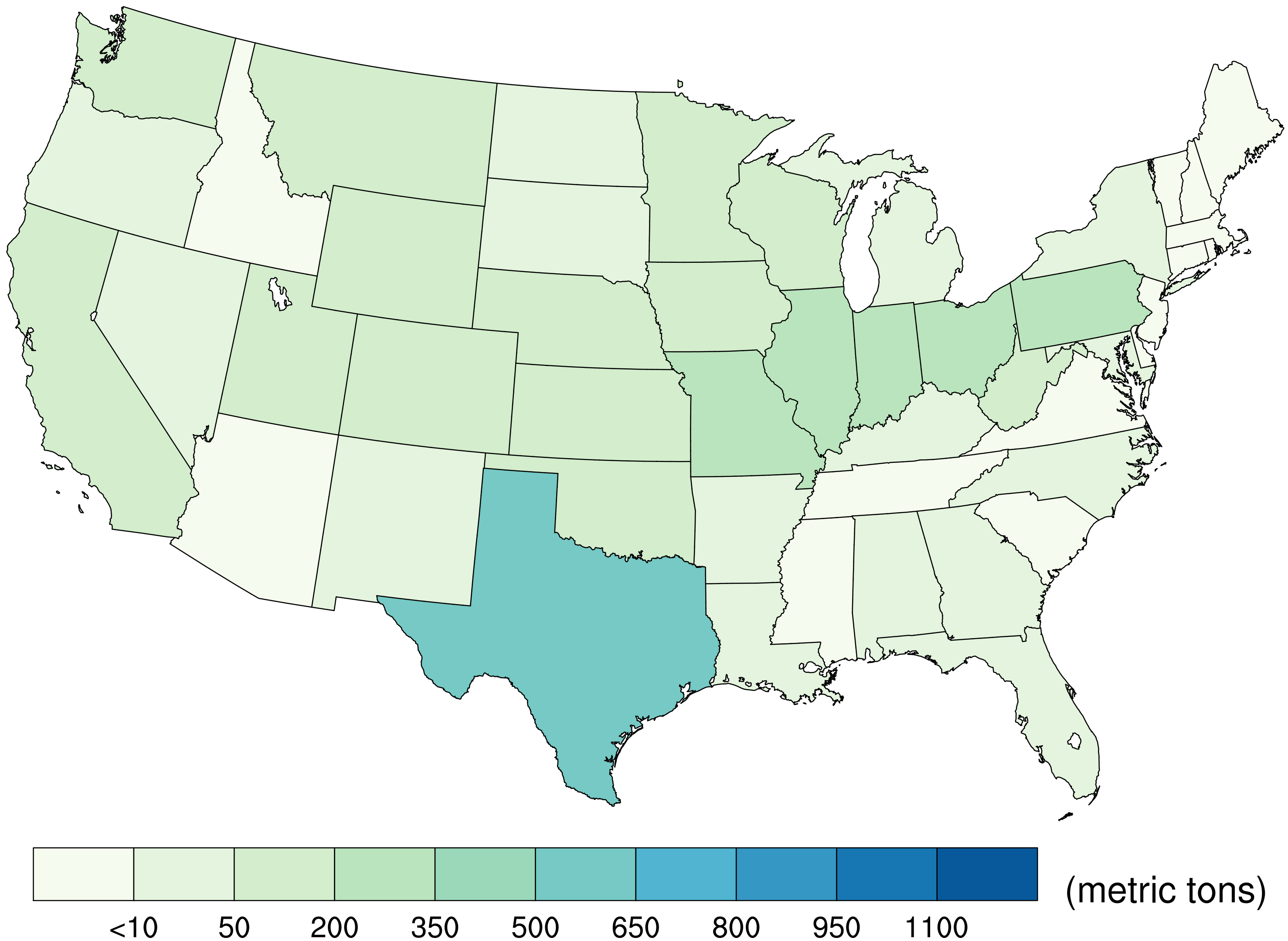
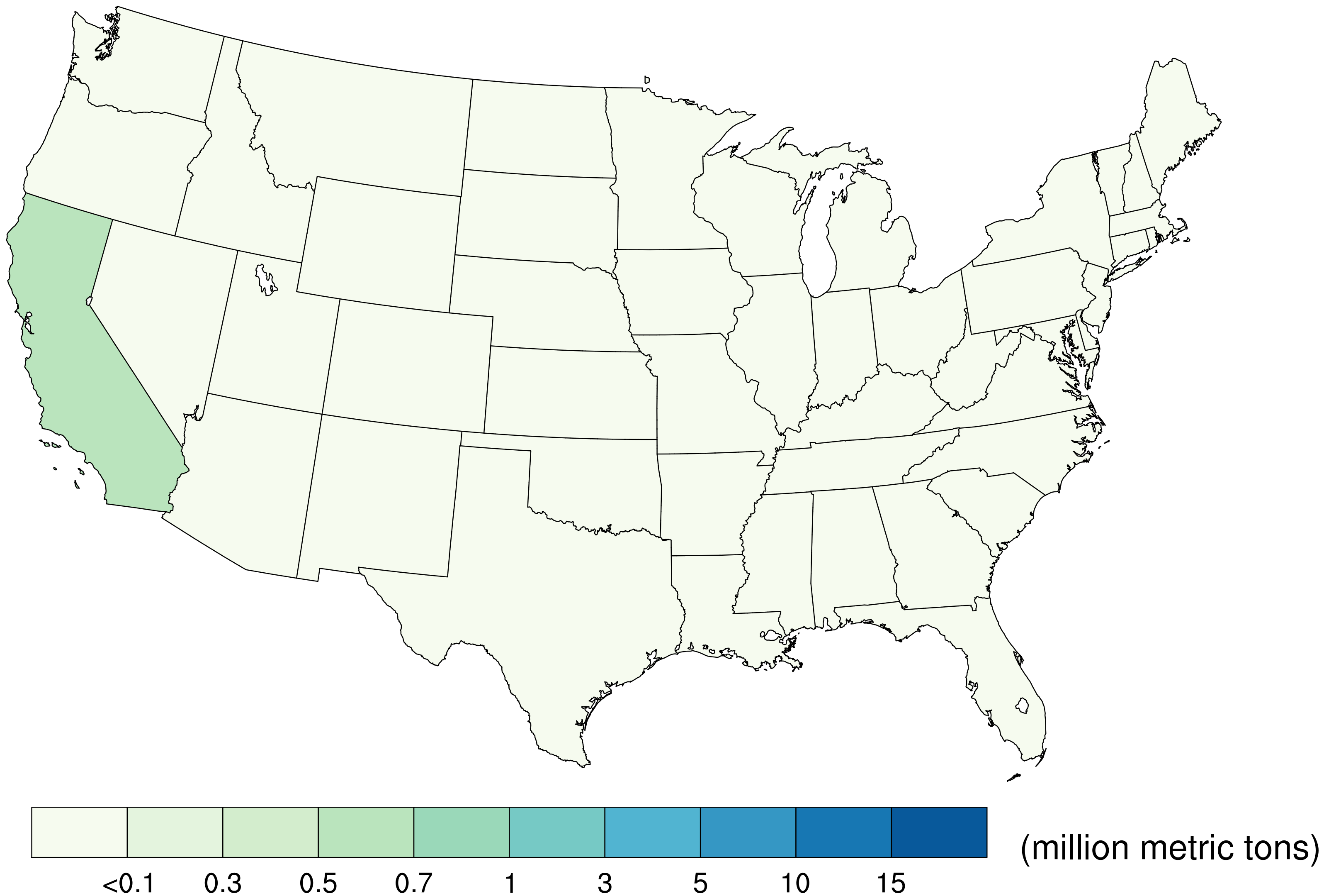
