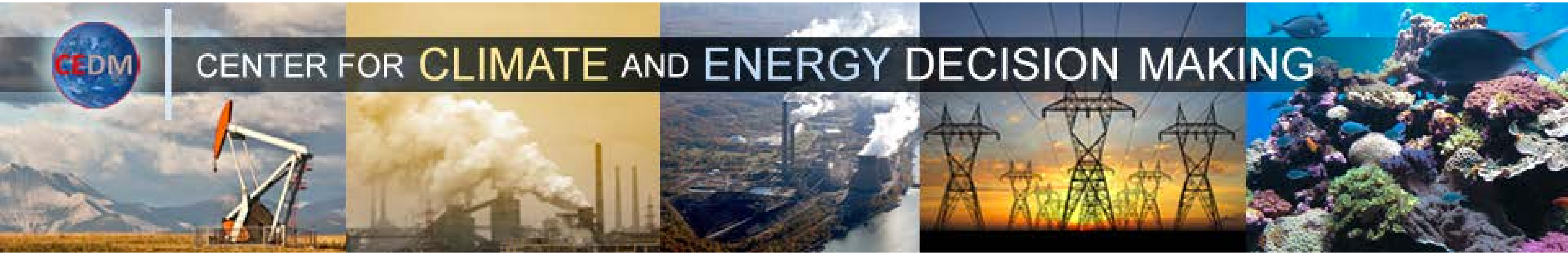
A framework for climate change decision-making under uncertainty

Ines Azevedo

Associate Professor
Department of Engineering and Public Policy
Carnegie Mellon University

Co-Director
Climate and Energy Decision Making Center



Outline

- How can we assess the health, environmental and climate change benefits from different interventions in the U.S. energy system?

- How can we display those results?

Are we helping the environment more by increasing solar in California or in Pennsylvania?

Are we helping the environment more if we choose a battery electric car or an hybrid?

In which states can we have the largest environmental and health benefits from more stringent building codes?

Where can we have the largest environmental and health benefits from increasing wind?

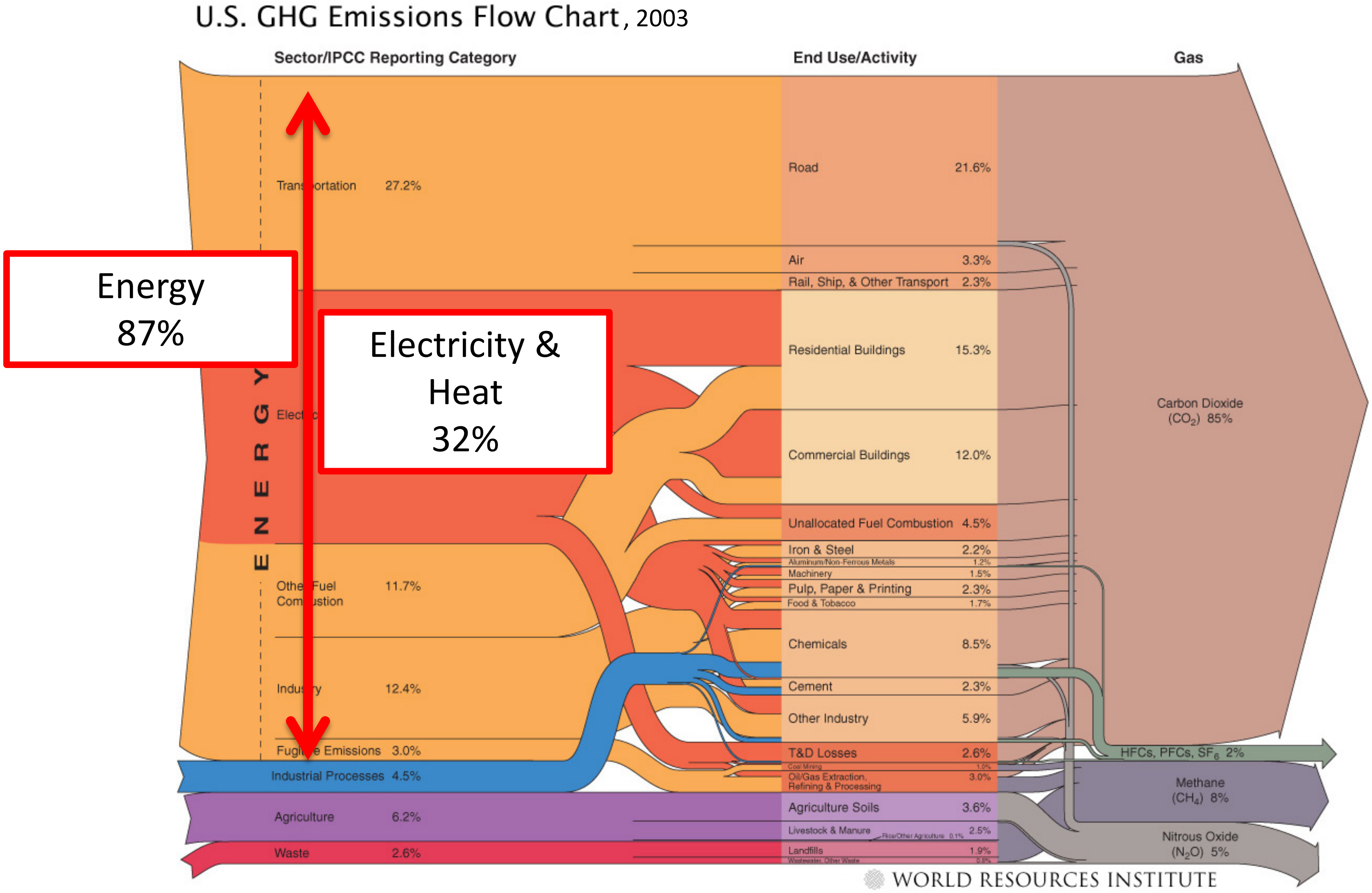
Are we helping the environment by increasing storage in our electricity grid?

All of these questions are related.

- When we pursue interventions in the grid what are the emissions that we are avoiding (or adding) to our energy system?

- What are the monetized benefits or costs of those emissions changes?

Energy services are responsible for the bulk of CO_2 emissions in the United States.



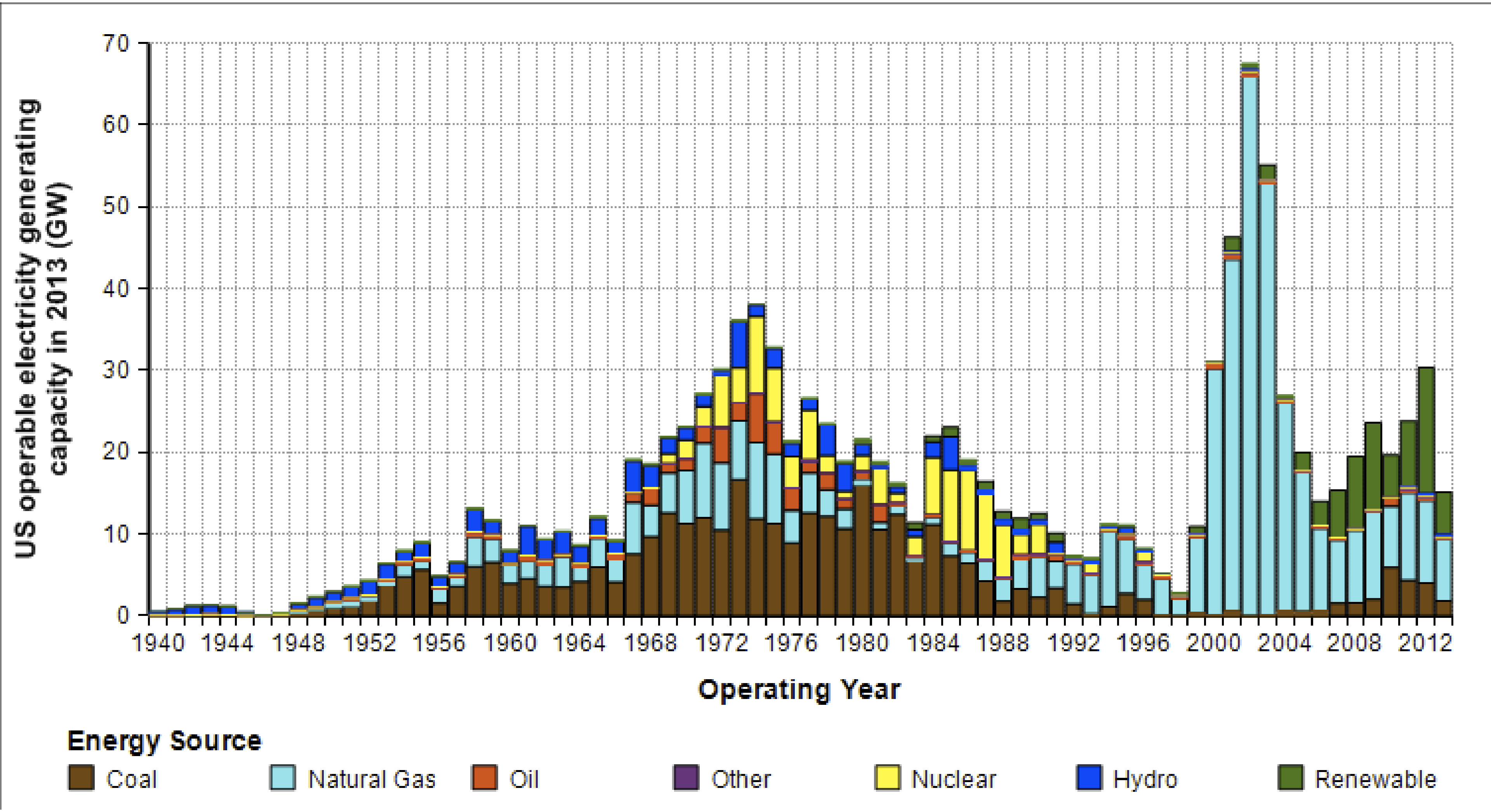
U.S. GHG Emissions Flow Chart, 2003

Energy
87%

Electricity & Heat
32%

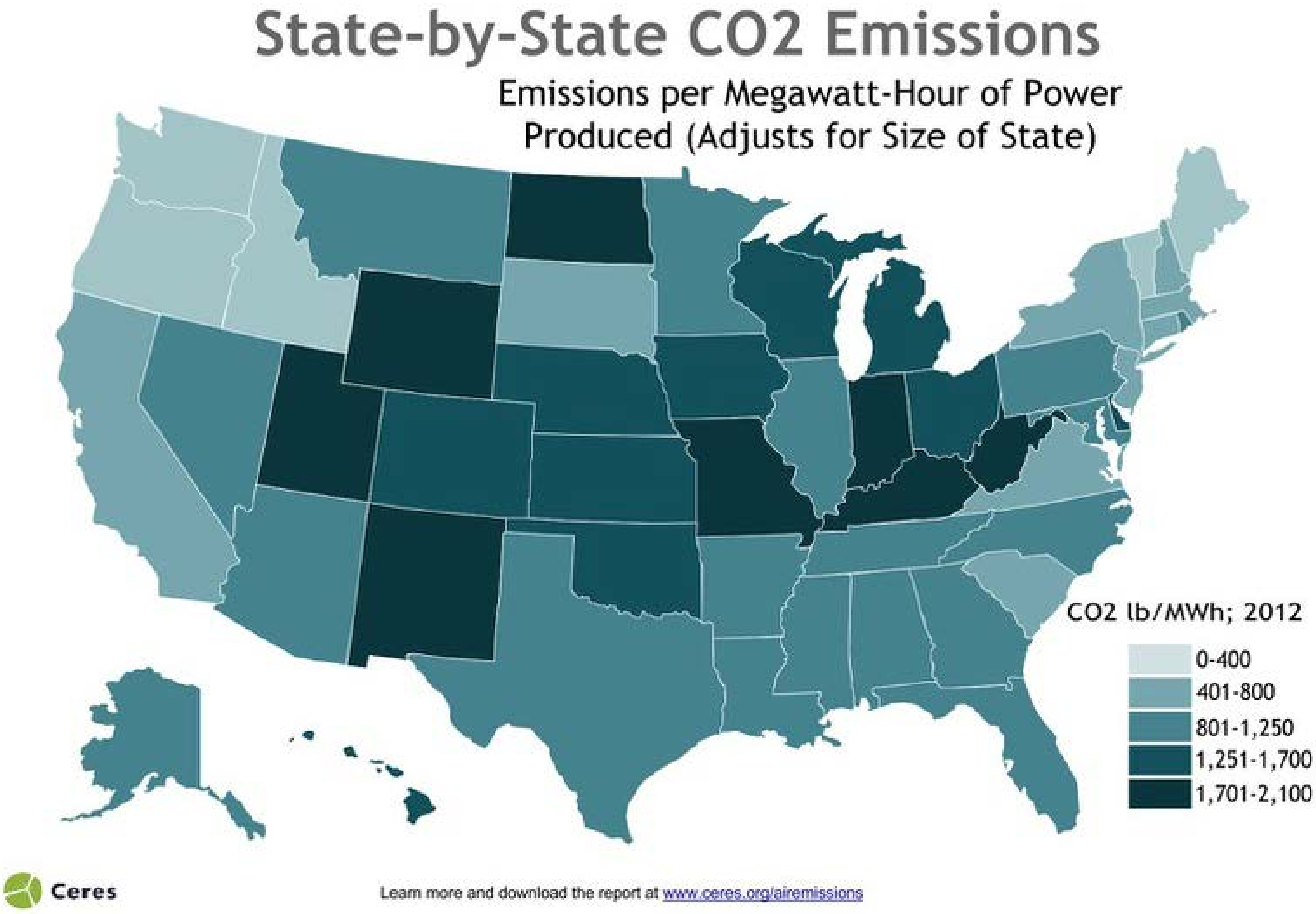
Source: http://www.wri.org/chart/us-greenhouse-gas-emissions-flow-chart

We have an aging and very carbon intensive electricity fleet

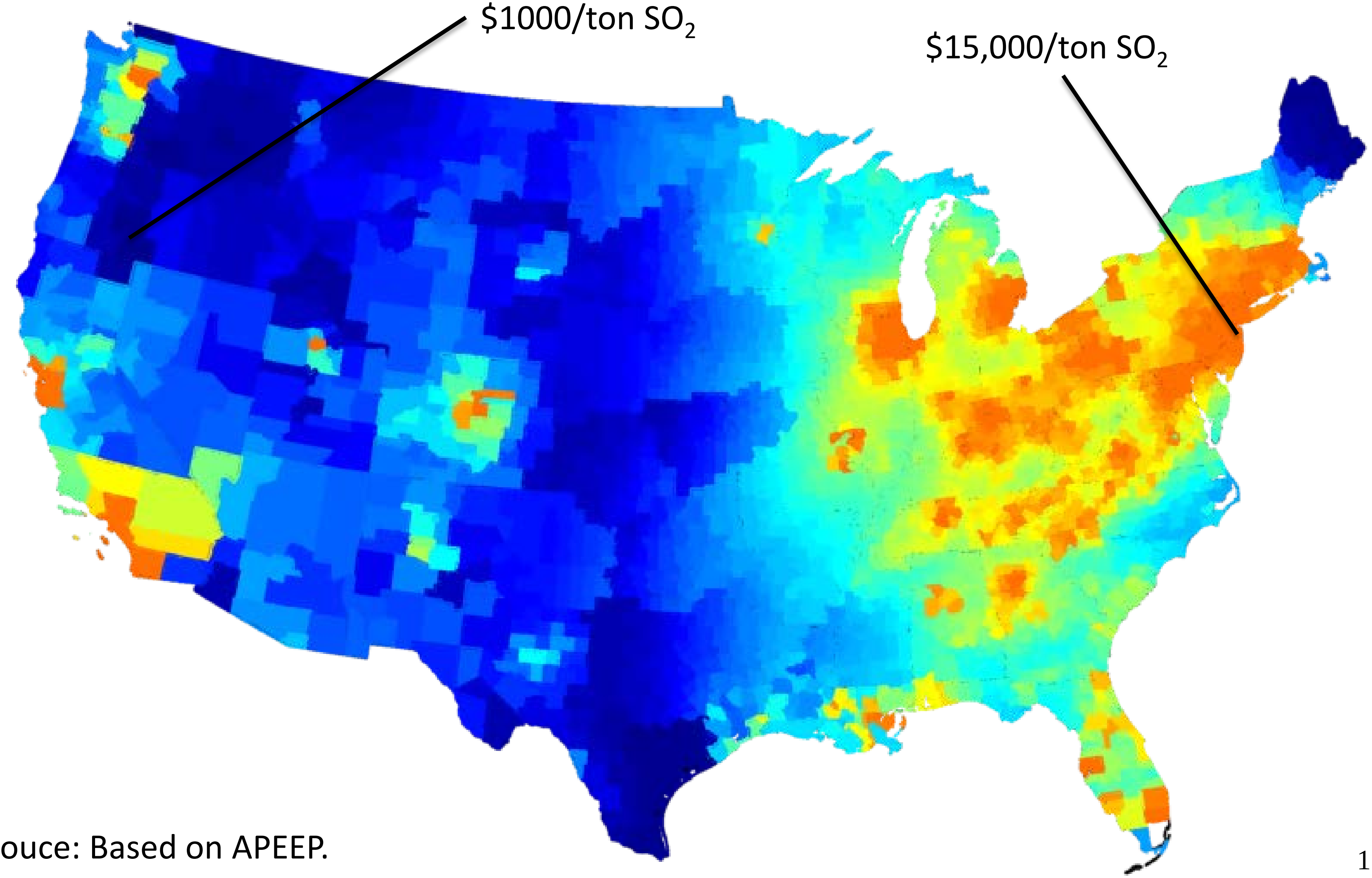


Attribution: Created by Evan Sherwin using data from EIA form 860 for operable US power plants

The effects of these interventions will differ because the electric grid mix differs across regions .... and over time.



