



De-carbonizing the electricity sector in the United States: what big data analytics can tell us about sustainable transitions.

Ines Lima Azevedo

Associate Professor

Department of Engineering and Public Policy

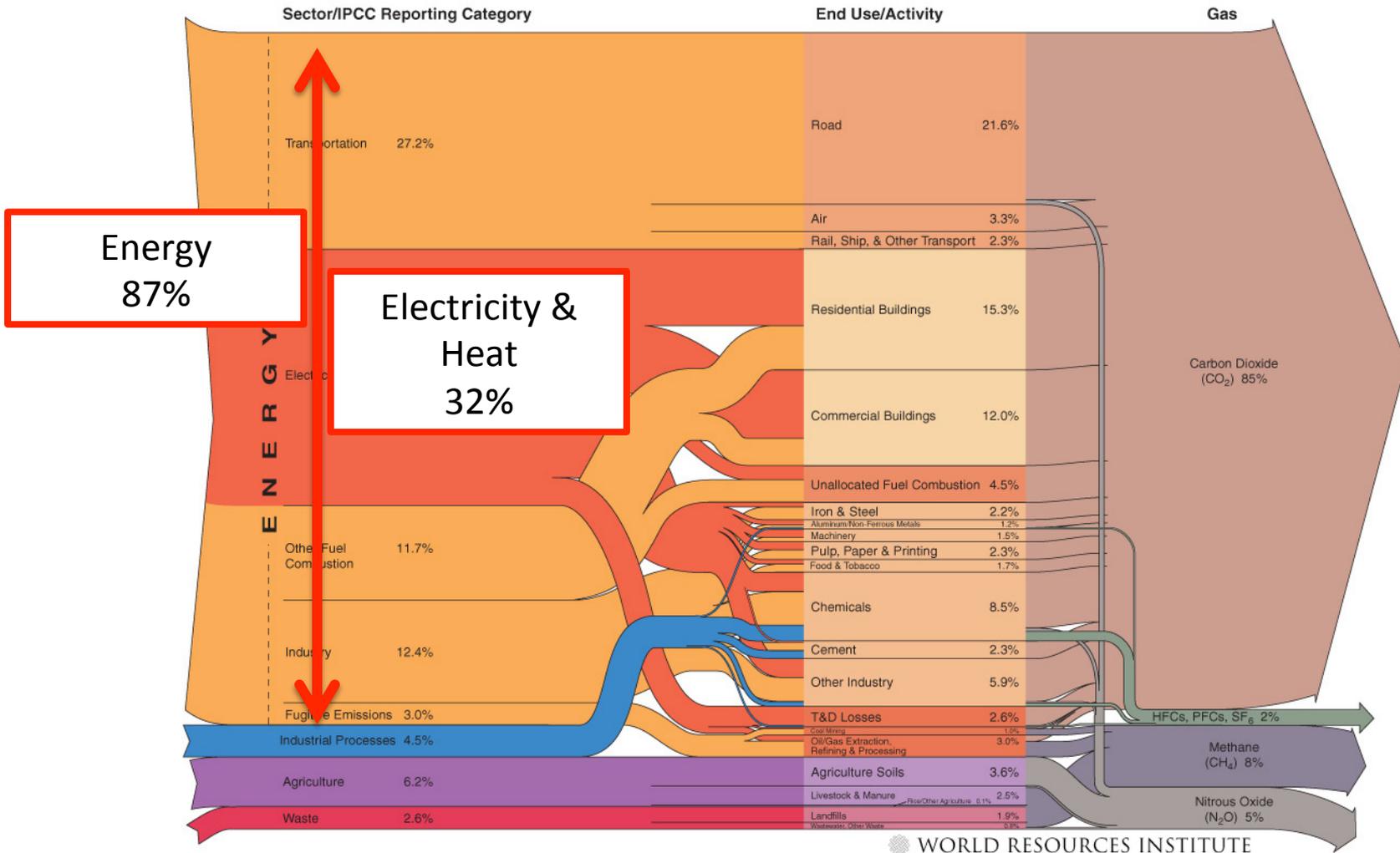
Carnegie Mellon University

Co-Director

Climate and Energy Decision Making Center

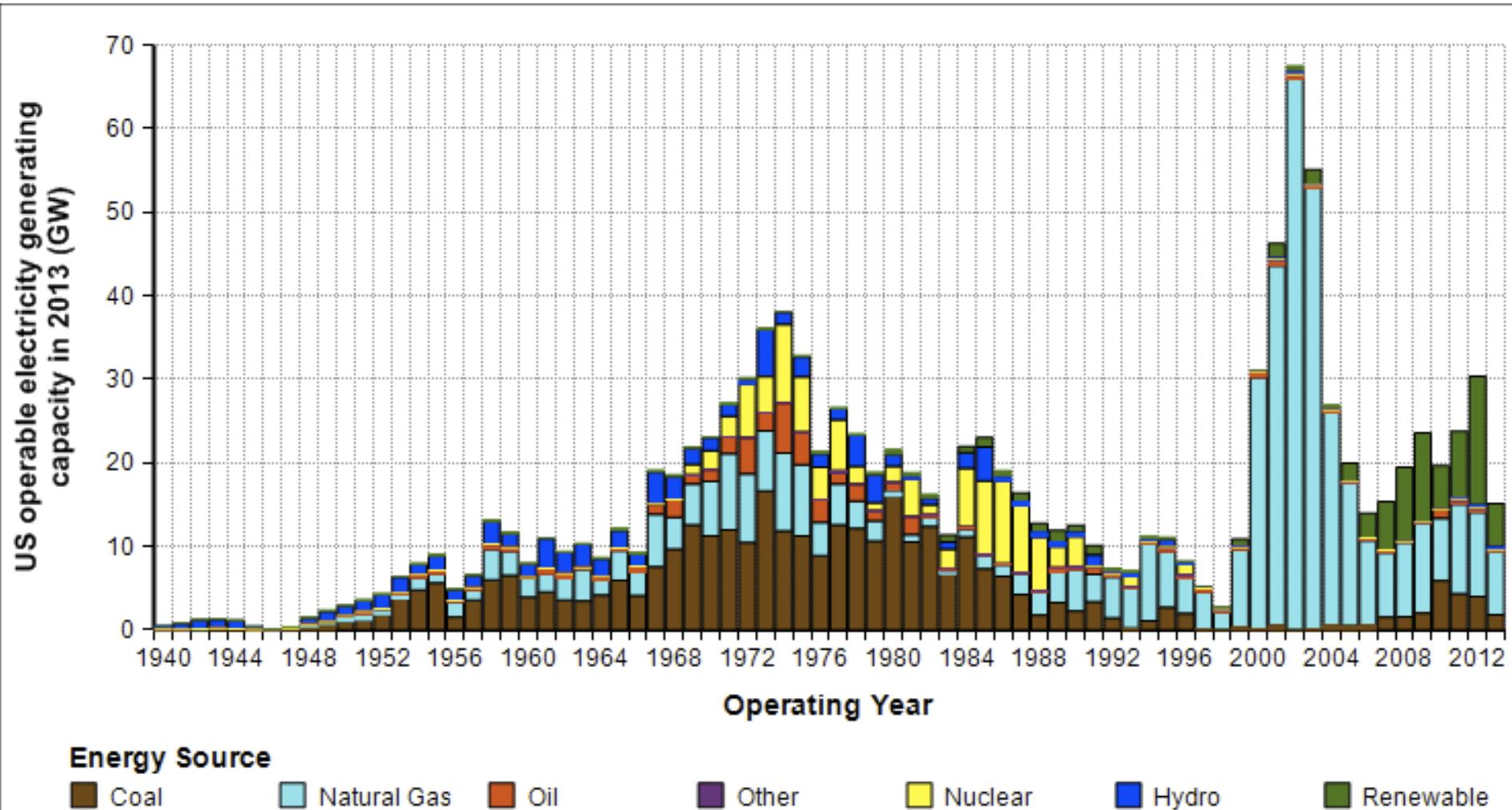
Energy services are responsible for the bulk of CO₂ emissions in the United States.