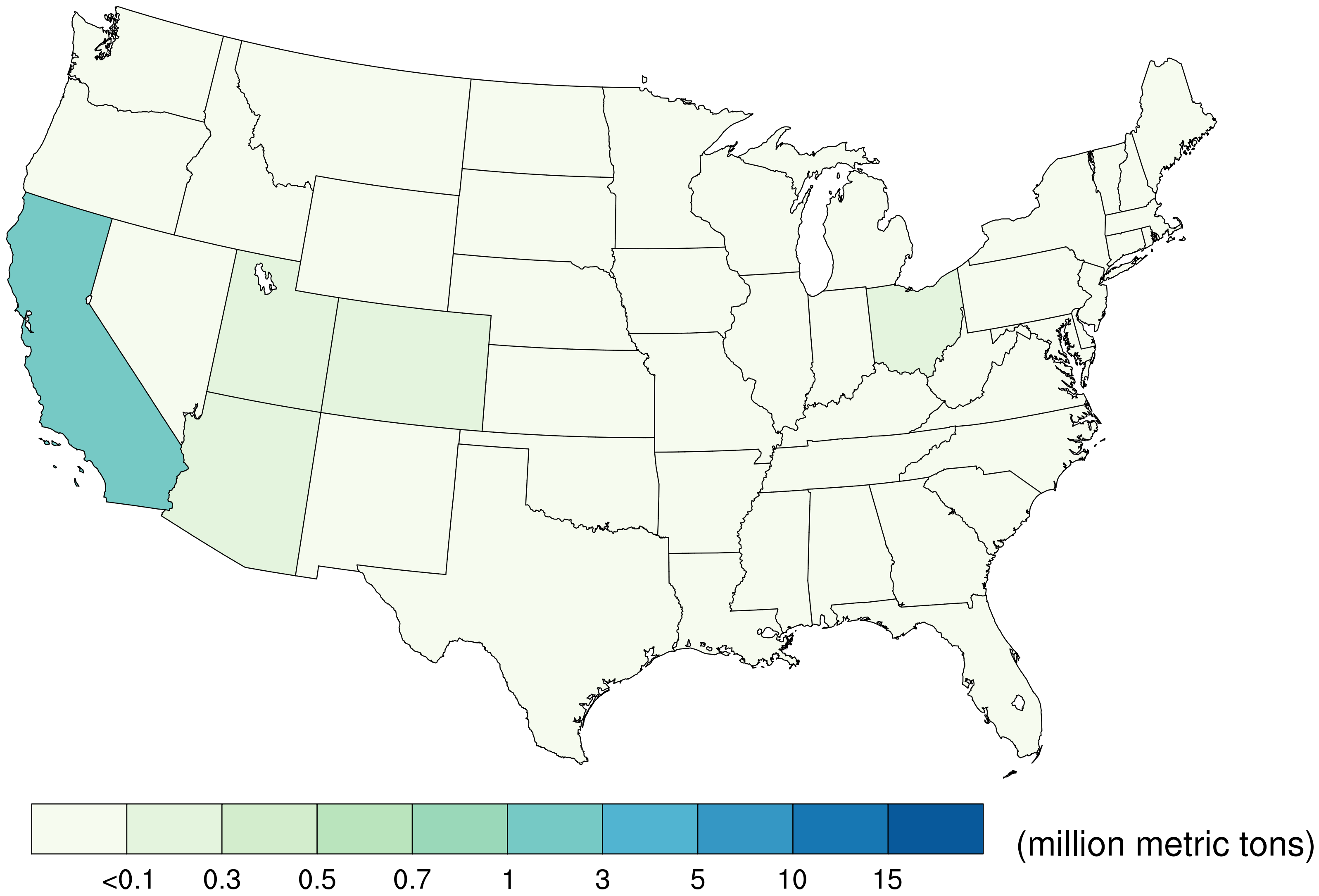