The effects of these interventions will differ because damages from criteria air pollutants vary tremendously across the country.



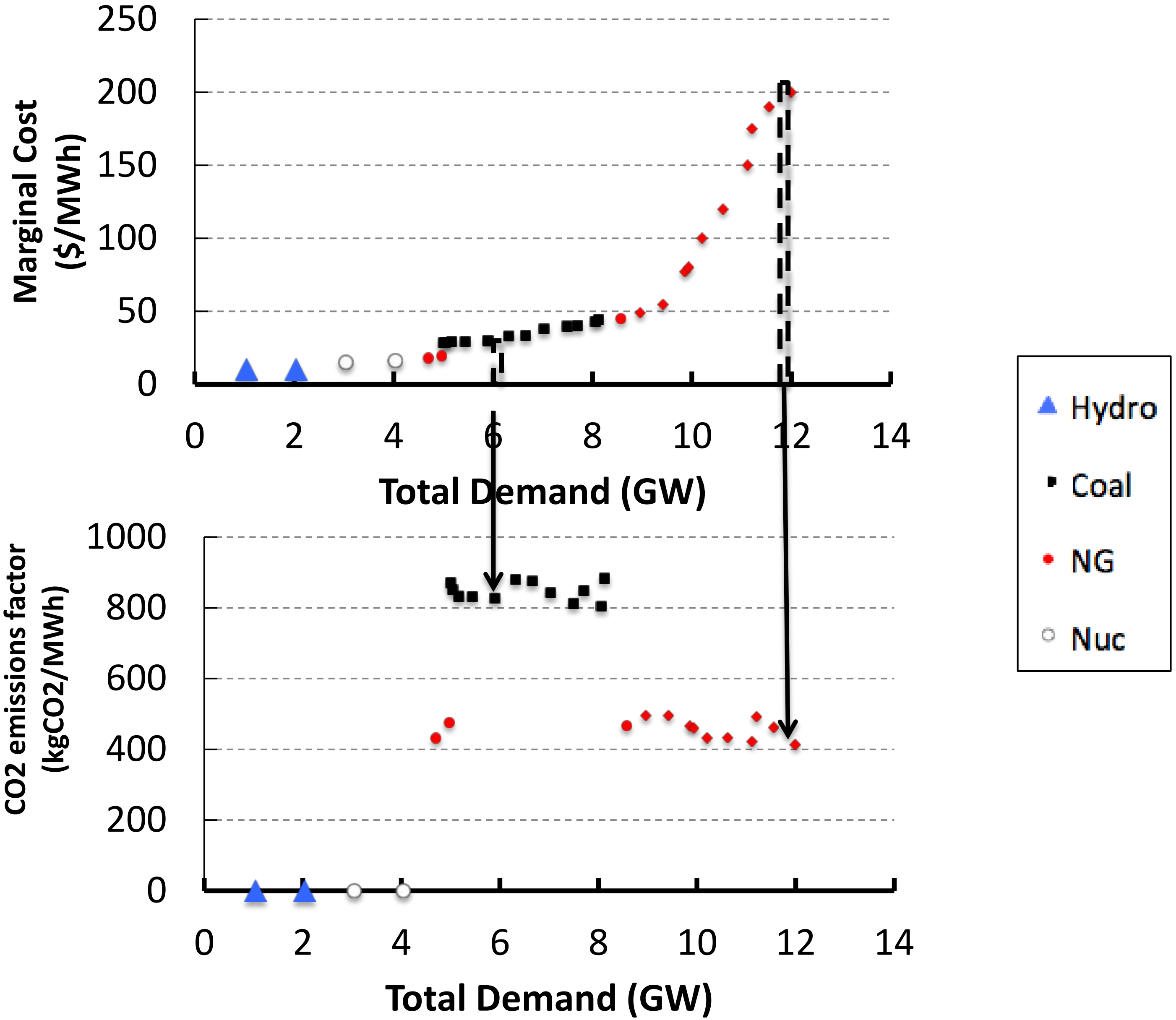
Srouce: Based on APEEP.

The effects of these interventions will differ because the use and provision of energy services also varies regionally and across time.

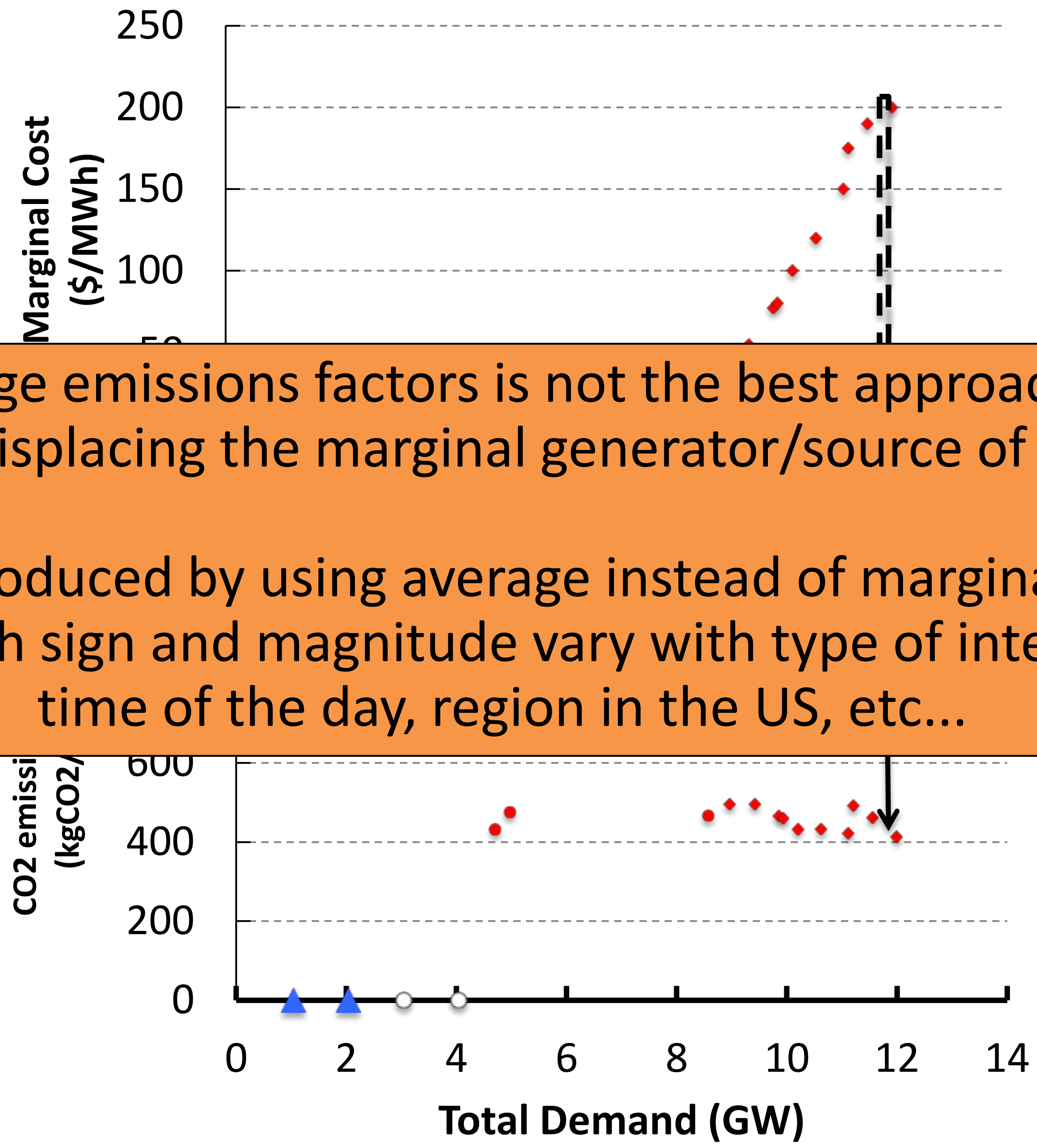
Question: how to understand the effects of interventions during this transition period?

- When we pursue interventions in the grid, such as increasing renewables, storage, enhancing the adoption of electric vehicles, increasing the stringency of building codes, etc, what are the emissions (of greenhouse gases and of criteria air pollutants) that we are avoiding (or adding) to our energy system?

- What are the monetized benefits or costs of those emissions changes?



Figures from Azevedo – this is a schematic only, it does not represent a real system



Using average emissions factors is not the best approach because we are displacing the marginal generator/source of energy.

The bias introduced by using average instead of marginal is hard to predict: both sign and magnitude vary with type of interventions, time of the day, region in the US, etc...

Figures from Azevedo – this is a schematic only, it does not represent a real system

Interventions in the system → **Temporal profile** → **Match with the generation that is displaced by interventions** → **Monetized values**

Wind

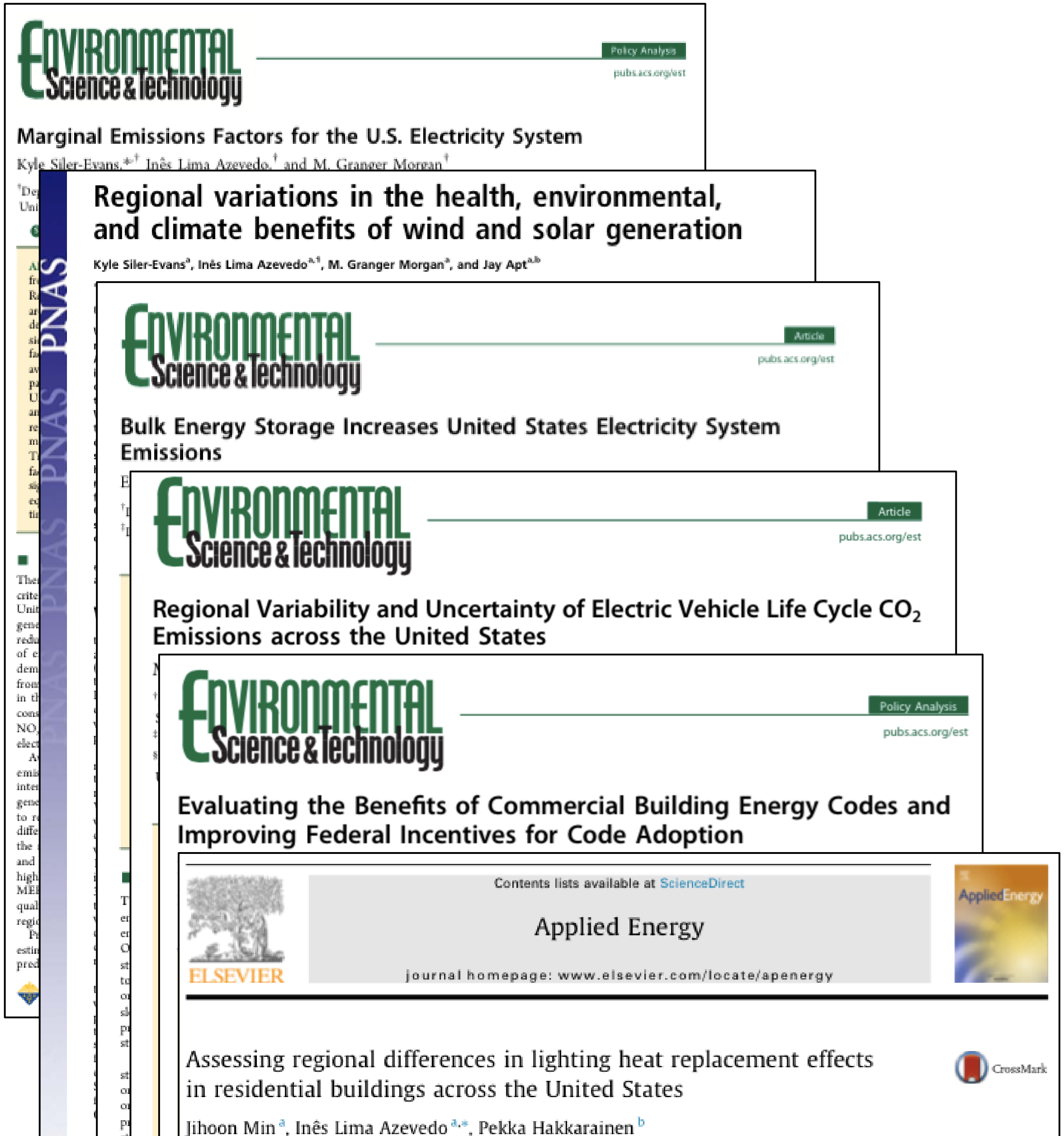
Solar

Storage

Electrified vehicles

Building codes

Efficient Lighting strategies



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Policy Analysis

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Marginal Emissions Factors for the U.S. Electricity System

Kyle Siler-Evans,[*,†] Inês Lima Azevedo,[†] and M. Granger Morgan[†]

PNAS

Regional variations in the health, environmental, and climate benefits of wind and solar generation

Kyle Siler-Evans[a], Inês Lima Azevedo[a,1], M. Granger Morgan[a], and Jay Apt[a,b]

Environmental Science & Technology

Article

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Bulk Energy Storage Increases United States Electricity System Emissions

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Regional Variability and Uncertainty of Electric Vehicle Life Cycle CO_2 Emissions across the United States

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Evaluating the Benefits of Commercial Building Energy Codes and Improving Federal Incentives for Code Adoption

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Assessing regional differences in lighting heat replacement effects in residential buildings across the United States

CrossMark

Jihoon Min[a], Inês Lima Azevedo[a,*], Pekka Hakkarainen[b]

Wouldn’t it be great if we had data to do this?

- We do!
  - The Environmental Protection Agency (EPA) collects measured data for every single fossil fuel power plant (larger than 25 MW) generation and emissions of CO_2, SO_2 and NO_x on an hourly basis.
  - We can find actual or simulated data for the hourly profiles of these interventions
  - And so we have a way to estimate the CO_2 emissions savings, the “co-benefits” from criteria air pollutant savings and their monetized value.

How does the performance of **wind** and **solar** vary regionally?

Three measures of performance:

- Energy production
- Climate benefits from displaced CO_2 emissions
- Health and environmental benefits from displaced criteria pollutants: SO_2, NO_x, $PM_{2.5}$

Regional variations in the health, environmental, and climate benefits of wind and solar generation

Kyle Siler-Evans[a], Inês Lima Azevedo[a,1], M. Granger Morgan[a], and Jay Apt[a,b]

[a]Engineering and Public Policy and [b]Tepper School of Business, Carnegie Mellon University, Pittsburgh, PA 15213

Edited by Edward L. Miles, University of Washington, Seattle, WA, and approved May 15, 2013 (received for review December 19, 2012)

When wind or solar energy displace conventional generation, the reduction in emissions varies dramatically across the United States. Although the Southwest has the greatest solar resource, a solar panel in New Jersey displaces significantly more sulfur dioxide, nitrogen oxides, and particulate matter than a panel in Arizona, resulting in 15 times more health and environmental benefits. A wind turbine in West Virginia displaces twice as much carbon dioxide as the same turbine in California. Depending on location, we estimate that the combined health, environmental, and climate benefits from wind or solar range from $10/MWh to $100/MWh, and the sites with the highest energy output do not yield the greatest social benefits in many cases. We estimate that the social benefits from existing wind farms are roughly 60% higher than the cost of the Production Tax Credit, an important federal subsidy for wind energy. However, that same investment could achieve greater health, environmental, and climate benefits if it were differentiated by region.

externalities | renewable electricity | renewable energy policy | air pollution

Wind and solar power provide health, environmental, and climate benefits by displacing conventional generators and therefore reducing emissions of carbon dioxide (CO_2) and criteria air pollutants, which include sulfur dioxide (SO_2), nitrogen oxides (NO_x), and fine particulate matter ($PM_{2.5}$). It is natural to think that the windiest or sunniest sites will yield the best performance. However, the reduction in emissions resulting from wind or solar depends not only on the energy produced but also on the conventional generators displaced, and that varies dramatically depending on location.

Previous research has explored the emissions implications of renewable energy (1–7). The US Department of Energy estimates that achieving 20% wind penetration in the United States would reduce CO_2 emissions by 825 million metric tons by 2030 (1). Valenteno et al. (2) estimate the avoided emissions resulting from wind energy in Illinois, with a focus on the effects of additional cycling of conventional power plants. The study finds that 10% wind penetration would result in a 12% reduction in CO_2 emissions, 13% reduction in NO_x, 8% reduction in SO_2, and an 11% reduction in PM. Lu et al. (3) estimate that the CO_2 reductions resulting from 30% wind penetration in Texas would cost approximately $20 per ton avoided. Kaffine et al. (4) estimate the emissions savings from wind energy for three regions of the United States. The study concludes that "emissions reductions in the Upper Midwest roughly cover government subsidies for wind generation, [while] environmental benefits in Texas and California fall short."

These studies vary greatly in the methods and assumptions used, the regions and pollutants covered, and the metrics reported, all of which prevent meaningful comparisons among studies. This work provides a systematic assessment of wind and solar energy across the United States. We estimate the monetized social benefits resulting from emissions reductions, and we explicitly consider differences in energy production, climate benefits from displaced CO_2 emissions, and health and environmental benefits from displaced SO_2, NO_x, and $PM_{2.5}$. In addition, we compare the social benefits from existing wind farms with the cost of the Production Tax Credit, an important federal subsidy for wind energy.