Appendix B: Solar Power -- Avoided Emissions by State

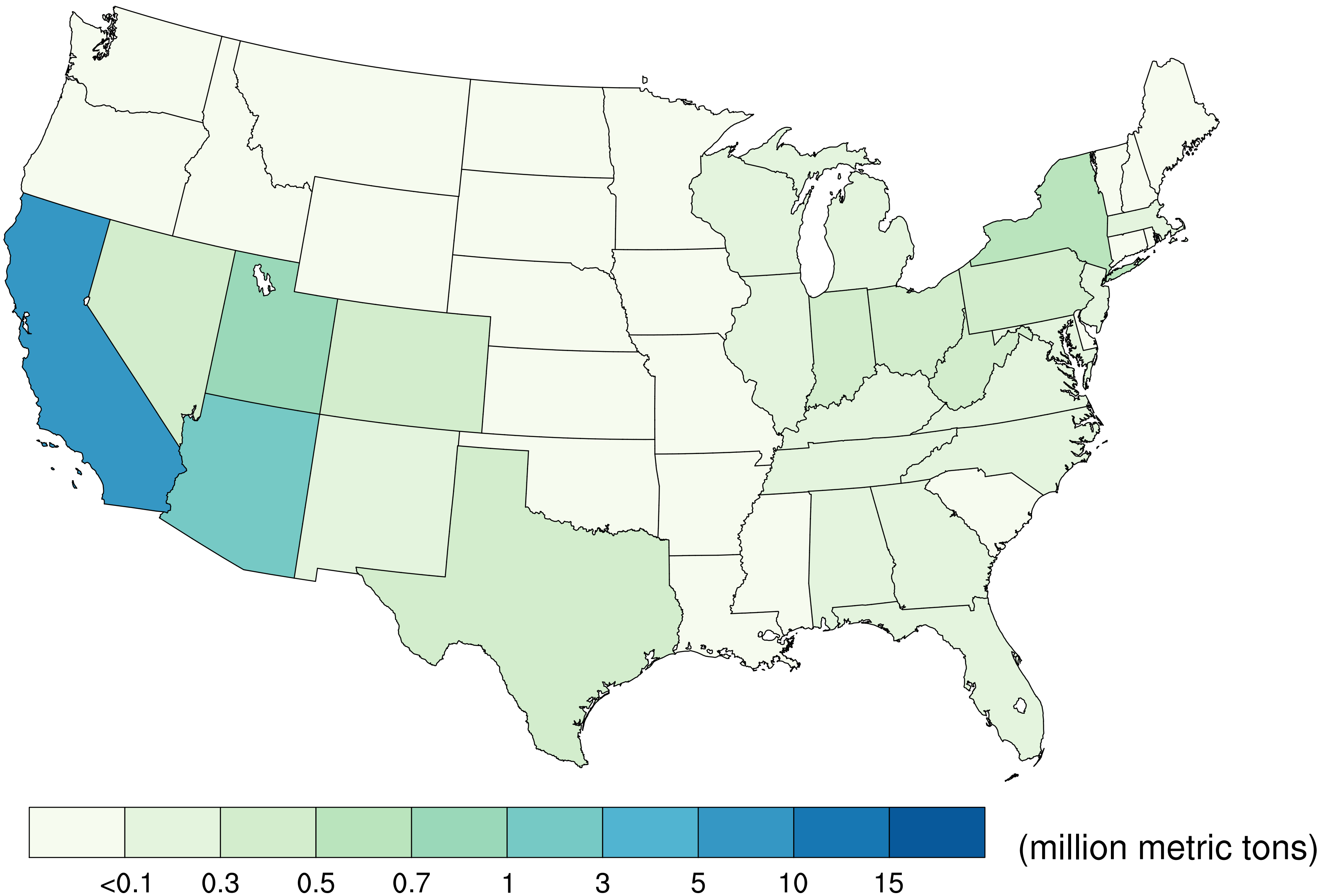
2007 CO_2 Avoided Emissions from Solar



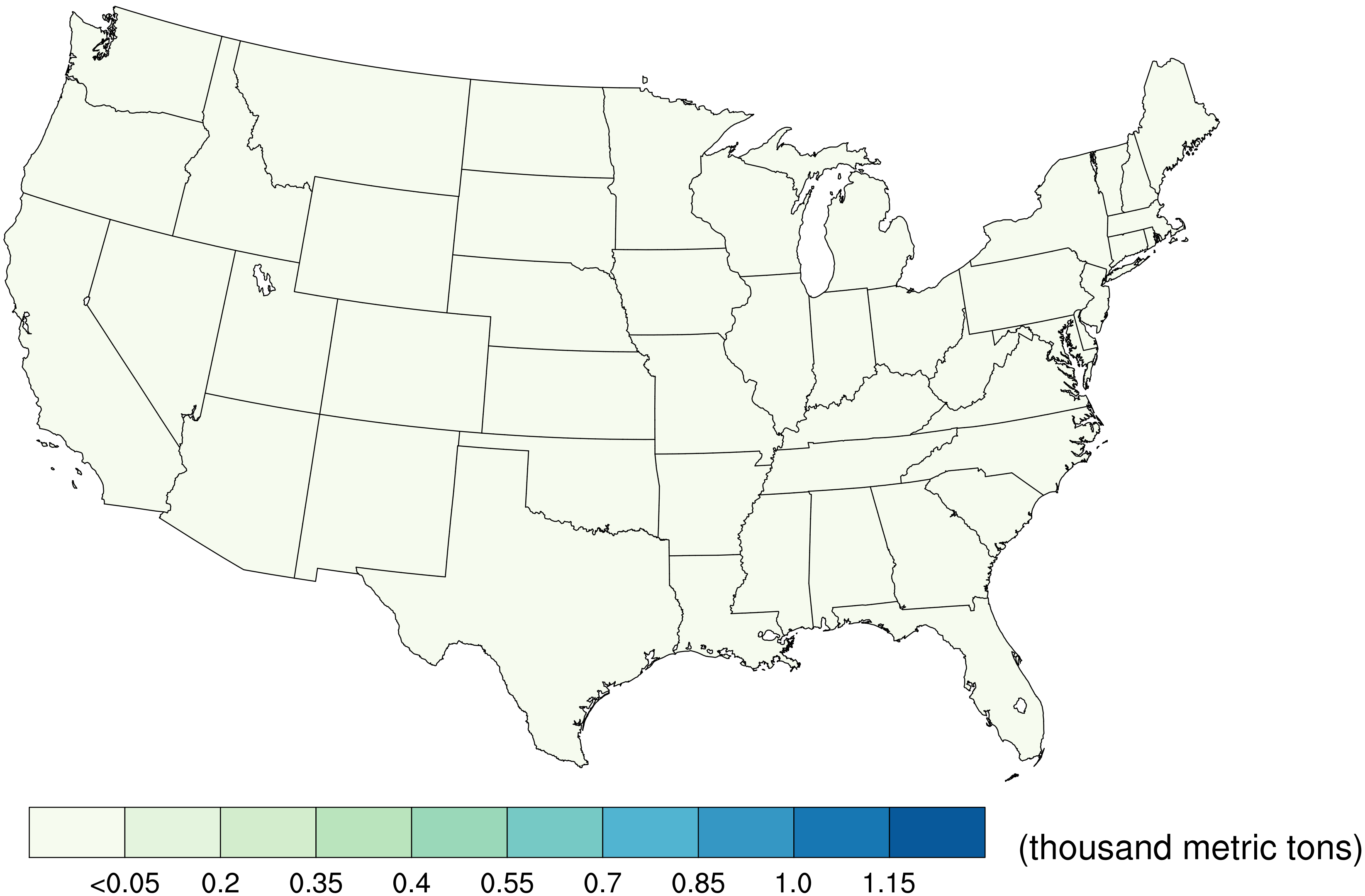
2011 CO_2 Avoided Emissions from Solar



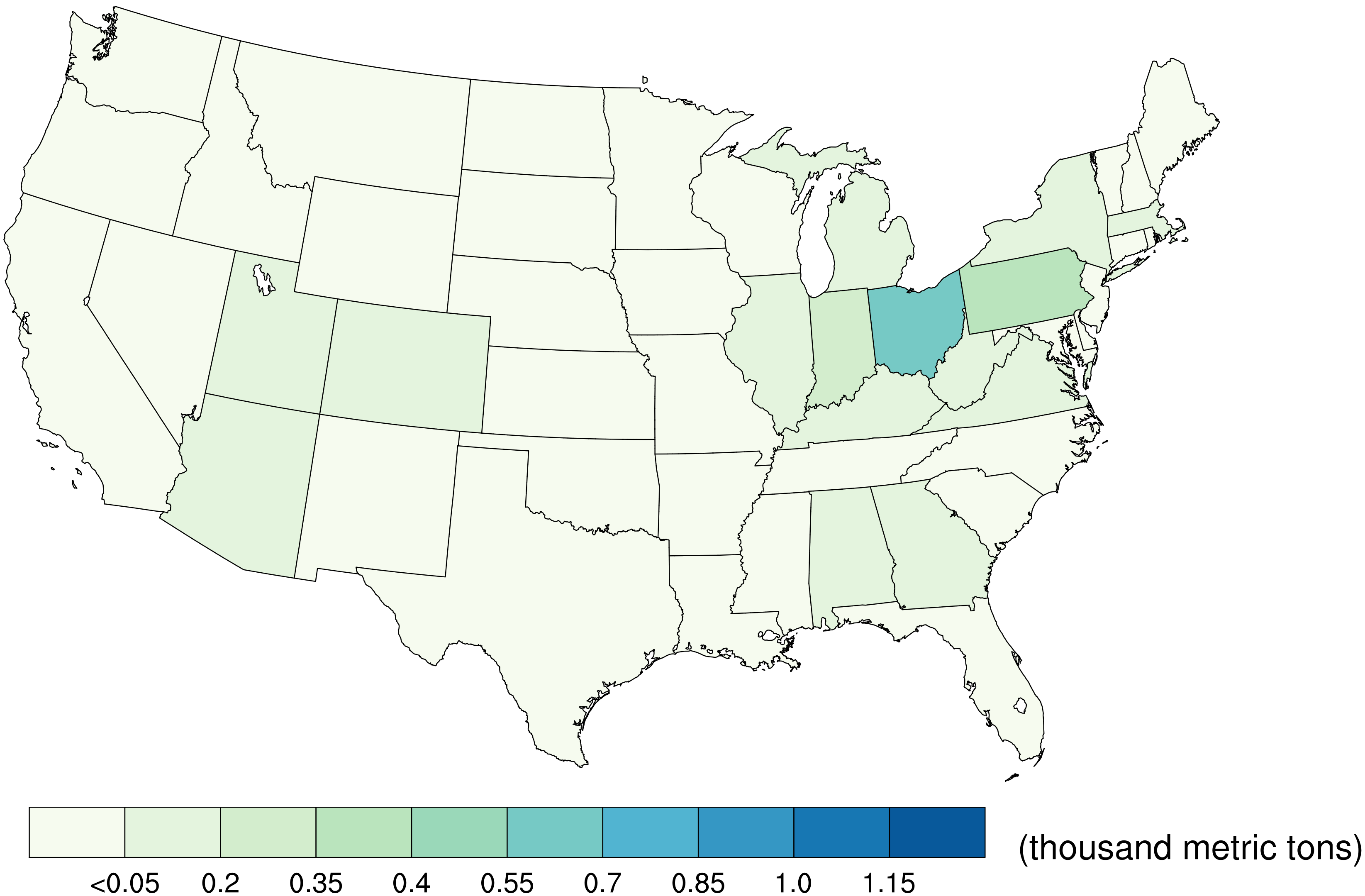
2015 CO_2 Avoided Emissions from Solar



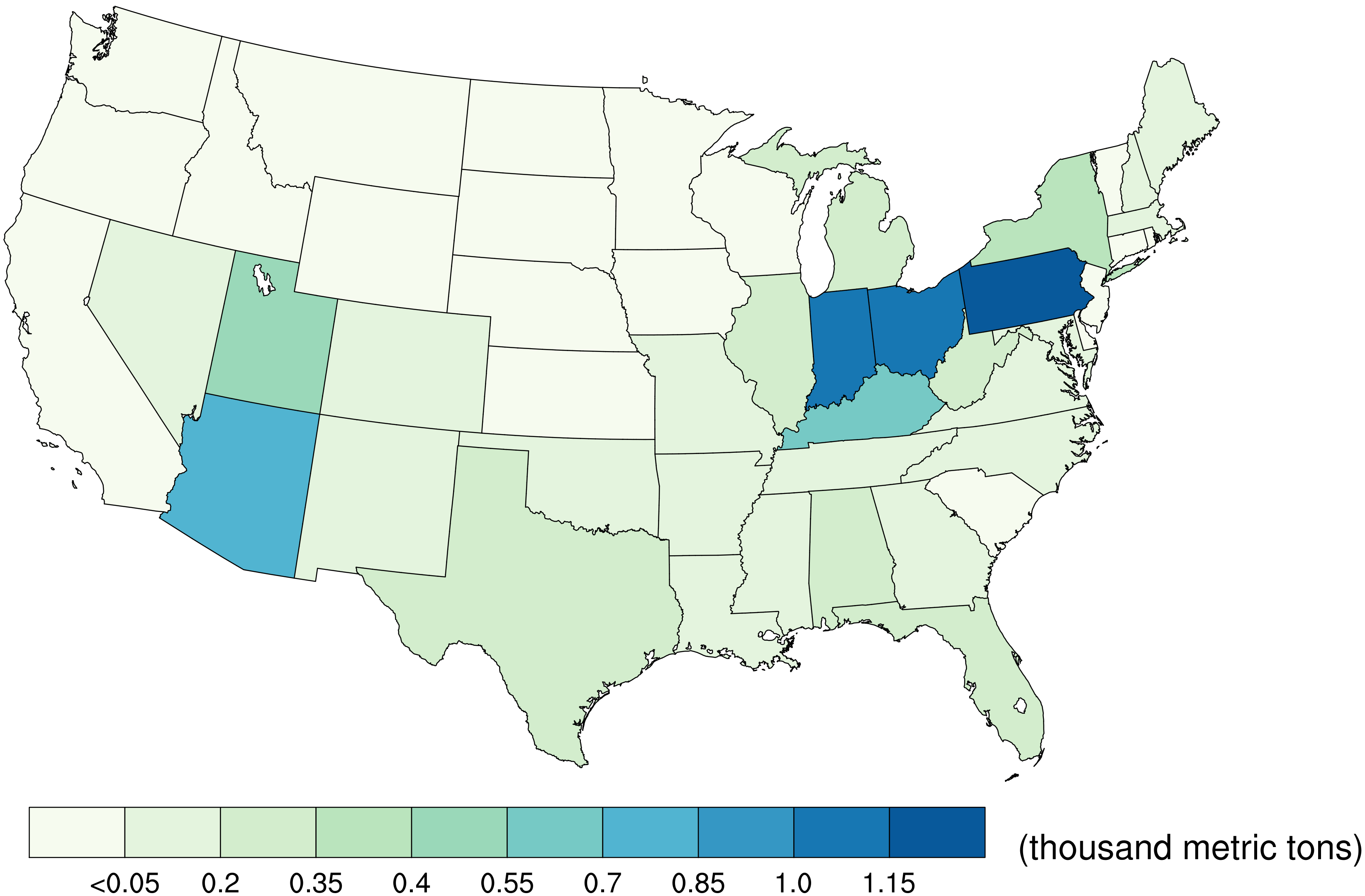
2007 SO_2 Avoided Emissions from Solar