Results

We evaluate a Vestas V90-3.0-MW wind turbine at more than 33,000 locations and a 1-kW photovoltaic (PV) solar panel at more than 900 locations across the United States. We assume that wind and solar displace the damages from marginal electricity production, which varies regionally and temporally. Damages from CO_2 emissions are monetized using a social cost of $20 per ton of CO_2. Location-specific damages from SO_2, NO_x, and $PM_{2.5}$ emissions are adopted from the Air Pollution Emission Experiments and Policy (APEEP) analysis model, which values mortality from air pollution at $6 million per life lost (often termed the value of a statistical life) (8). For more than 1,400 fossil-fueled power plants, dollar-per-ton damage values for each pollutant are combined with plant-level emissions data to estimate the health, environmental, and climate damages for each hour from 2009 through 2011. Finally, we use regressions of measured hourly emissions and generation data to estimate the reduction in damages that occurs when conventional generators are displaced by wind or solar. To account for regional differences, regressions are performed separately for the 22 subregions defined in the Emissions and Generation Resource Integrated Database (eGRID). eGRID subregions were created by the US Environmental Protection Agency (EPA) using Power Control Areas as a guide. Although not perfect, they provide an estimate for the group of plants serving loads within a region (9).

Results are presented in Fig. 1. For both wind (Fig. 1 *A*–*C*) and solar (Fig. 1 *D*–*F*), we consider three measures of performance: capacity factor, which is the ratio of the annual energy production to the maximum energy production at full-power operation (Fig. 1 *A* and *D*); annual avoided CO_2 emissions (Fig. 1 *B* and *E*); and annual health and environmental benefits from displaced SO_2, NO_x, and $PM_{2.5}$ emissions (Fig. 1 *C* and *F*). For consistency, we provide all results on a per-kilowatt-installed or per-megawatt-hour basis. All monetary values are in 2010 dollars.

Social Benefits of Wind Energy. From an energy standpoint, wind turbines perform best in the Great Plains south through west Texas, where capacity factors can exceed 40%. The wind resource is poor in much of the West and moderate in much of the East. It is also poor in the Southeast, which is excluded from our assessment owing to data limitations (Fig. S1).

We report two metrics for reductions in CO_2 emissions—kilograms of CO_2 avoided annually and the corresponding social benefits, assuming a social cost of $20 per ton of CO_2. Wind turbines are most effective at displacing CO_2 emissions when located in the Midwest, where the wind resource is excellent and

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Author contributions: K.S.-E., I.L.A., M.G.M., and J.A. designed research; K.S.-E. performed research; and K.S.-E., I.L.A., M.G.M., and J.A. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: A spreadsheet of the full results reported in this paper for both wind and solar is available at http://cedmcenter.org/tools-for-cedm/marginal-emissions-factors-repository/.

[1]To whom correspondence should be addressed. E-mail: iazevedo@cmu.edu.

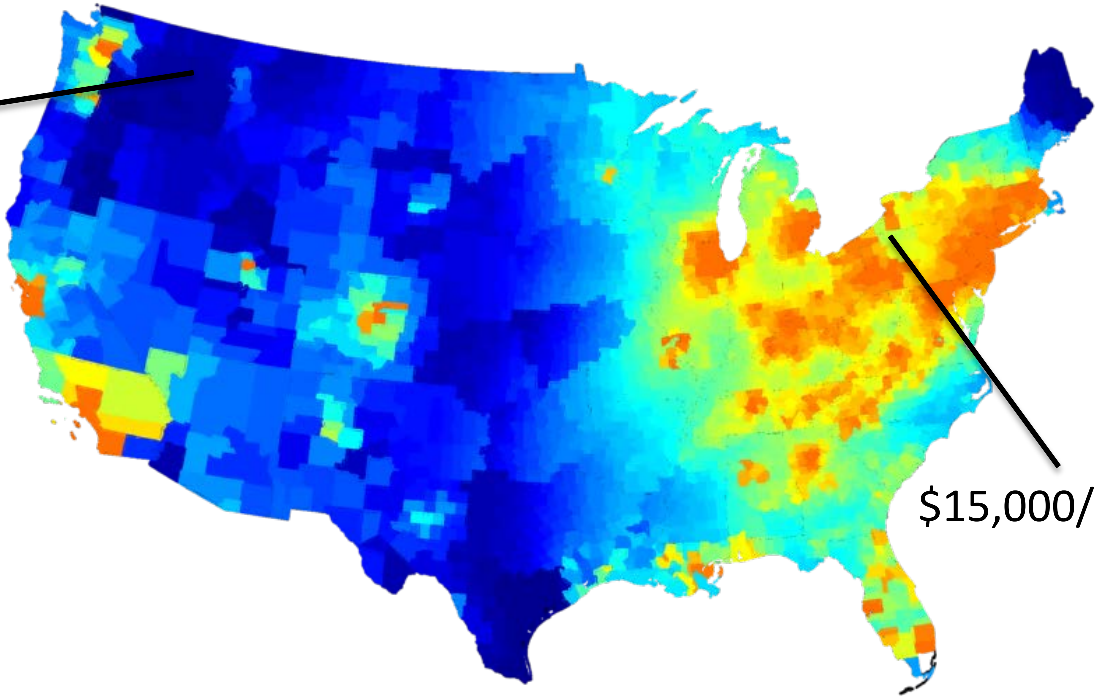
This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1221978110/-/DCSupplemental.

www.pnas.org/cgi/doi/10.1073/pnas.1221978110

Estimating environmental and health benefits

For each county: damages ($/ton) by stack height for each pollutant (CO_2, SO_2, NO_x, $PM_{2.5}$)

Data from: APEEP



$1000/ton SO_2

$15,000/ton SO_2

Estimating environmental and health benefits

For each county: damages (\$/ton) by stack height for each pollutant (SO_2, NO_x, $PM_{2.5}$)

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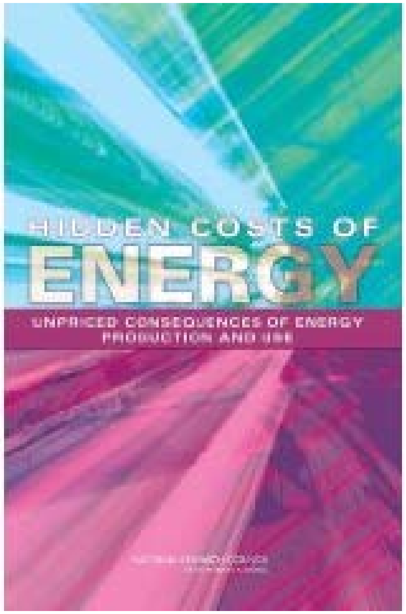

Similar framework to the NRC report on “Hidden Costs of Energy”

Air Pollution Emissions Experiments and Policy analysis model (APEEP)

- Estimate the dispersion of pollutants and the resulting concentrations in all US counties
- Use dose-response function to estimate physical impacts:
  - Health effects, reduced crop and timber yield, degradation of materials, reduced visibility, etc…
- Monetize impacts:
  - Value of a statistical life (\$6M), market value of lost commodities, etc…

Estimating environmental and health benefits

1

For each county: damages (\$/ton) by stack height for each pollutant (SO_2, NO_x, $PM_{2.5}$)

Data from: APEEP

Results from the APEEP model provide average county dollar-per-ton damages for each pollutant (SO_2, NO_x, $PM_{2.5}$) emitted by point sources

For CO_2, we use \$20/tonCO2

US Interagency Working Group on Social Cost of Carbon (2010): four values for SCC in 2010 (\$2007): \$5, \$21, \$35 and \$65 per ton CO_2

Estimating environmental and health benefits

For each county: damages ($/ton) by stack height for each pollutant (SO_2, NO_x, $PM_{2.5}$)

Data from: APEEP

2

For 1400 plants: location, fuel type, stack height and hourly emissions of CO_2, SO_2, NO_x, $PM_{2.5}$

Data from: CEMS (2009-2011), eGRID (2009), NEI (2005)

Continuous Emissions Monitoring System (CEMS) (2009-2011)

- Hourly SO_2, NO_x, CO_2, and gross power output for 1400 fossil fuel power plants

National Emissions Inventory (NEI) (2005)

- Annual $PM_{2.5}$ emissions, stack heights of generators

Emissions & Generation Resource Integrated Database (eGRID) (2009)

- Plant locations, fuel type

Estimating environmental and health benefits

1

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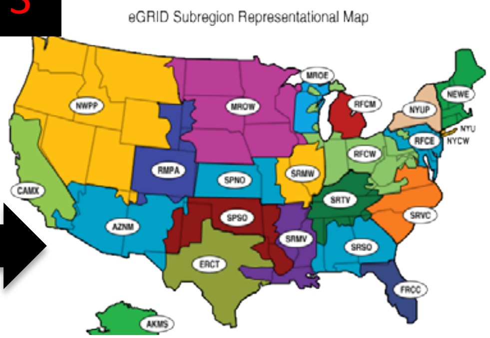

For each eGRID sub-region and each pollutant:

hourly damages (\$/h) = damages (\$/ton) x hourly emissions (ton pollutant/h)

Estimating environmental and health benefits

1

For each county: damages (\$/ton) by stack height for each pollutant (SO_2, NO_x, $PM_{2.5}$)

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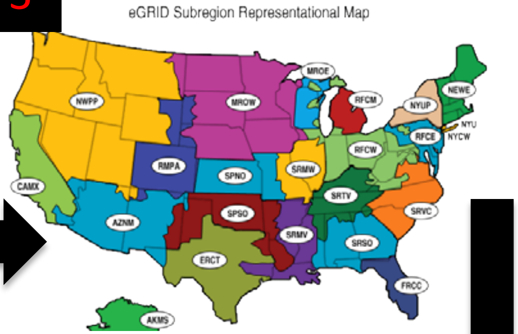

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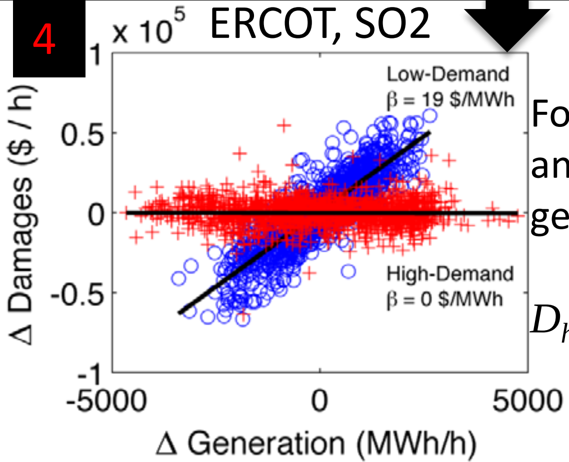
4



For each eGRID sub-region and pollutant, for 20 gross generation bins:

$$D_{h+1} - D_h = \beta(G_{h+1} - G_t) + \varepsilon$$

Estimating environmental and health benefits

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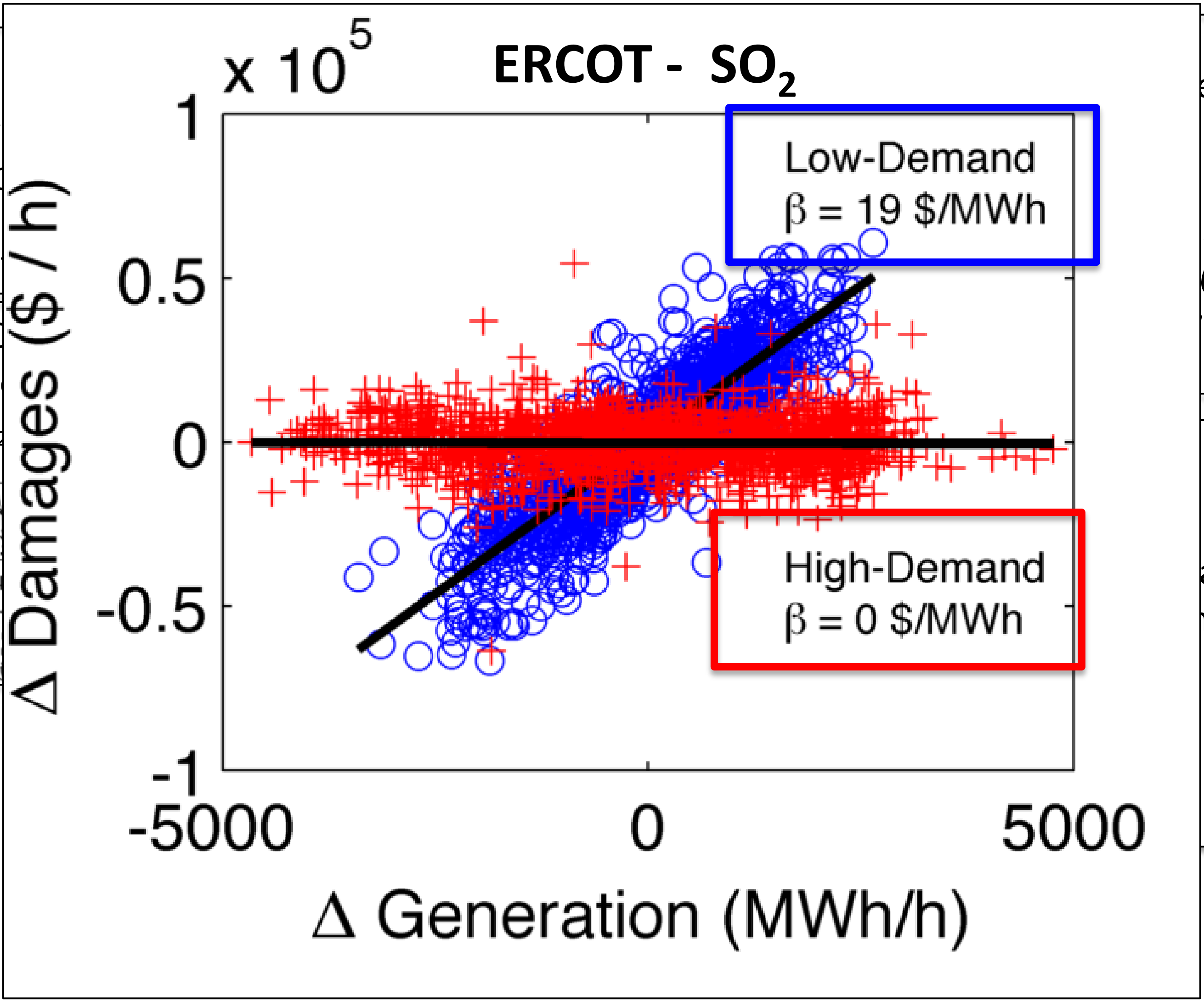
stack h
CO$_2$, SO$_2$



eGRID sub-region
pollutant:

mages ($/h) =
($/ton) x hourly
(ton pollutant/h)

GRID sub-region
ant, for 20 gross
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Estimating environmental and health benefits

1

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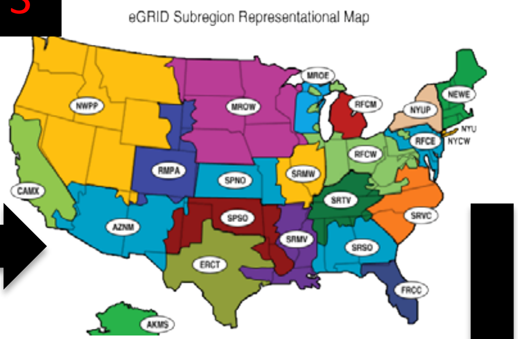

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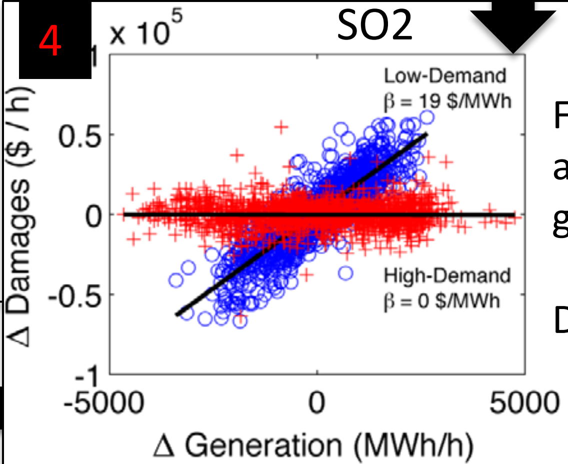
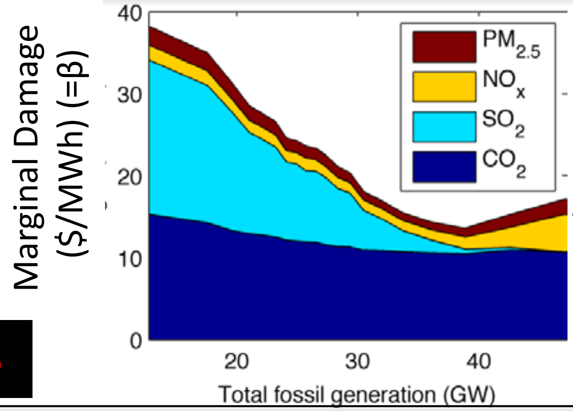
4



For each eGRID sub-region and pollutant, for 20 gross generation bins:

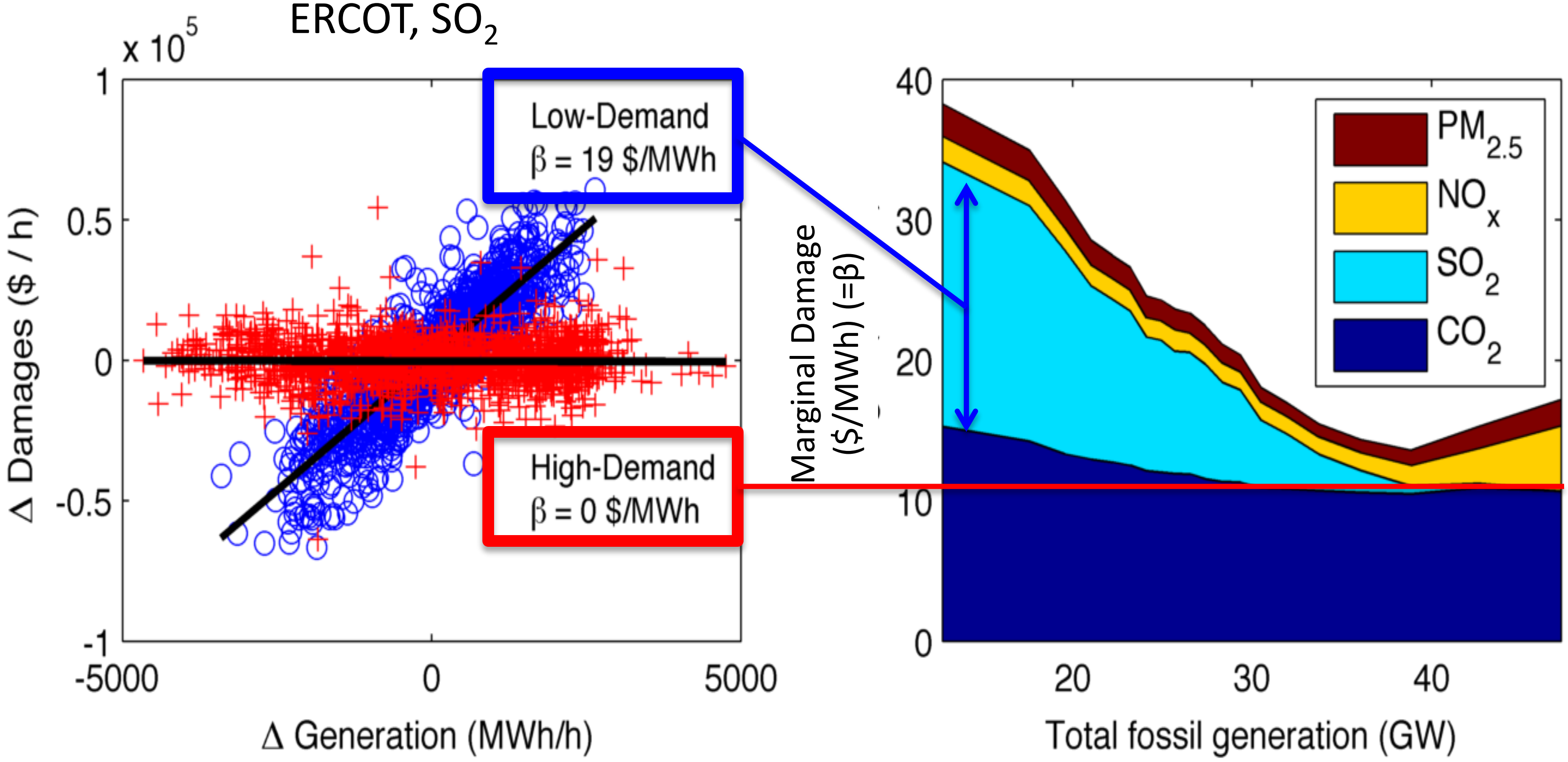
$$D_{h+1}-D_h = \beta(G_{h+1}-G_t) + \varepsilon$$

5



Then we have estimates of marginal damages ($/MWh) for each demand bin as function of gross generation for each pollutant

ERCOT, SO_2



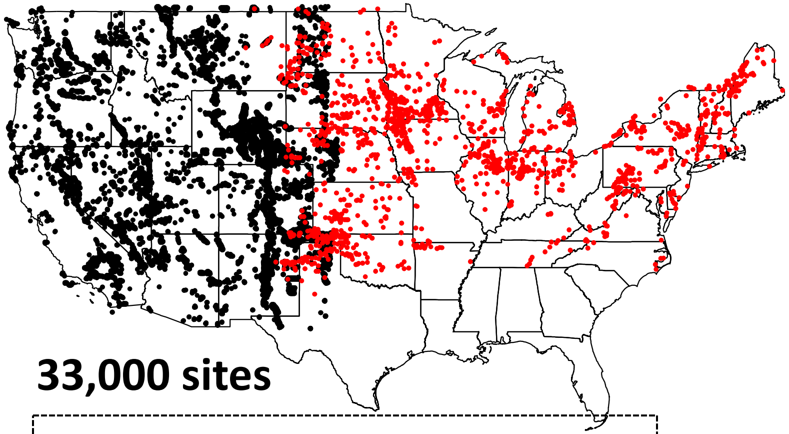
Low-Demand
β = 19 $/MWh

High-Demand
β = 0 $/MWh

Estimating environmental and health benefits

6

WIND



33,000 sites

Eastern Wind Integration and Transmissions Study (EWITS)

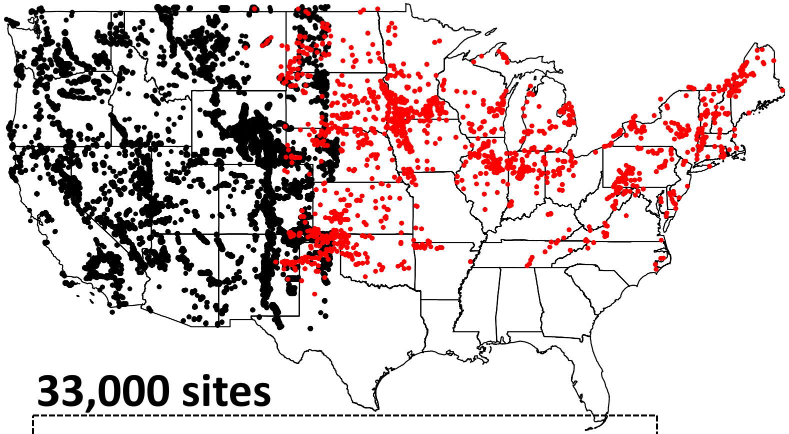
Western Wind and Solar Integration Study (WWSIS)

Hourly wind power output

Estimating environmental and health benefits

6

WIND



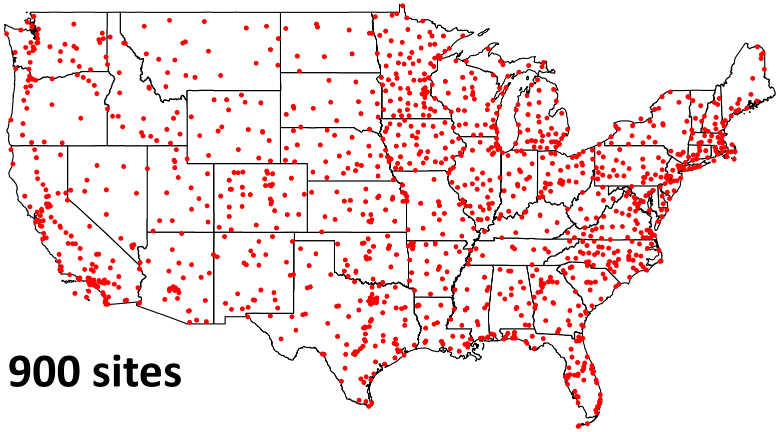
33,000 sites

Eastern Wind Integration and Transmissions Study (EWITS)

Western Wind and Solar Integration Study (WWSIS)

Hourly wind power output

SOLAR

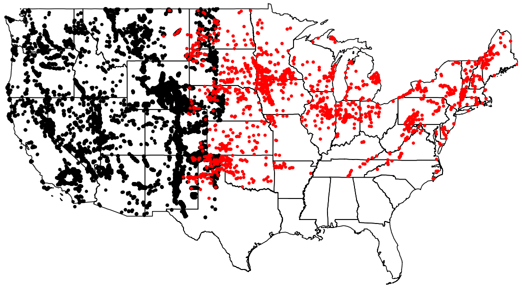


900 sites

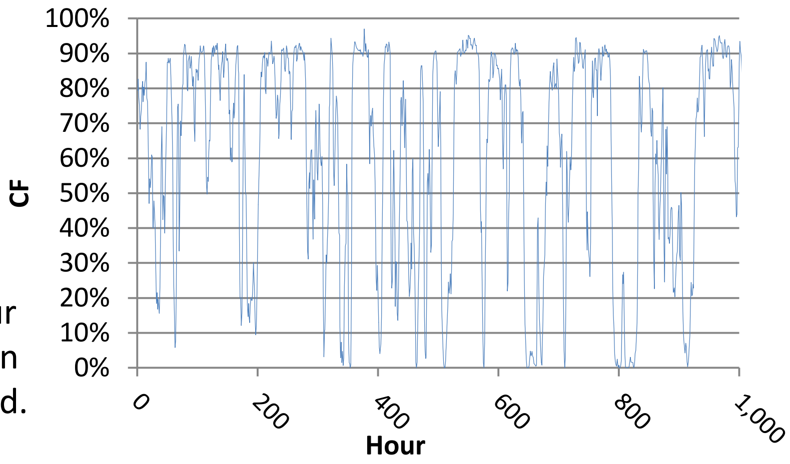
National Solar Radiation Database

Estimating environmental and health benefits

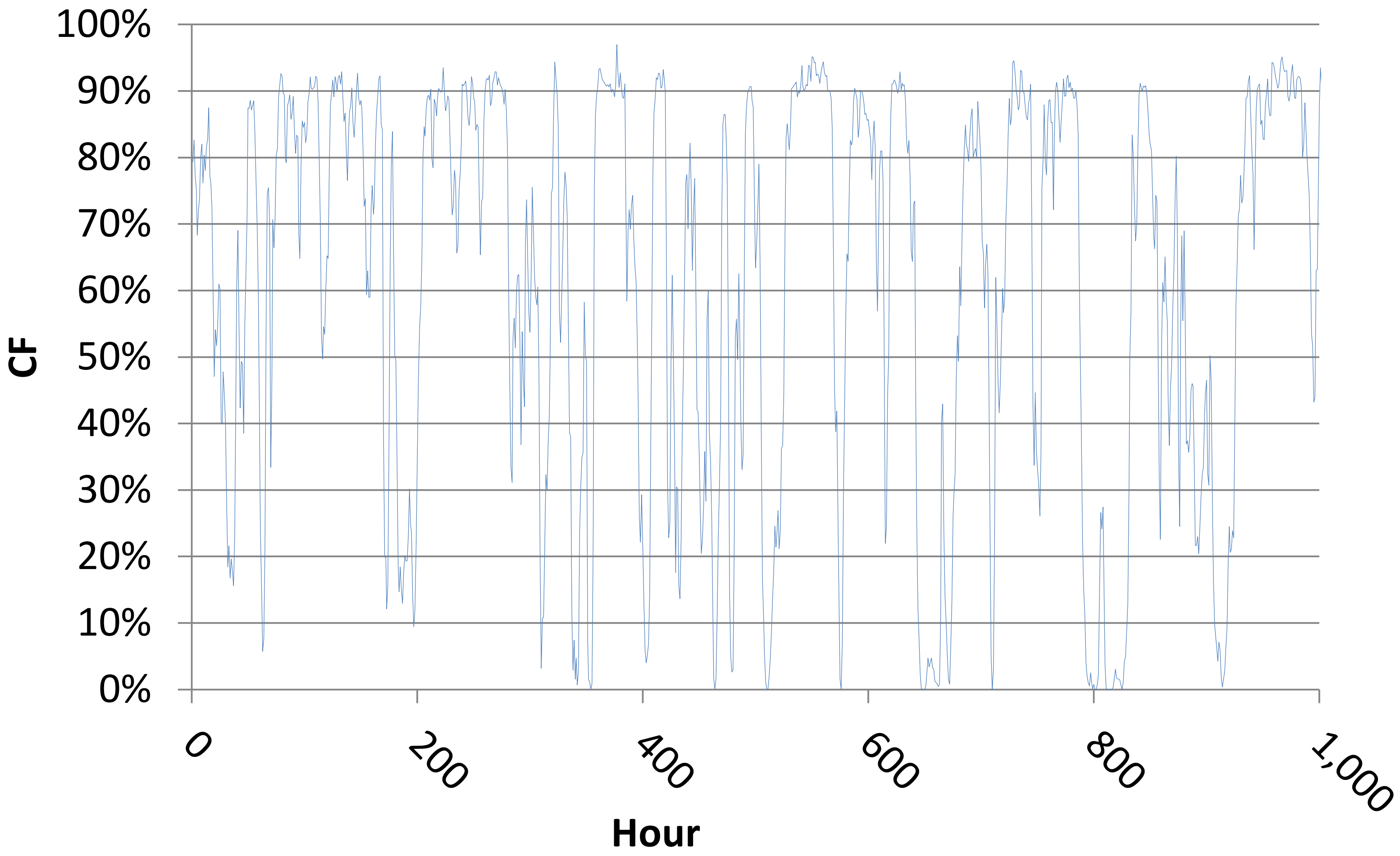
6



For each wind & solar site and for each hour of the year, we match wind/solar generation with the gross generation that it is displaced.



Estimating environmental and health benefits



Estimating environmental and health benefits

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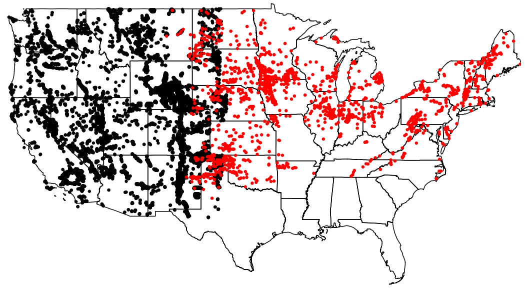

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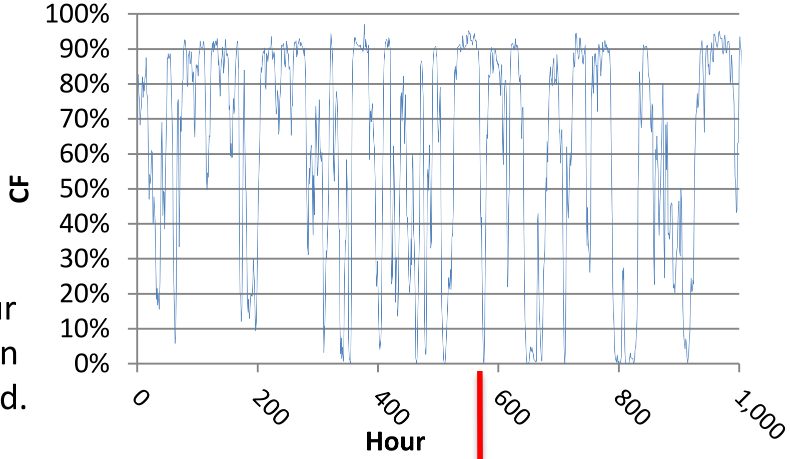

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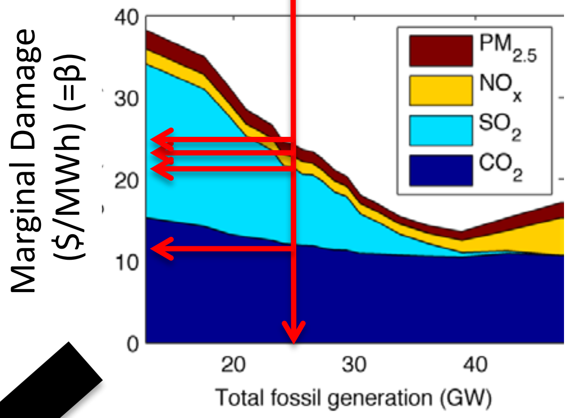
We then Identify the damages associated with gross generation. For each hour, we multiply the associated damages ($/MWh) by the wind/solar output.



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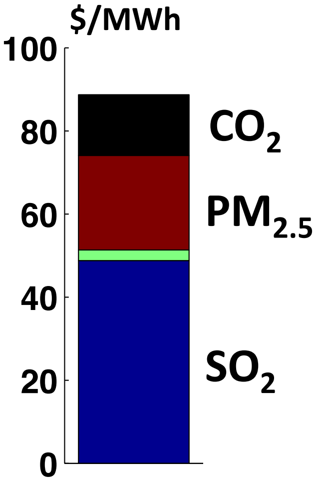
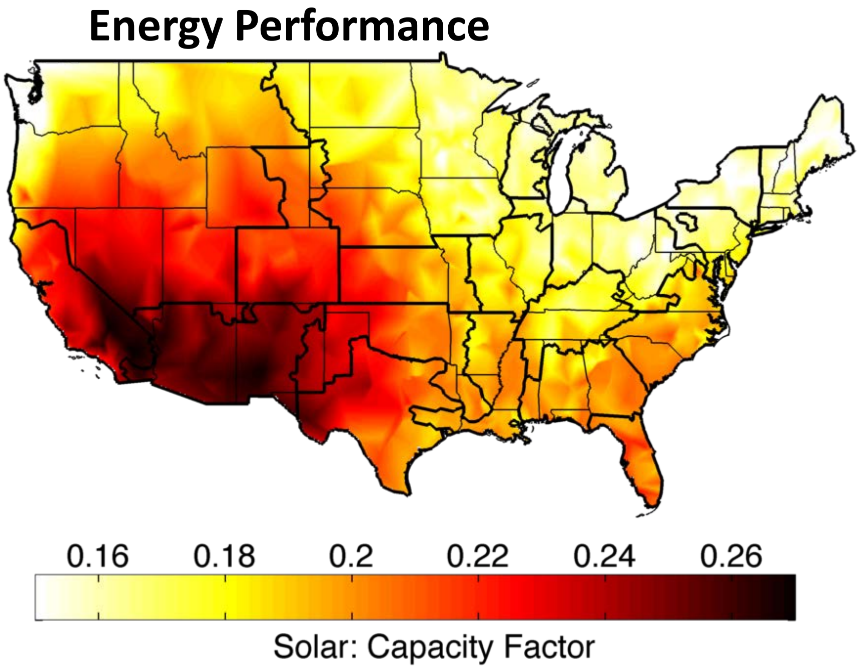


We finally add all damages avoided for each site for all hours of the year and divide by the total generation or capacity installed from wind/solar in each eGRID sub-region, finding the weighted marginal damages for each site

Solar PV - The locations that provide the largest electricity output are not the ones that have the largest climate, health, and environmental benefits.