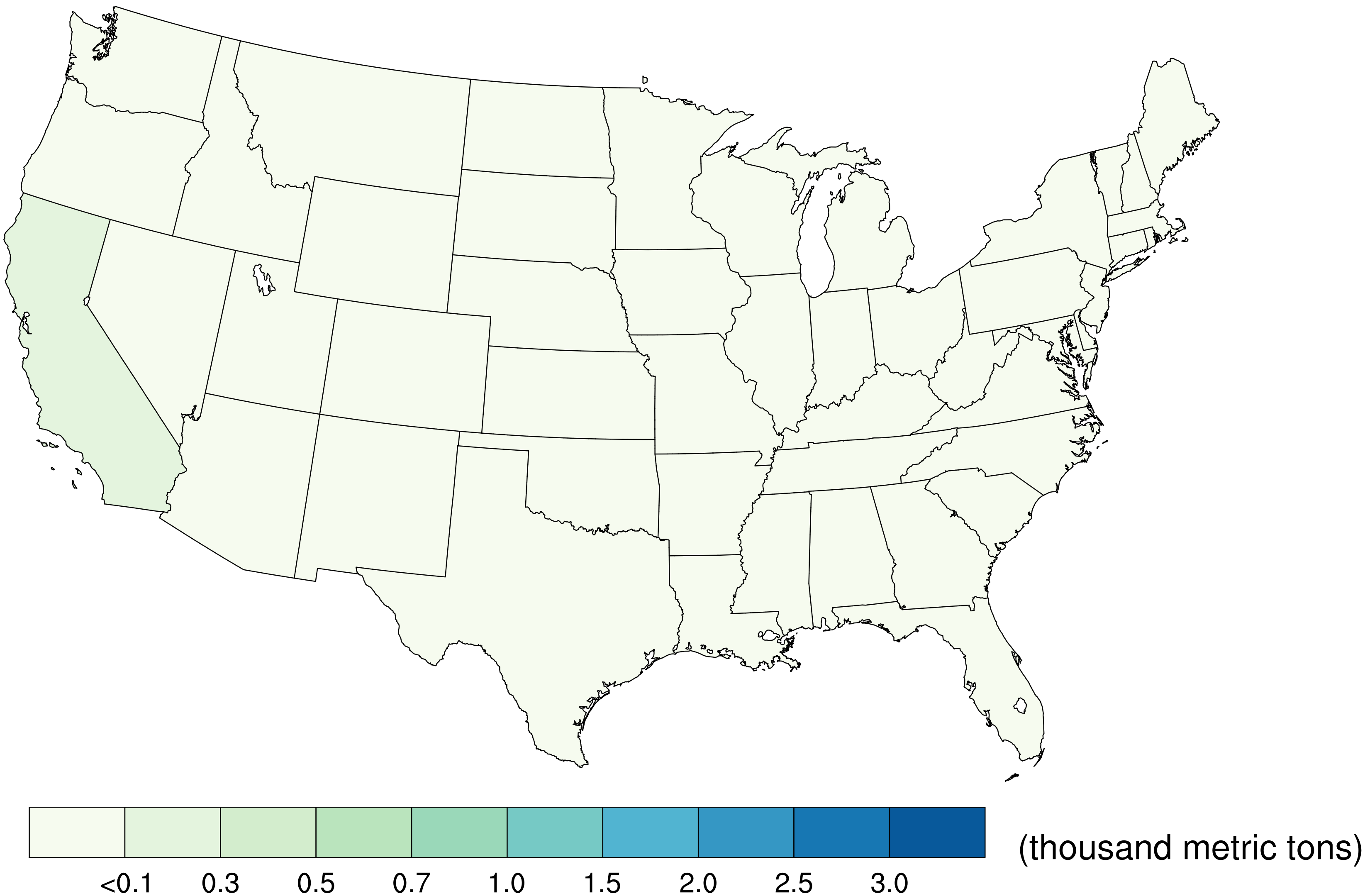
2011 SO_2 Avoided Emissions from Solar



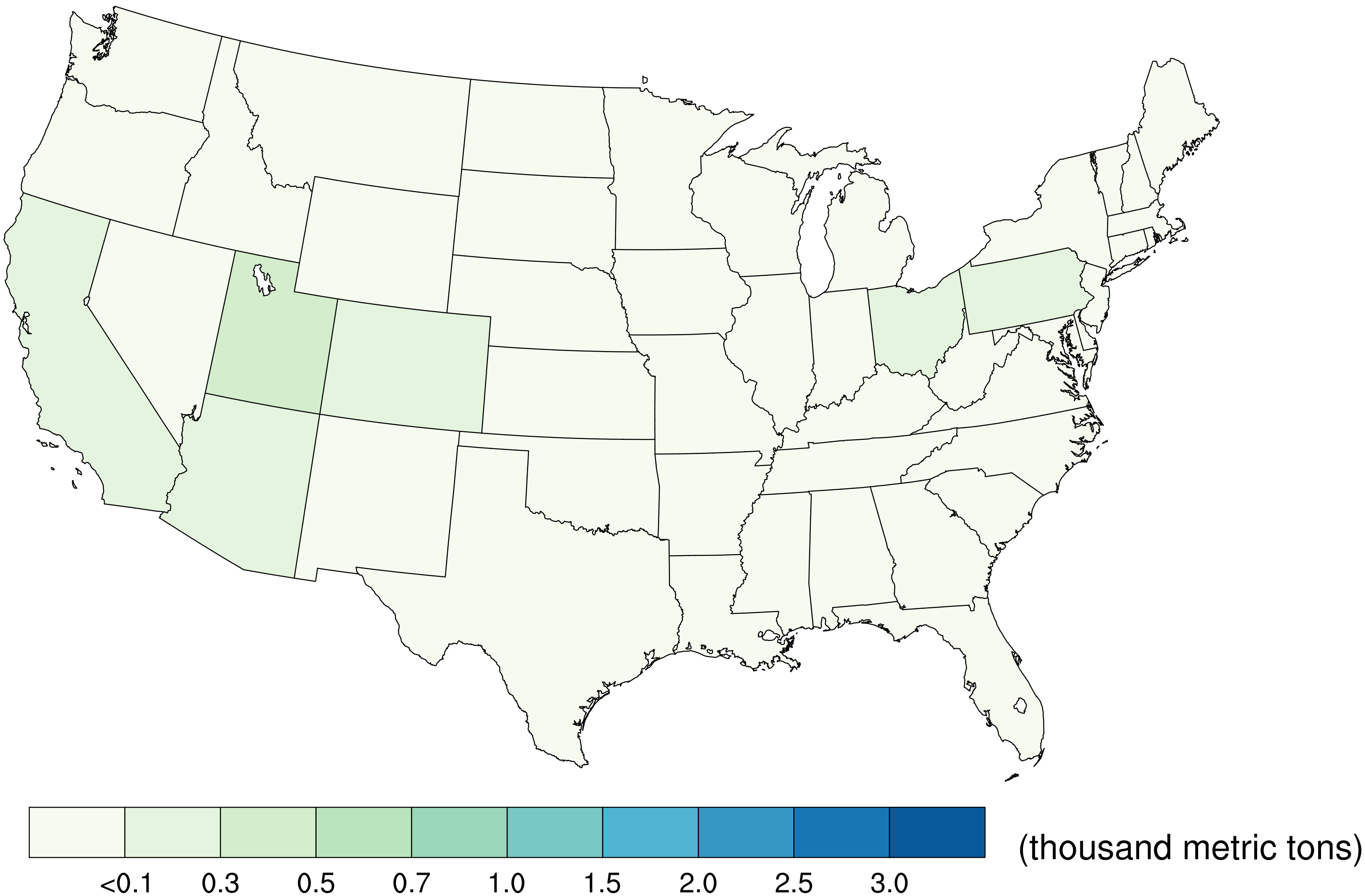
2015 SO_2 Avoided Emissions from Solar



2007 NO_x Avoided Emissions from Solar