This is exactly what we expect: solar performs best in places like Arizona, New Mexico and southern California.

A solar panel in Arizona will produce about 45% more energy than a panel in Maine.

References: (1) Siler-Evans, K., Azevedo, I. L., Morgan, M.G, Apt, J. (2013). Regional variations in the health, environmental, and climate benefits from wind and solar generation, *Proceedings of the National Academy of Sciences*, 110 (29), 11768-11773; (2) Siler-Evans. K., Azevedo, I.L., Morgan, M.G., (2012). Marginal emissions factors for the US electricity system. *Environmental Science & Technology, 46* (9): 4742–4748.

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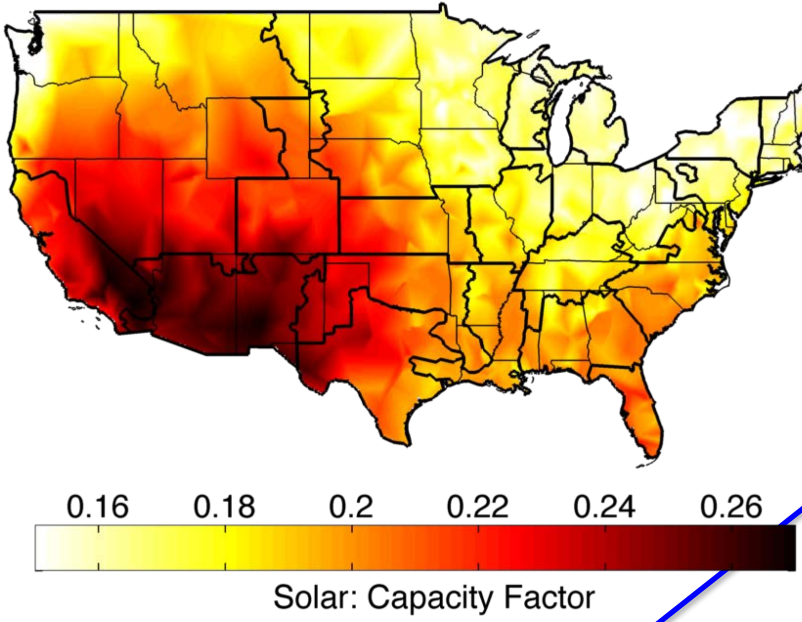
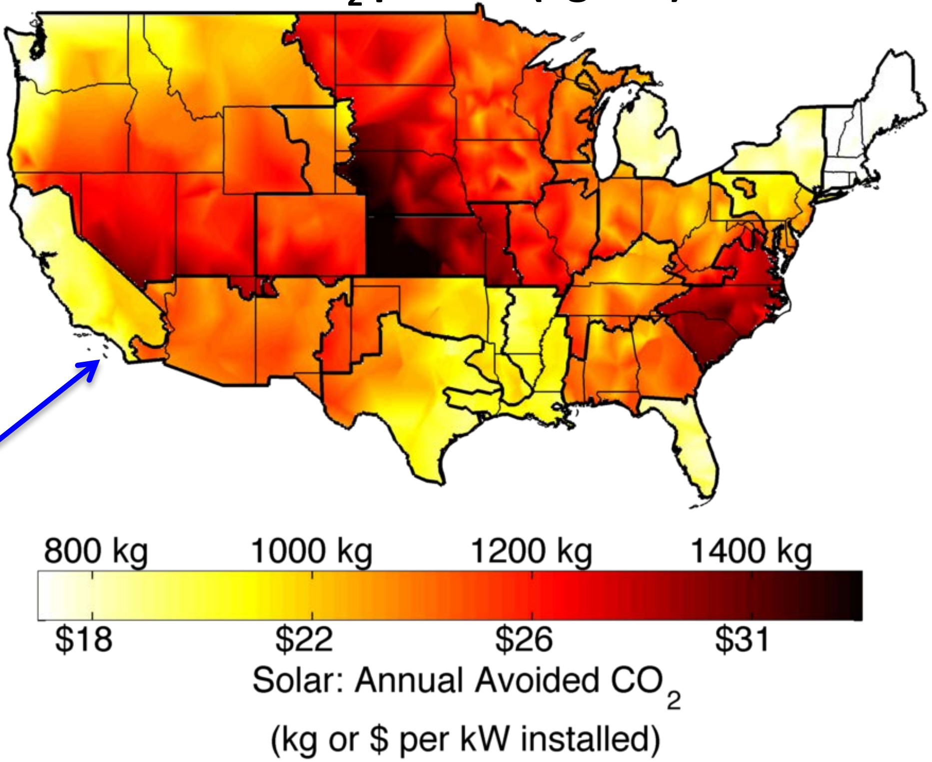
Energy Performance



Avoided CO_2 per kW (kg & $)



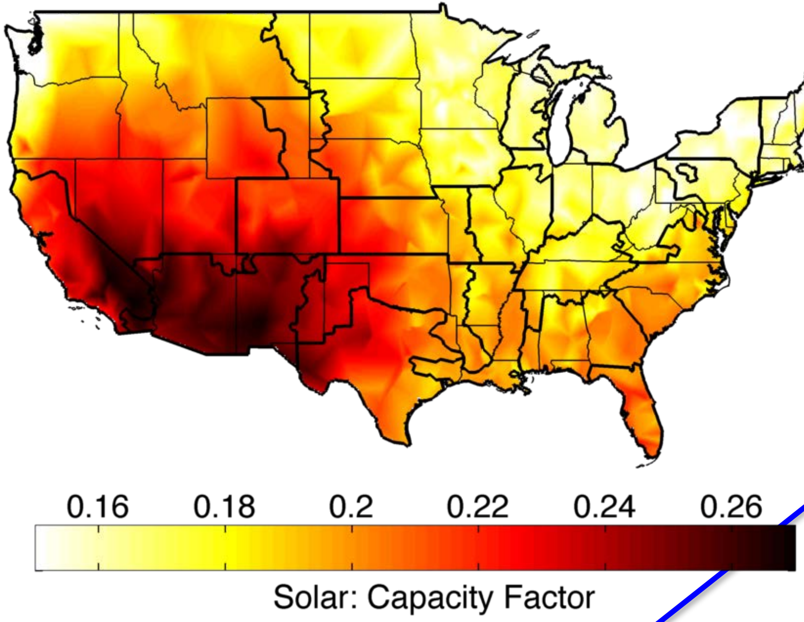
Best regions: Kansas, Nebraska, or the Dakotas

…moderate solar resources, but you're primarily displacing carbon-intensive coal plants.

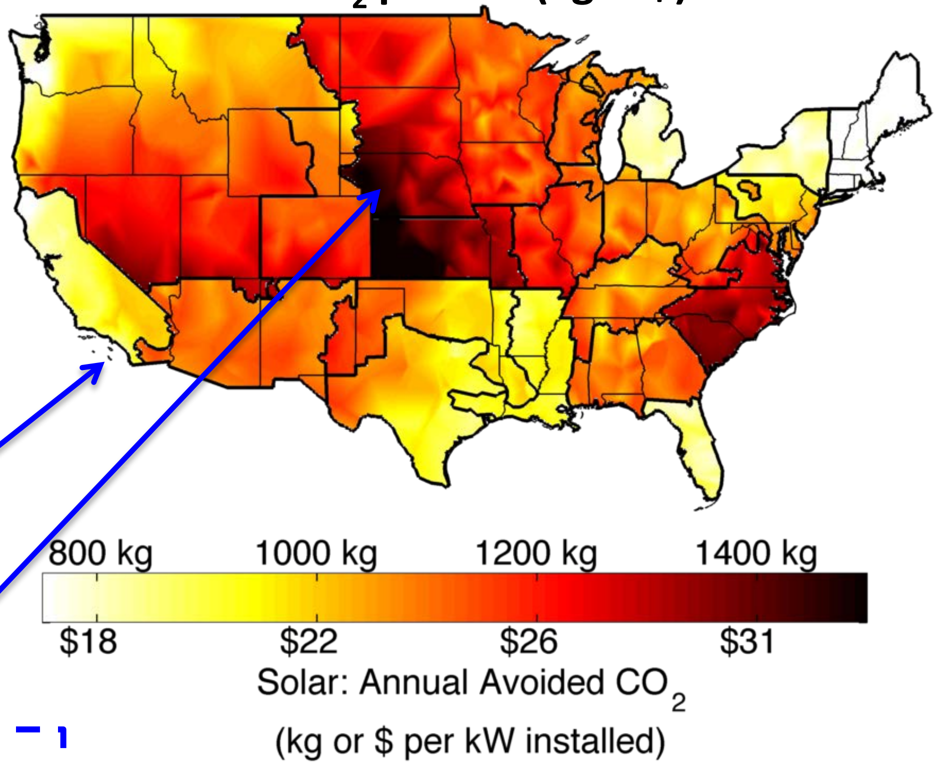
References: (1) Siler-Evans, K., Azevedo, I. L., Morgan, M.G, Apt, J. (2013). Regional variations in the health, environmental, and climate benefits from wind and solar generation, *Proceedings of the National Academy of Sciences*, 110 (29), 11768-11773; (2) Siler-Evans. K., Azevedo, I.L., Morgan, M.G., (2012). Marginal emissions factors for the US electricity system. *Environmental Science & Technology, 46* (9): 4742–4748.

Solar PV - The locations that provide the largest electricity output are not the ones that have the largest climate, health, and environmental benefits.

Energy Performance



Avoided CO_2 per kW (kg & $)



Best regions: Kansas,

carbon-intensive coal plants.

In California or Arizona, gas-fired generators are predominantly on the margin and as a result, solar panels displace relatively little CO_2 emissions.

References: (1) Siler-Evans, K., Azevedo, I. L., Morgan, M.G, Apt, J. (2013). Regional variations in the health, environmental, and climate benefits from wind and solar generation, *Proceedings of the National Academy of Sciences*, 110 (29), 11768-11773; (2) Siler-Evans. K., Azevedo, I.L., Morgan, M.G., (2012). Marginal emissions factors for the US electricity system. *Environmental Science & Technology, 46* (9): 4742–4748.

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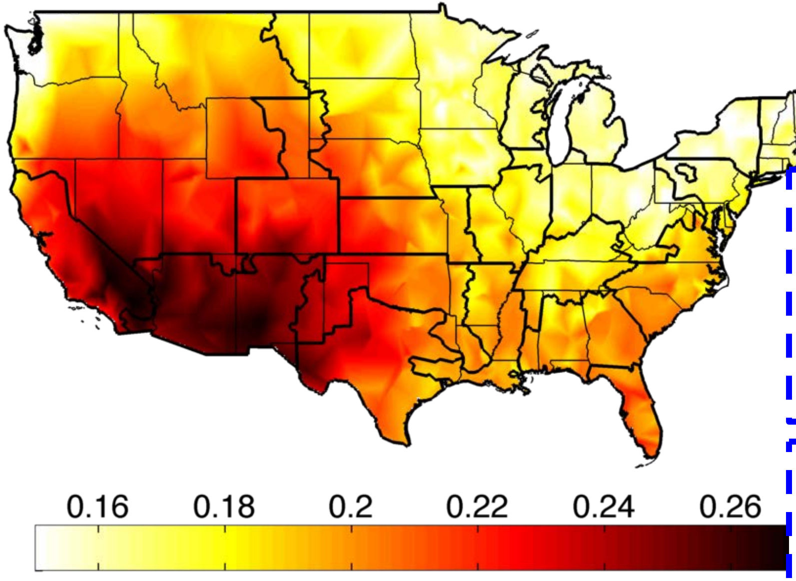
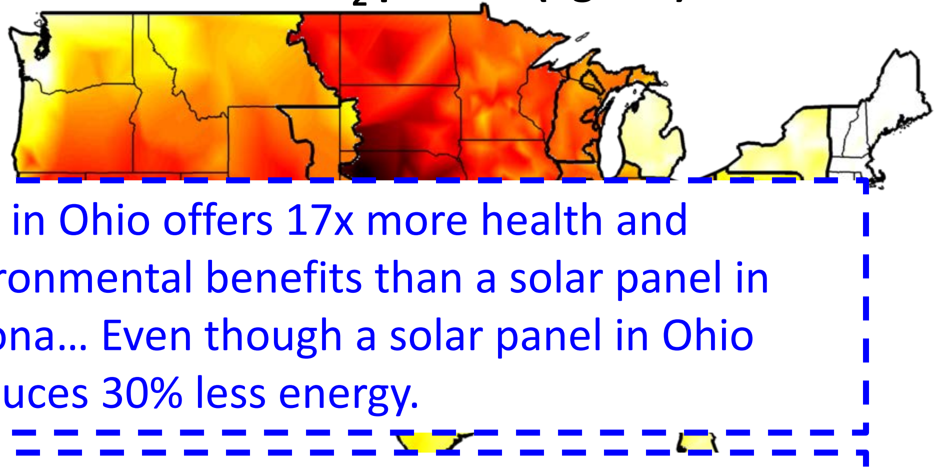


Solar: Capacity Factor

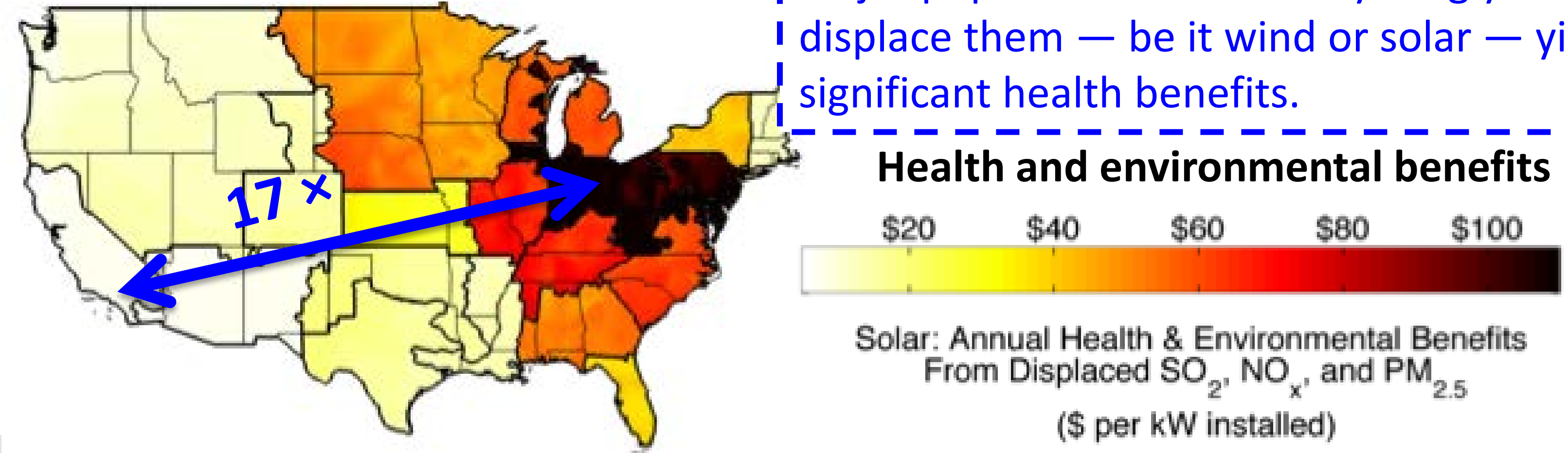
Avoided CO_2 per kW (kg & $)



A PV in Ohio offers 17x more health and environmental benefits than a solar panel in Arizona… Even though a solar panel in Ohio produces 30% less energy.

The reason for this is simple: coal is at the margin in these areas and they are upwind of major population centers. Anything you do to displace them — be it wind or solar — yields significant health benefits.

Health and environmental benefits

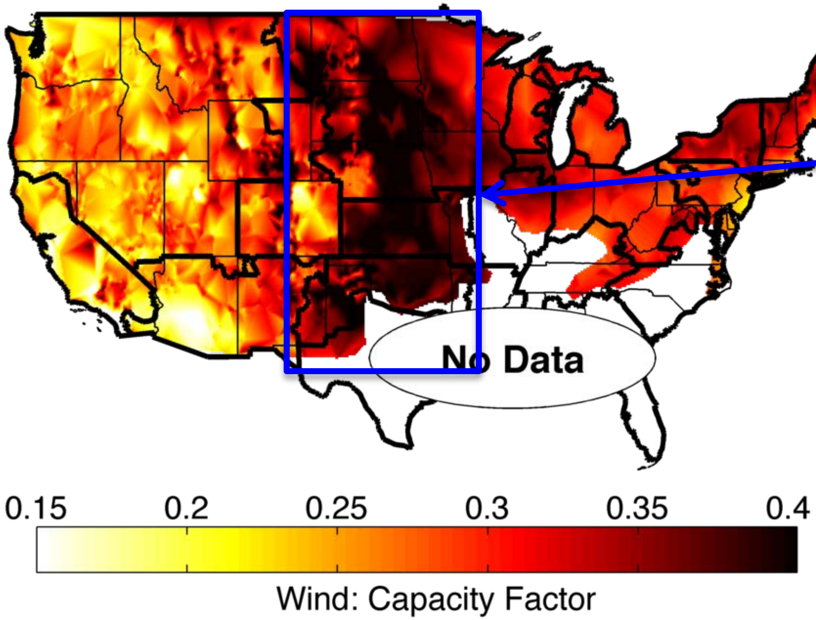


Solar: Annual Health & Environmental Benefits From Displaced SO_2, NO_x, and $PM_{2.5}$ ($ per kW installed)

References: (1) Siler-Evans, K., Azevedo, I. L., Morgan, M.G, Apt, J. (2013). Regional variations in the health, environmental, and climate benefits from wind and solar generation, *Proceedings of the National Academy of Sciences*, 110 (29), 11768-11773; (2) Siler-Evans. K., Azevedo, I.L., Morgan, M.G., (2012). Marginal emissions factors for the US electricity system. *Environmental Science & Technology, 46* (9): 4742–4748.

Wind - The locations that provide the largest electricity output align with the locations that provide the largest CO_2 savings, but not criteria air pollutant savings.

Energy Performance



From an energy standpoint, wind turbines perform best in the Great Plains through West Texas, where capacity factors can reach 40%.

References: (1) Siler-Evans, K., Azevedo, I. L., Morgan, M.G, Apt, J. (2013). Regional variations in the health, environmental, and climate benefits from wind and solar generation, *Proceedings of the National Academy of Sciences*, 110 (29), 11768-11773; (2) Siler-Evans. K., Azevedo, I.L., Morgan, M.G., (2012). Marginal emissions factors for the US electricity system. *Environmental Science & Technology, 46* (9): 4742–4748.

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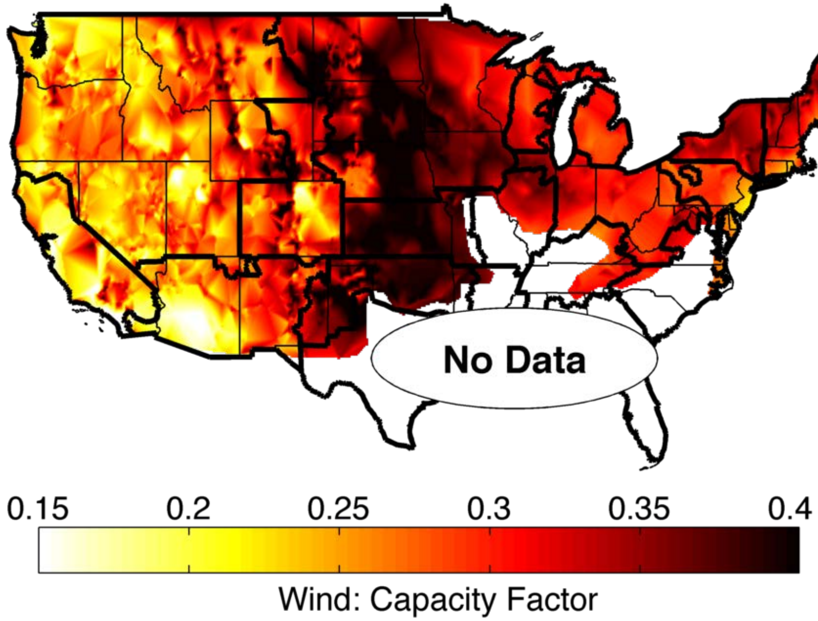
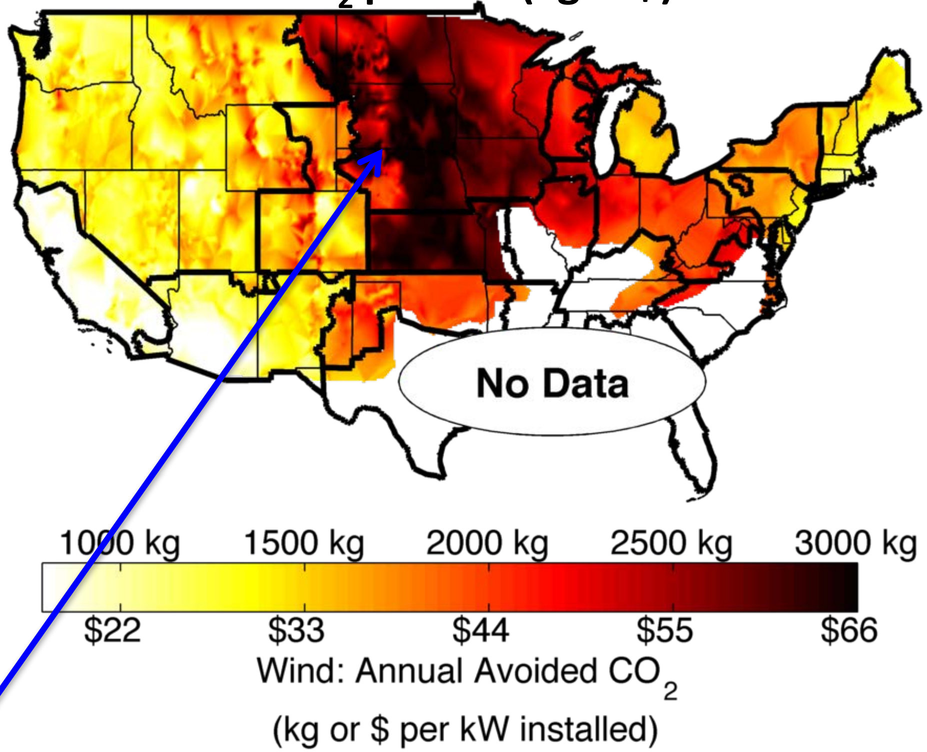
Energy Performance



Avoided CO_2 per kW (kg & $)



Wind turbines are most effective at displacing CO_2 emissions when located in Midwest, where the wind resource is excellent and wind energy primarily displaces coal-fired generators.

References: (1) Siler-Evans, K., Azevedo, I. L., Morgan, M.G, Apt, J. (2013). Regional variations in the health, environmental, and climate benefits from wind and solar generation, *Proceedings of the National Academy of Sciences*, 110 (29), 11768-11773; (2) Siler-Evans. K., Azevedo, I.L., Morgan, M.G., (2012). Marginal emissions factors for the US electricity system. *Environmental Science & Technology, 46* (9): 4742–4748.

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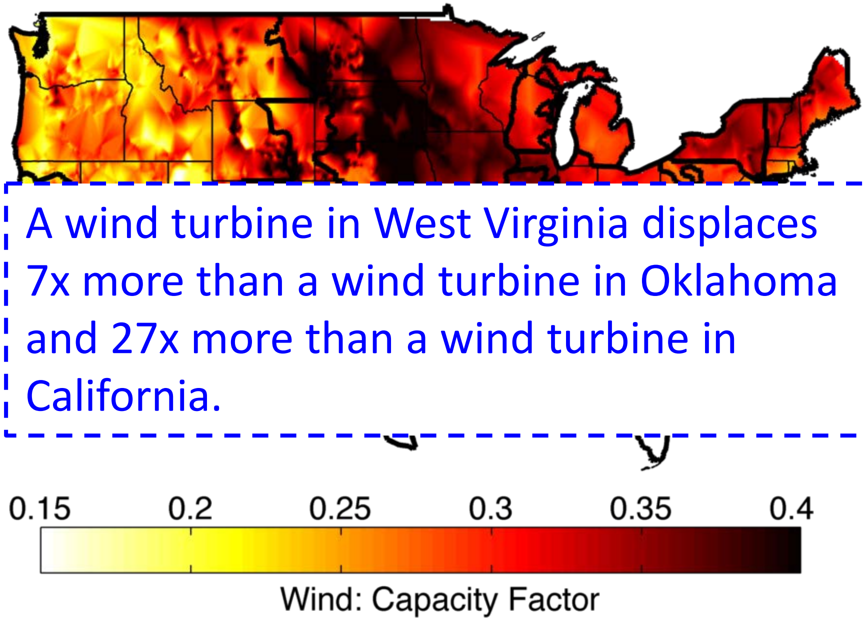
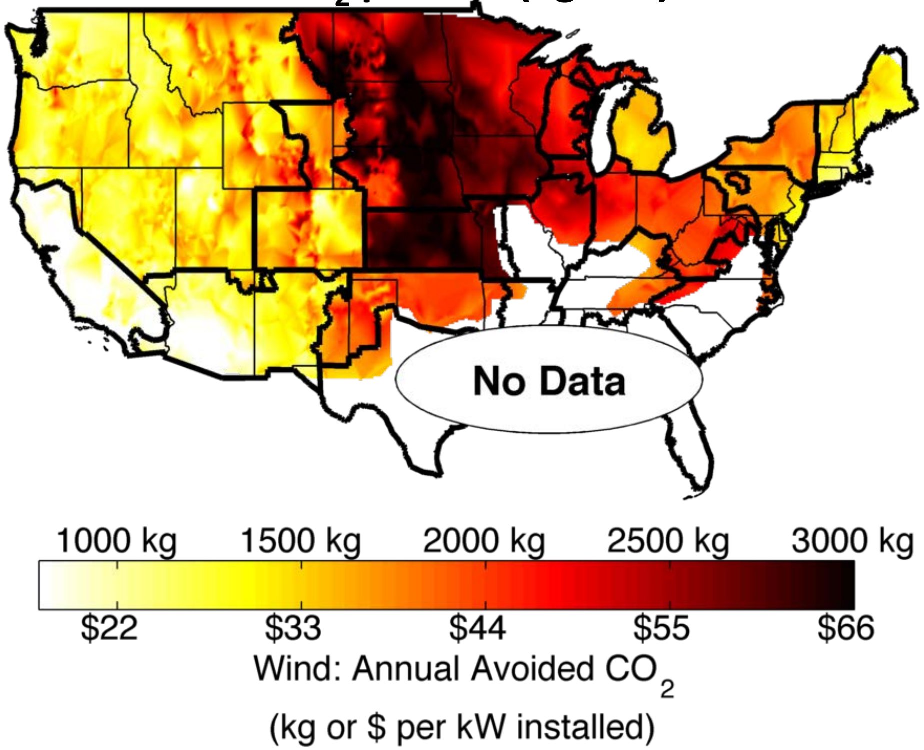
Energy Performance

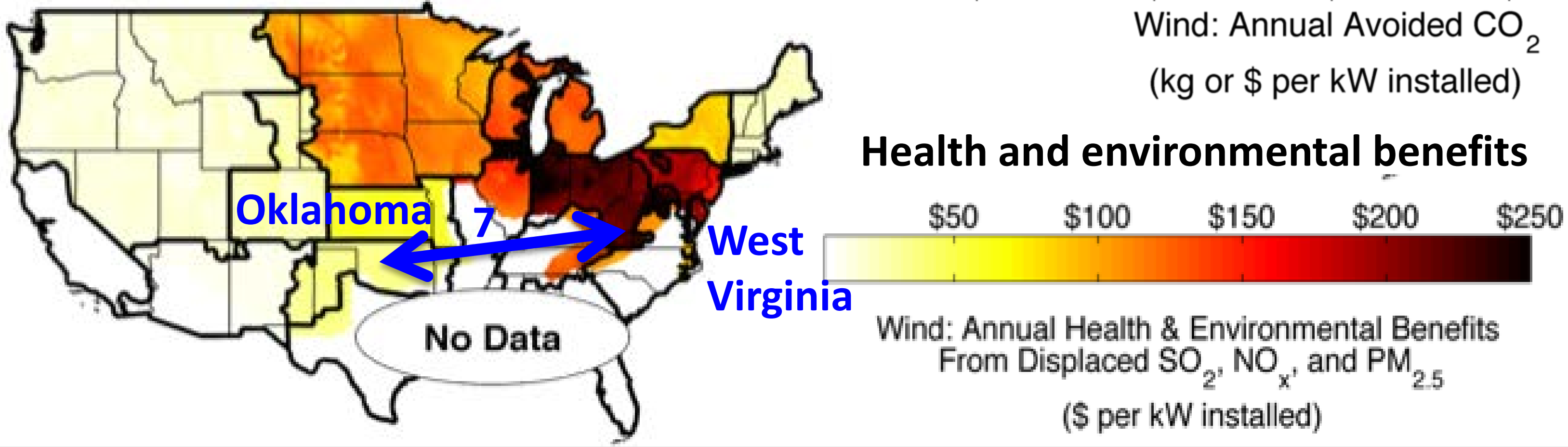


A wind turbine in West Virginia displaces 7x more than a wind turbine in Oklahoma and 27x more than a wind turbine in California.

Avoided CO_2 per kW (kg & $)

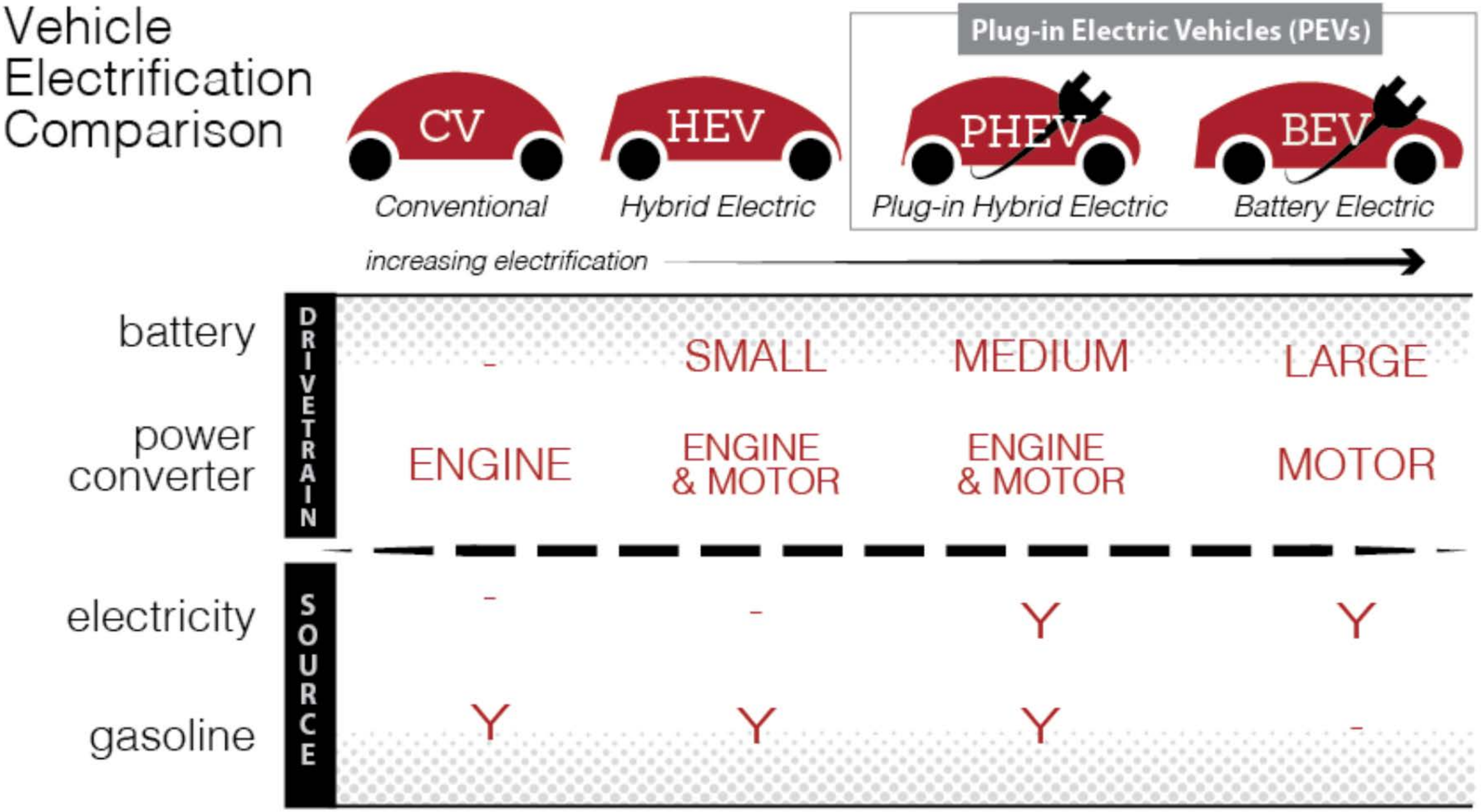


Health and environmental benefits



References: (1) Siler-Evans, K., Azevedo, I. L., Morgan, M.G, Apt, J. (2013). Regional variations in the health, environmental, and climate benefits from wind and solar generation, *Proceedings of the National Academy of Sciences*, 110 (29), 11768-11773; (2) Siler-Evans. K., Azevedo, I.L., Morgan, M.G., (2012). Marginal emissions factors for the US electricity system. *Environmental Science & Technology, 46* (9): 4742–4748.

Are we helping the environment more if we choose a battery electric car or an hybrid?