2011 NO_x Avoided Emissions from Solar



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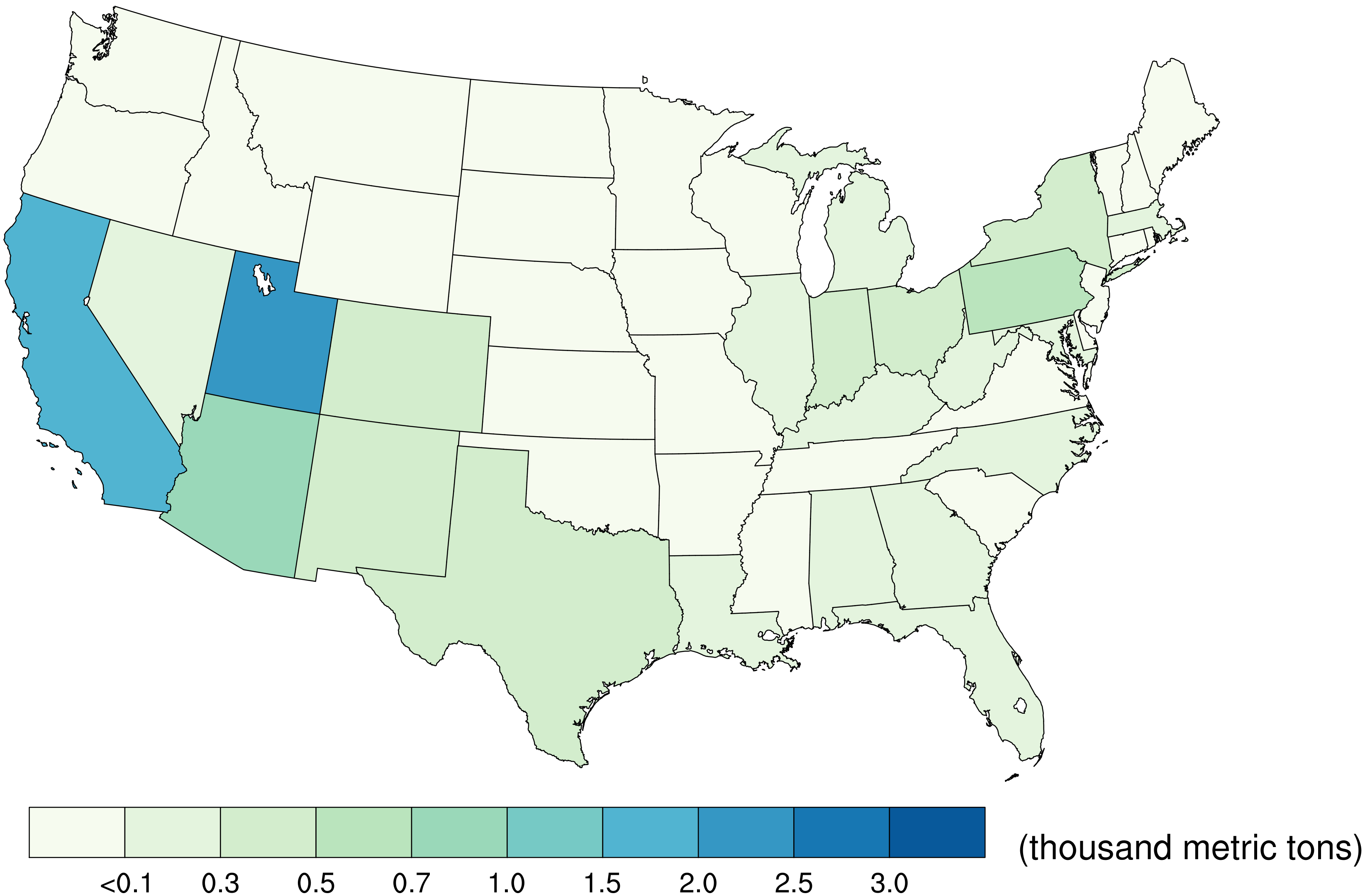
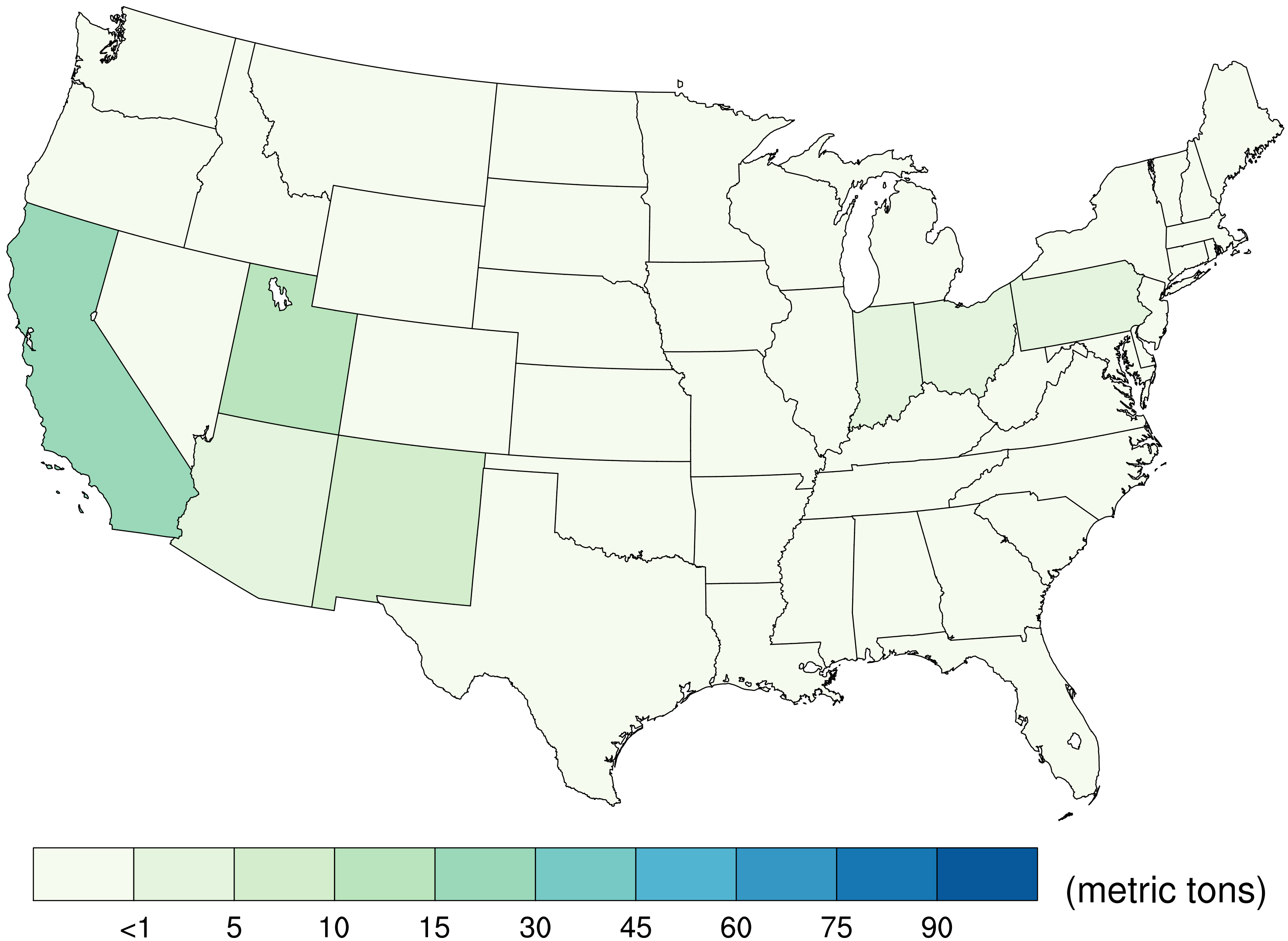