Vehicle Electrification Comparison

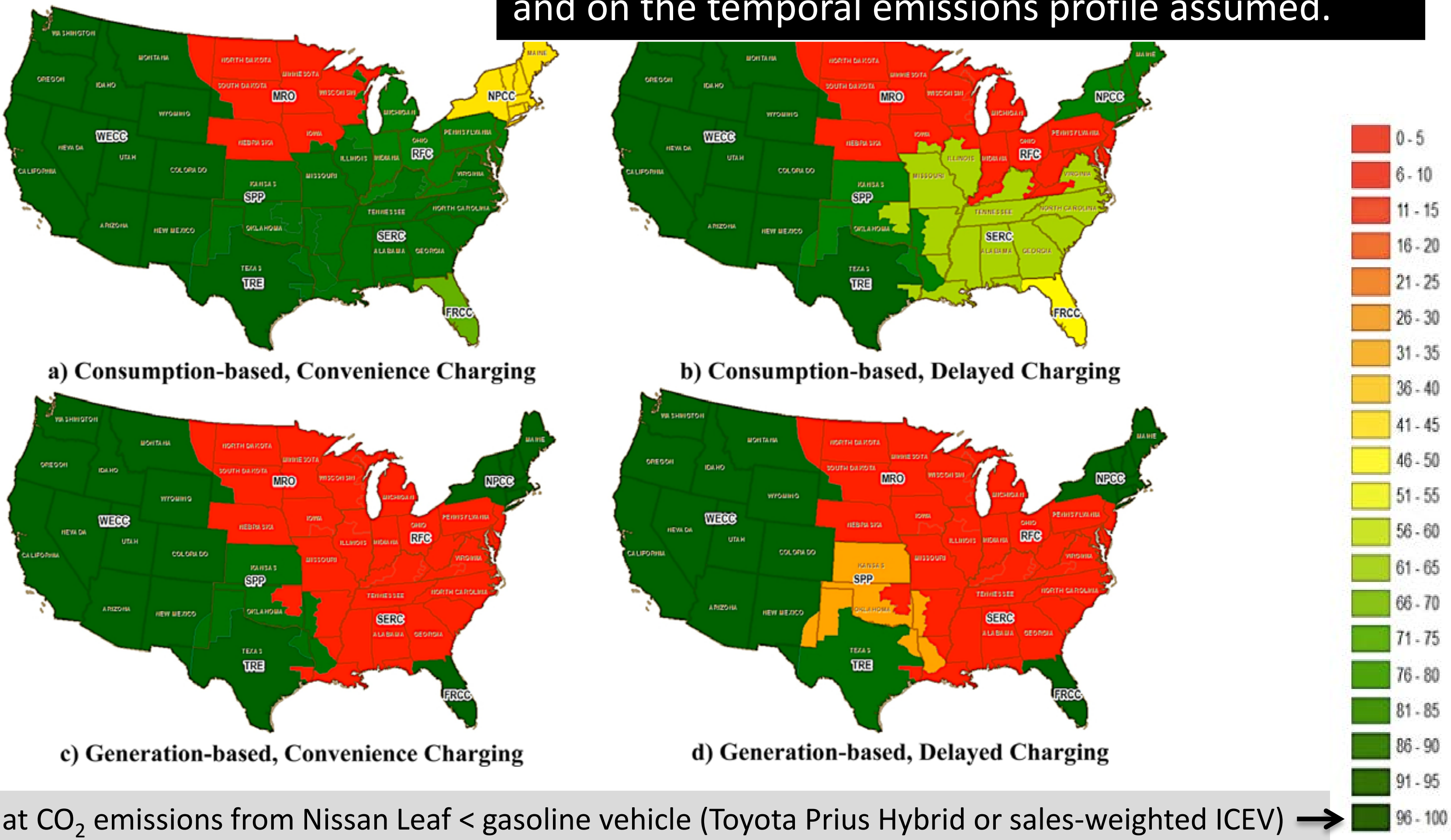
Plug-in Electric Vehicles (PEVs)

increasing electrification →

		CV Conventional	HEV Hybrid Electric	PHEV Plug-in Hybrid Electric	BEV Battery Electric
DRIVETRAIN	battery	-	SMALL	MEDIUM	LARGE
	power converter	ENGINE	ENGINE & MOTOR	ENGINE & MOTOR	MOTOR
SOURCE	electricity	-	-	Y	Y
	gasoline	Y	Y	Y	-

Electrified vehicles - There is no one size fits all: the Nissan Leaf has lower CO_2 emissions than Toyota Prius (hybrid) in parts of the country (green) where in other parts, the Prius or ICEV have lower emissions (red).

But these results depend on when the car is charged and on the temporal emissions profile assumed.



a) Consumption-based, Convenience Charging

b) Consumption-based, Delayed Charging

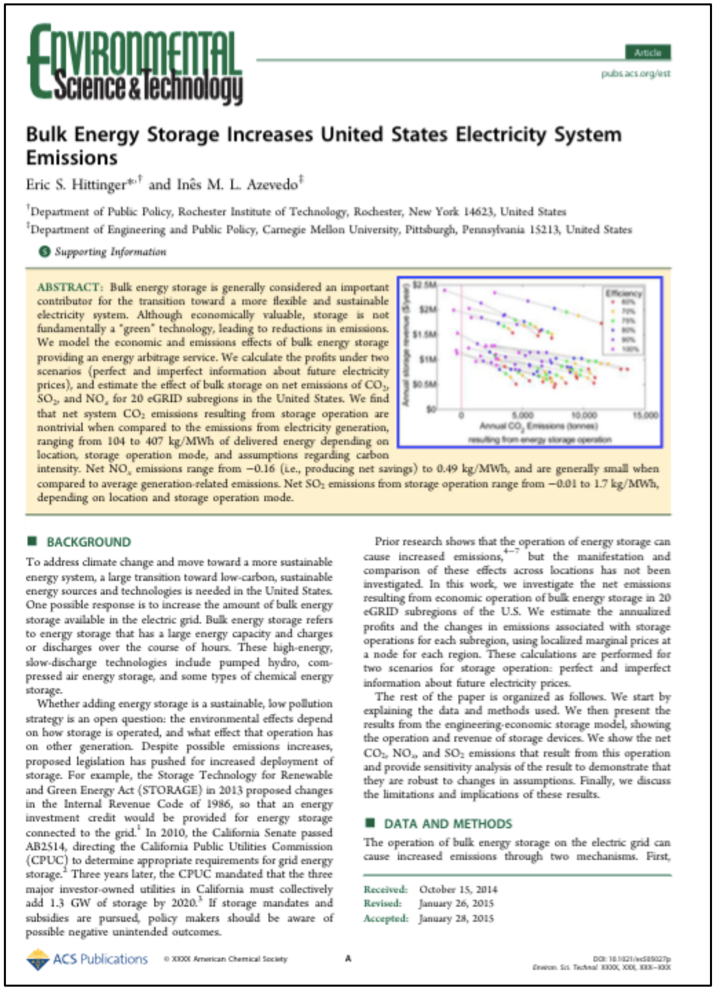
c) Generation-based, Convenience Charging

d) Generation-based, Delayed Charging

Probability that CO_2 emissions from Nissan Leaf < gasoline vehicle (Toyota Prius Hybrid or sales-weighted ICEV) →

Reference: Tamayao, M., Michalek, J., Hendrickson, C., Azevedo I.L., (2015). Regional variability and uncertainty of electric vehicle life cycle CO_2 emissions across the United States, accepted to *ES&T* in May 2015;

Are we reducing emissions by increase storage around the country?



Article

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Bulk Energy Storage Increases United States Electricity System Emissions

Eric S. Hittinger*,† and Inês M. L. Azevedo‡

†Department of Public Policy, Rochester Institute of Technology, Rochester, New York 14623, United States
‡Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, United States

Supporting Information

ABSTRACT: Bulk energy storage is generally considered an important contributor for the transition toward a more flexible and sustainable electricity system. Although economically valuable, storage is not fundamentally a "green" technology, leading to reductions in emissions. We model the economic and emissions effects of bulk energy storage providing an energy arbitrage service. We calculate the profits under two scenarios (perfect and imperfect information about future electricity prices), and estimate the effect of bulk storage on net emissions of CO_2, SO_2, and NO_x for 20 eGRID subregions in the United States. We find that net system CO_2 emissions resulting from storage operation are nontrivial when compared to the emissions from electricity generation, ranging from 104 to 407 kg/MWh of delivered energy depending on location, storage operation mode, and assumptions regarding carbon intensity. Net NO_x emissions range from −0.16 (i.e., producing net savings) to 0.49 kg/MWh, and are generally small when compared to average generation-related emissions. Net SO_2 emissions from storage operation range from −0.01 to 1.7 kg/MWh, depending on location and storage operation mode.

BACKGROUND

To address climate change and move toward a more sustainable energy system, a large transition toward low-carbon, sustainable energy sources and technologies is needed in the United States. One possible response is to increase the amount of bulk energy storage available in the electric grid. Bulk energy storage refers to energy storage that has a large energy capacity and charges or discharges over the course of hours. These high-energy, slow-discharge technologies include pumped hydro, compressed air energy storage, and some types of chemical energy storage.

Whether adding energy storage is a sustainable, low pollution strategy is an open question: the environmental effects depend on how storage is operated, and what effect that operation has on other generation. Despite possible emissions increases, proposed legislation has pushed for increased deployment of storage. For example, the Storage Technology for Renewable and Green Energy Act (STORAGE) in 2013 proposed changes in the Internal Revenue Code of 1986, so that an energy investment credit would be provided for energy storage connected to the grid.[1] In 2010, the California Senate passed AB2514, directing the California Public Utilities Commission (CPUC) to determine appropriate requirements for grid energy storage.[2] Three years later, the CPUC mandated that the three major investor-owned utilities in California must collectively add 1.3 GW of storage by 2020.[3] If storage mandates and subsidies are pursued, policy makers should be aware of possible negative unintended outcomes.

Prior research shows that the operation of energy storage can cause increased emissions,[4−7] but the manifestation and comparison of these effects across locations has not been investigated. In this work, we investigate the net emissions resulting from economic operation of bulk energy storage in 20 eGRID subregions of the U.S. We estimate the annualized profits and the changes in emissions associated with storage operations for each subregion, using localized marginal prices at a node for each region. These calculations are performed for two scenarios for storage operation: perfect and imperfect information about future electricity prices.

The rest of the paper is organized as follows. We start by explaining the data and methods used. We then present the results from the engineering-economic storage model, showing the operation and revenue of storage devices. We show the net CO_2, NO_x, and SO_2 emissions that result from this operation and provide sensitivity analysis of the result to demonstrate that they are robust to changes in assumptions. Finally, we discuss the limitations and implications of these results.

DATA AND METHODS

The operation of bulk energy storage on the electric grid can cause increased emissions through two mechanisms. First,

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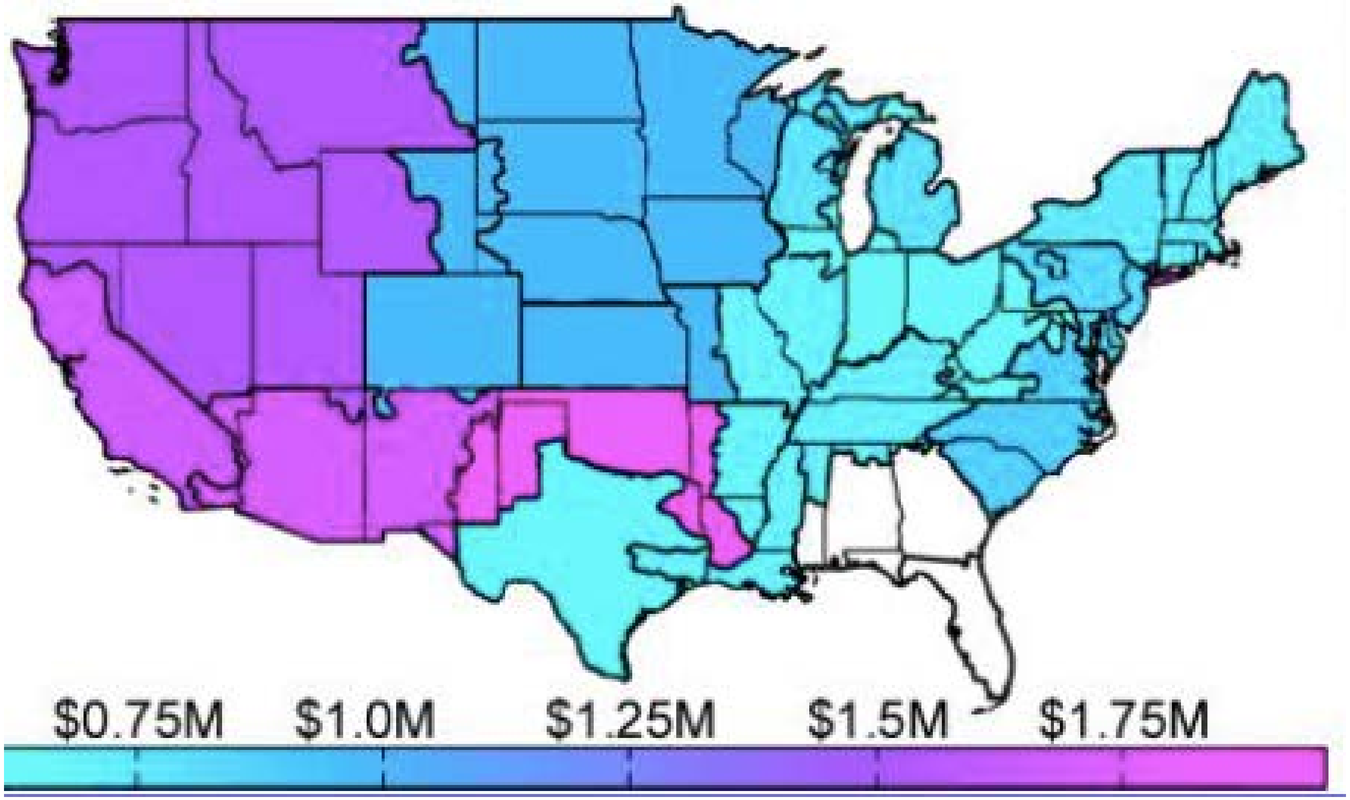
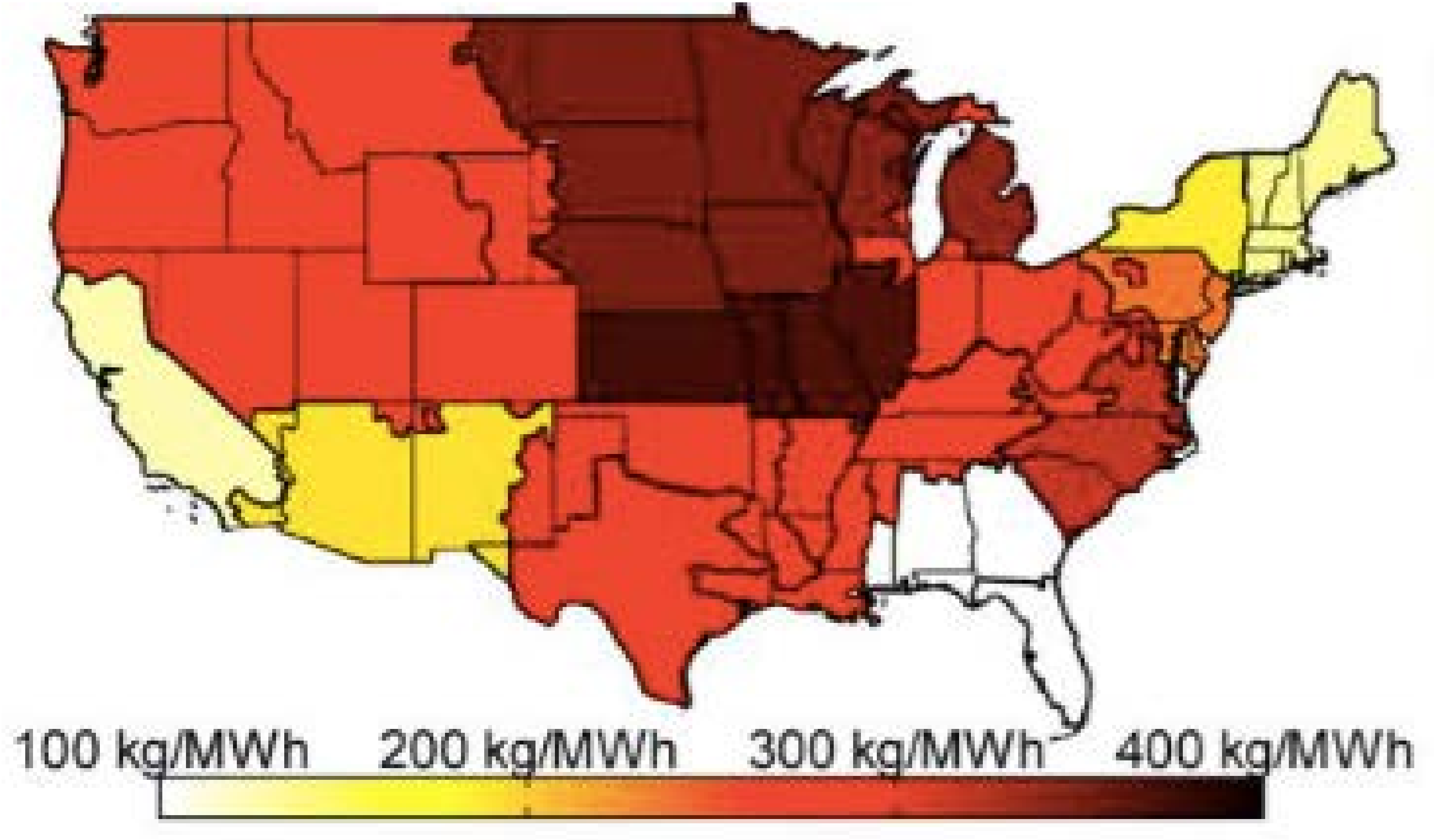
Environ. Sci. Technol. XXXX, XXX, XXX−XXX