2007 $PM_{2.5}$ Avoided Emissions from Solar



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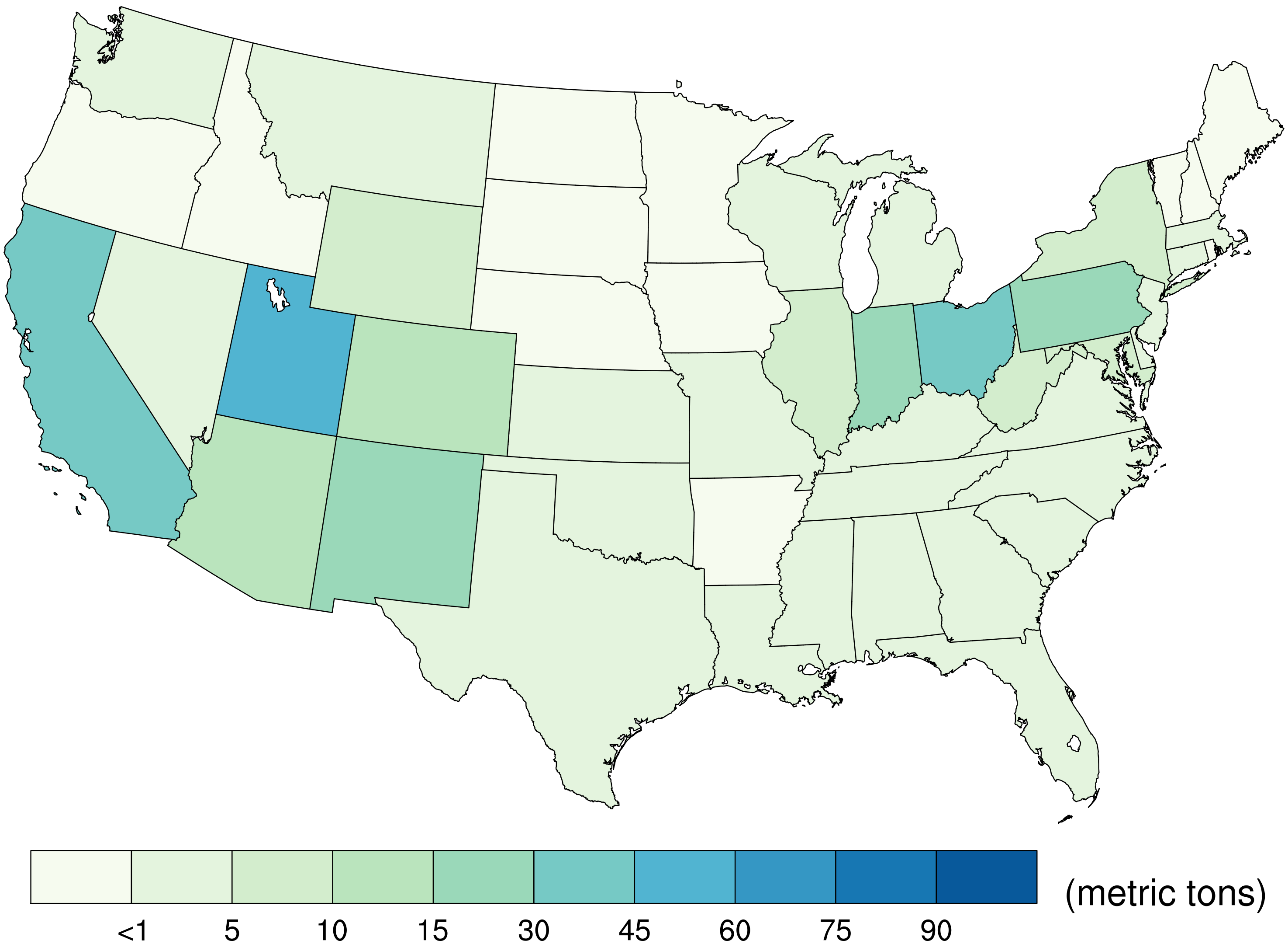

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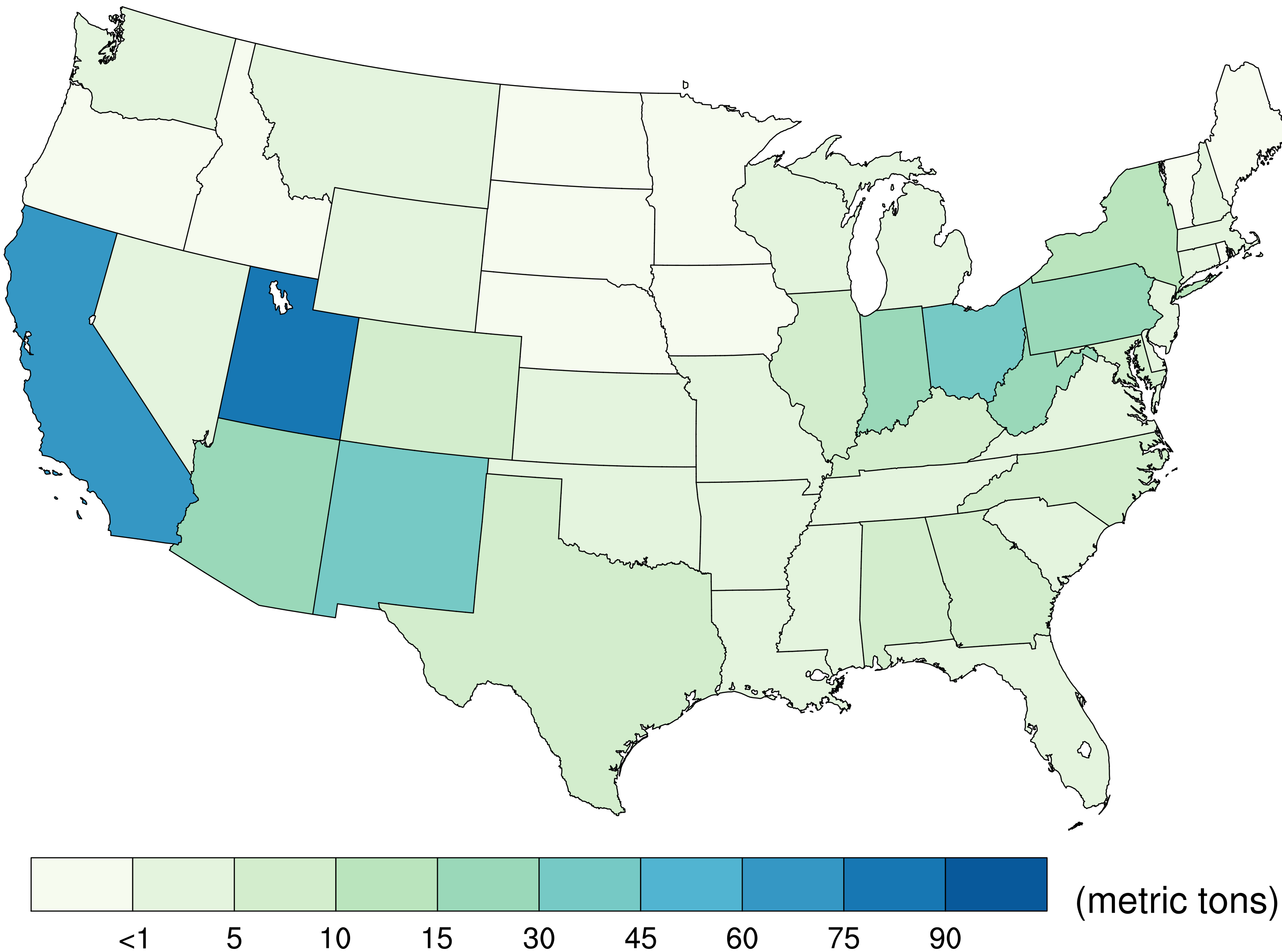


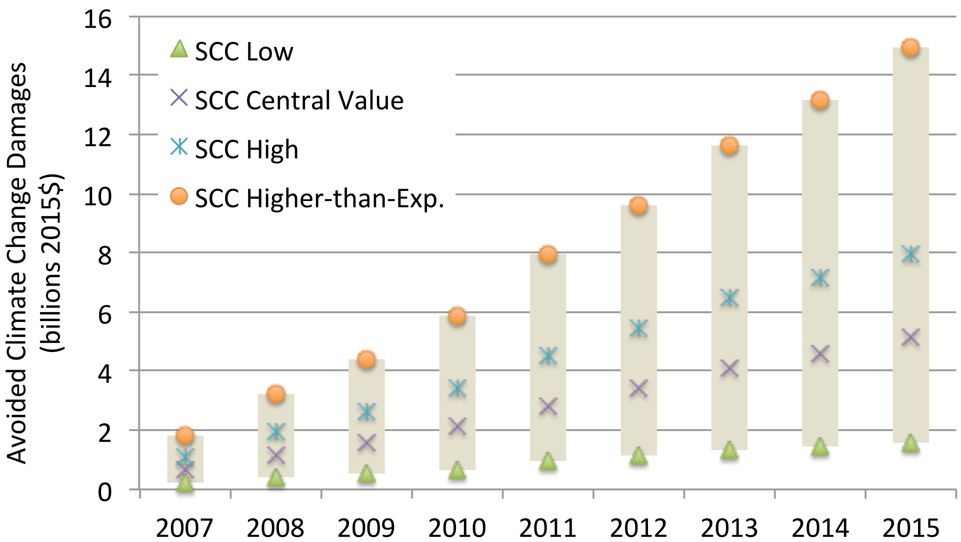
Appendix C: ‘Social Cost of Carbon’ (SCC) Valuation based on the U.S. Interagency Working Group Estimates

Estimating Avoided Climate and Health Impacts from CO_2

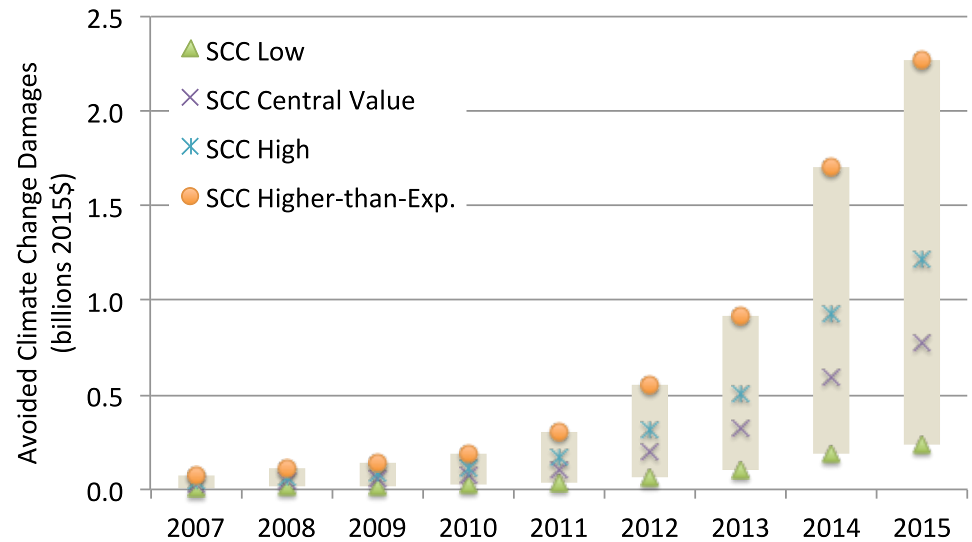
- Monetized CO_2 benefits based on four U.S. Interagency Working Group 'Social Cost of Carbon' (SCC) estimates
- Central Value: ranges from $31 – $40 per $MTCO_2$ from 2007 – 2015
- SCC includes global impacts on agricultural productivity, human health, property damages, and ecosystem services

National Avoided Climate Damages IWG SCC

Wind



Solar



	2007 - 2015				2015			
	Total Benefits (Billions 2015$)		Avg. Marginal Benefits (¢/kWh)		Total Benefits (Billions 2015$)		Avg. Marginal Benefits (¢/kWh)	
	Central	Range	Central	Range	Central	Range	Central	Range
Wind	25.5	8.3 – 72.5	2.4	0.8 – 6.9	5.1	1.6 – 14.9	2.7	0.8 – 7.9
Solar	2.2	0.7 – 6.3	2.0	0.6 – 5.6	0.8	0.2 – 2.3	2.1	0.6 – 6.0