Revenue



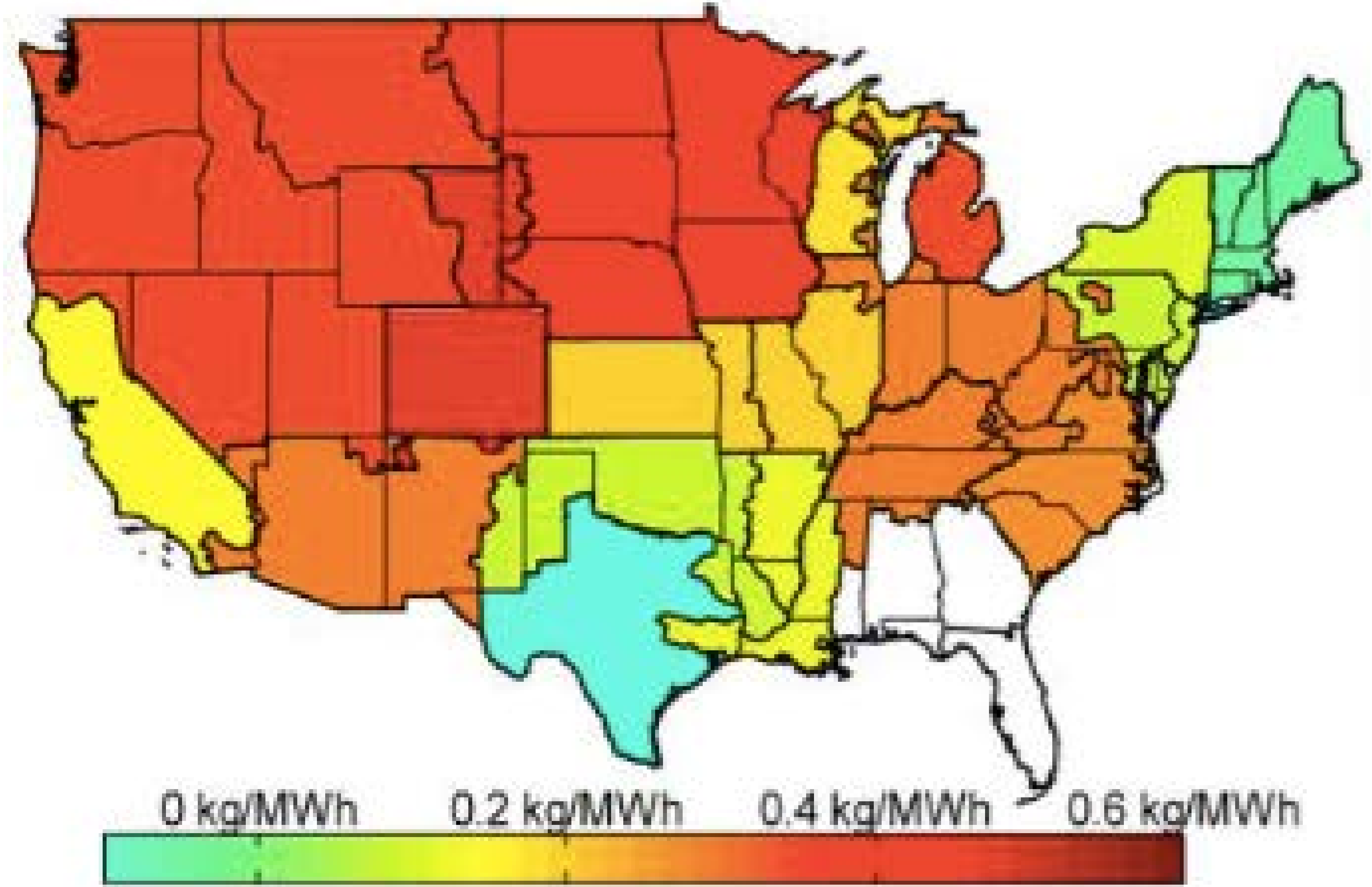
- Large large potential market, but very low revenue rates.
- Only the most inexpensive storage technologies could produce a profit in this market.

Storage: for most locations across the country, using storage for energy arbitrage will increase emissions of CO_2 and of criteria air pollutants



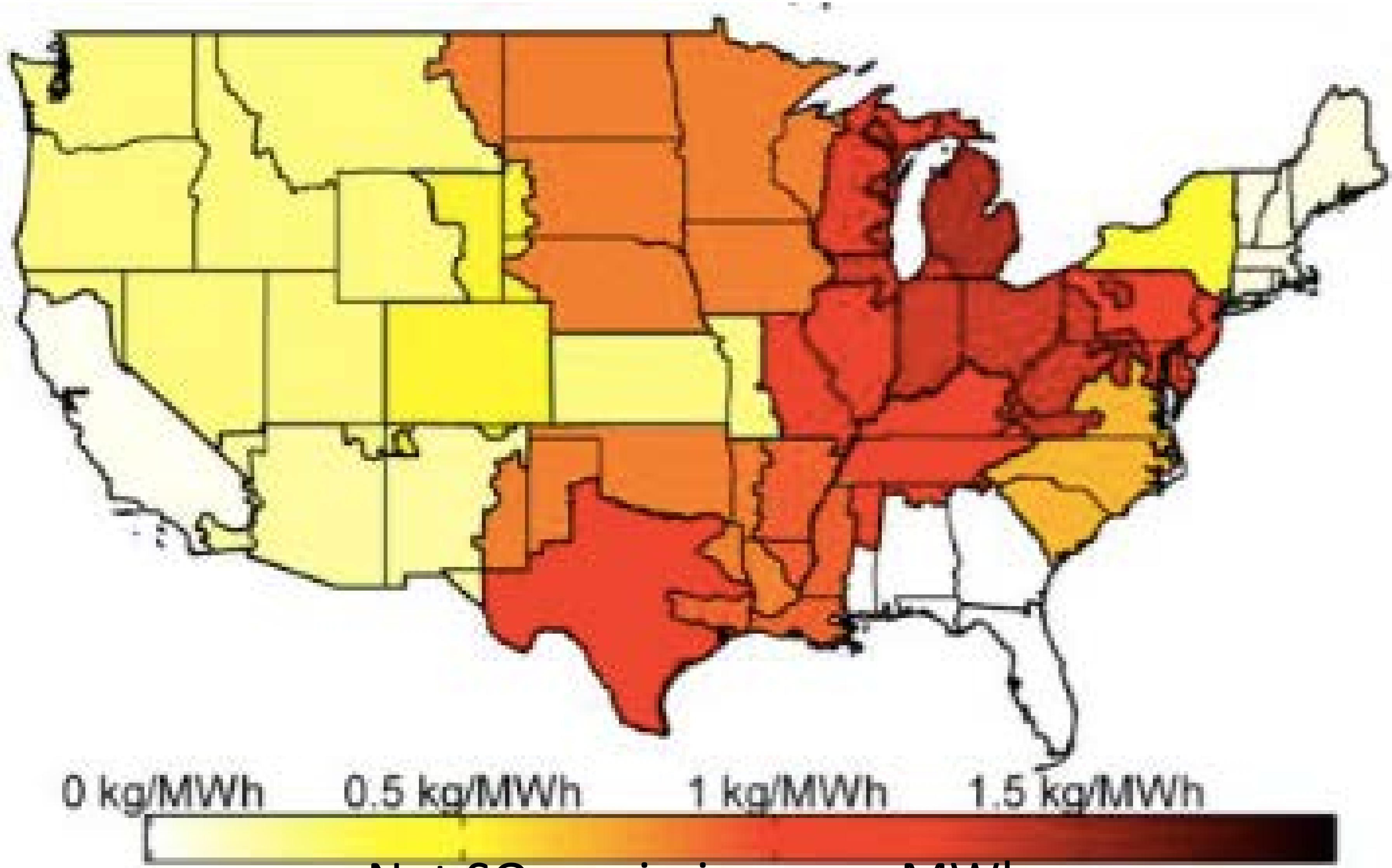
Net CO_2 emissions per MWh

Storage: for most locations across the country, using storage for energy arbitrage will increase emissions of CO_2 and of criteria air pollutants



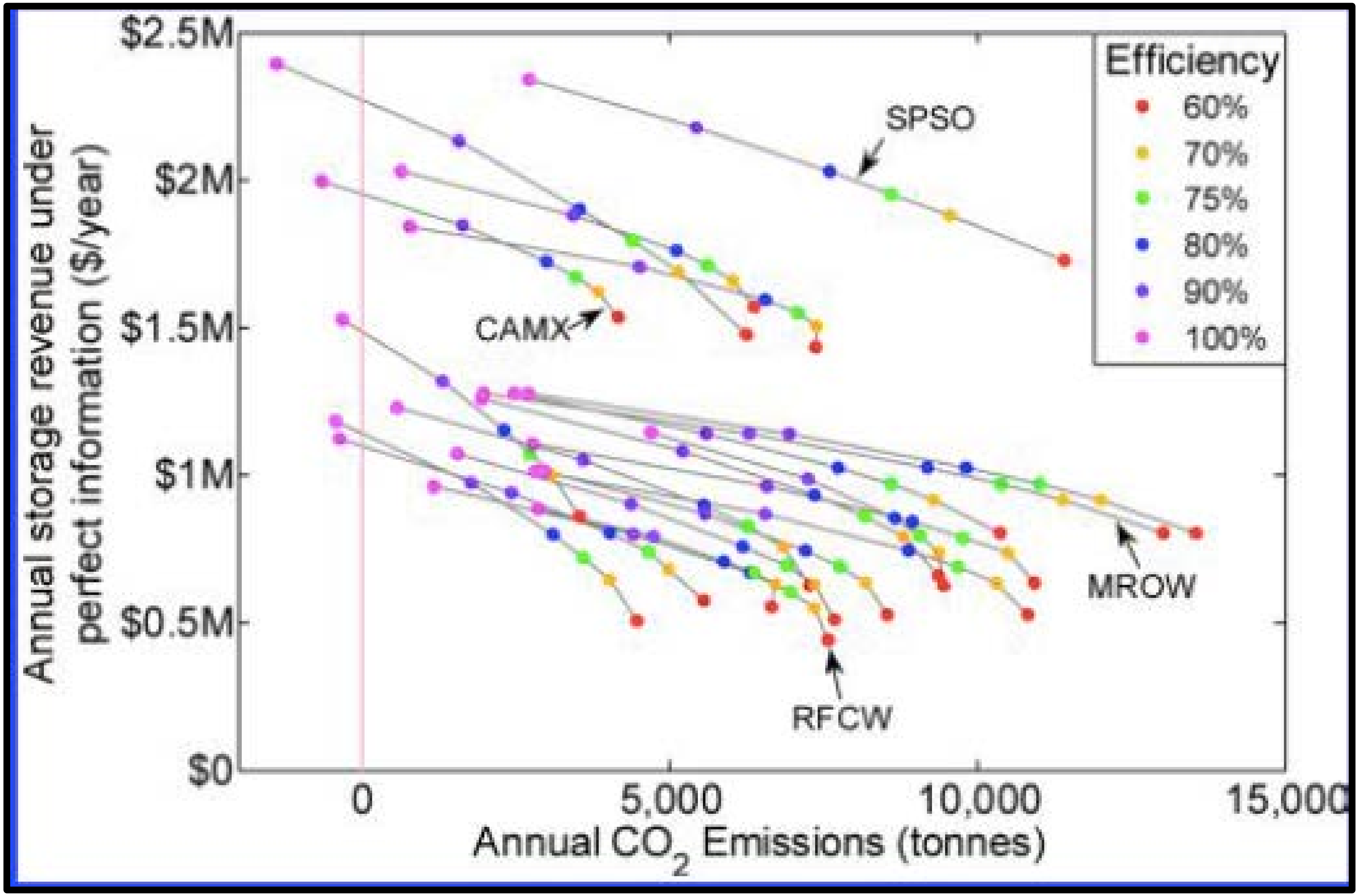
Net NO_x emissions per MWh

Storage: for most locations across the country, using storage for energy arbitrage will increase emissions of CO_2 and of criteria air pollutants

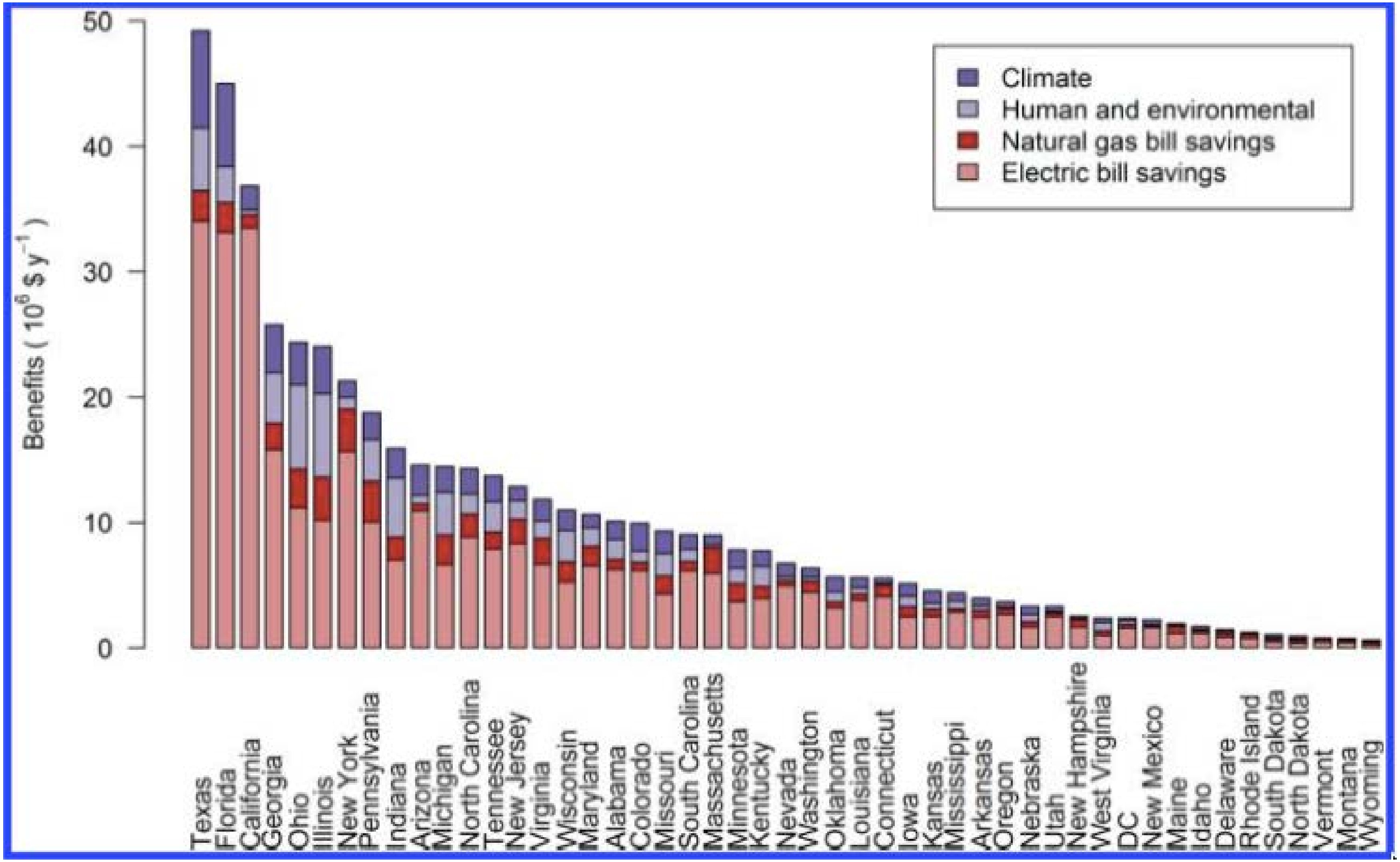


Net SO_2 emissions per MWh

Sensitivity Analysis



Building codes - Moving to ASHRAE 90.1−2010 relative to a baseline building code ASHRAE 90.1−2007 has very different implications in terms of benefits from climate, health and environmental damage reduction.



Reference: Gilbraith, N., Azevedo, I.L., Jaramillo, P., (2014). Regional energy and GHG savings from building codes across the United States, *Environmental Science & Technology;*

Final notes

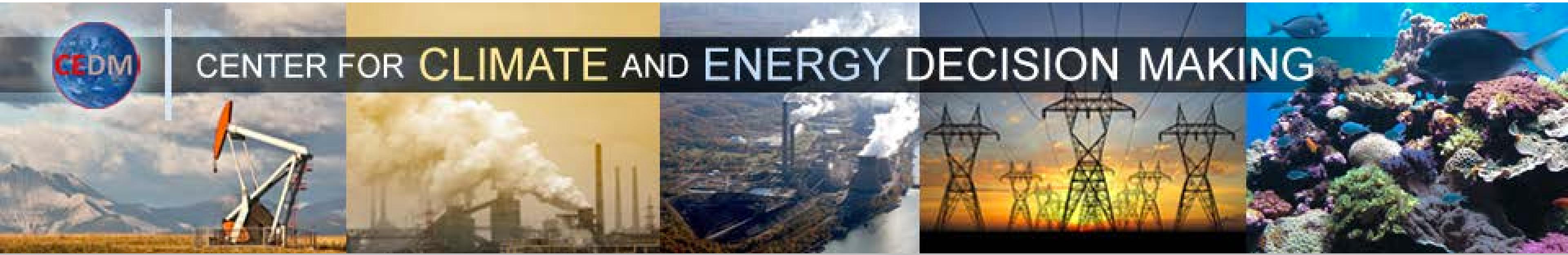
- A major transition in our energy system is needed.
  - We want to determine which strategies will provide the intended goals.
- Focusing on greenhouse gases and criteria air pollutants together makes sense.
- Location, temporal patterns, and behavior will determine the health, environmental and climate change effects of these interventions.

A framework for climate change decision-making under uncertainty

Ines Azevedo: iazevedo@cmu.edu

Associate Professor
Department of Engineering and Public Policy
Carnegie Mellon University

Co-Director
Climate and Energy Decision Making Center



Siler-Evans, K., Azevedo, I. L., Morgan, M.G, Apt, J. (2013). Regional variations in the health, environmental, and climate benefits from wind and solar generation, *Proceedings of the National Academy of Sciences*, 110 (29), 11768-11773; Siler-Evans. K., Azevedo, I.L., Morgan, M.G., (2012). Marginal emissions factors for the US electricity system. *Environmental Science & Technology, 46* (9): 4742–4748.; Hittinger, E., Azevedo, I.L., (2015). Bulk Energy Storage Increases US Electricity System Emissions, *Environmental Science & Technology*, 49 (5), 3203-3210; Tamayao, M., Michalek, J., Hendrickson, C., Azevedo I.L., (2015). Regional variability and uncertainty of electric vehicle life cycle CO_2 emissions across the United States, *ES&T* (2015); Gilbraith, N., Azevedo, I.L., Jaramillo, P., (2014). Regional energy and GHG savings from building codes across the United States, *Environmental Science & Technology;*