U.S. GHG Emissions Flow Chart, 2003



WORLD RESOURCES INSTITUTE

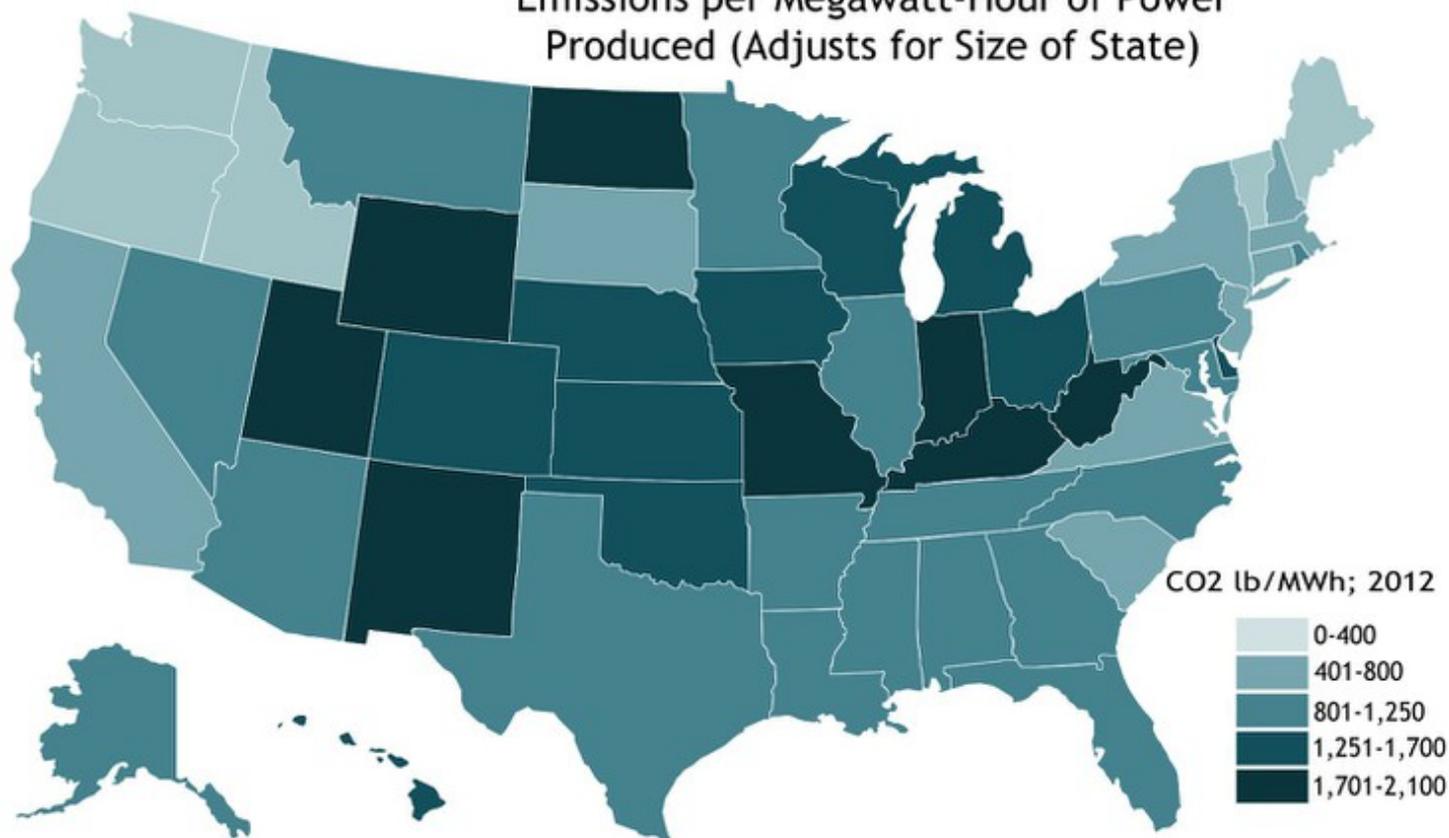
US fleet is old and dirty.



The US grid is diverse in its carbon intensity.

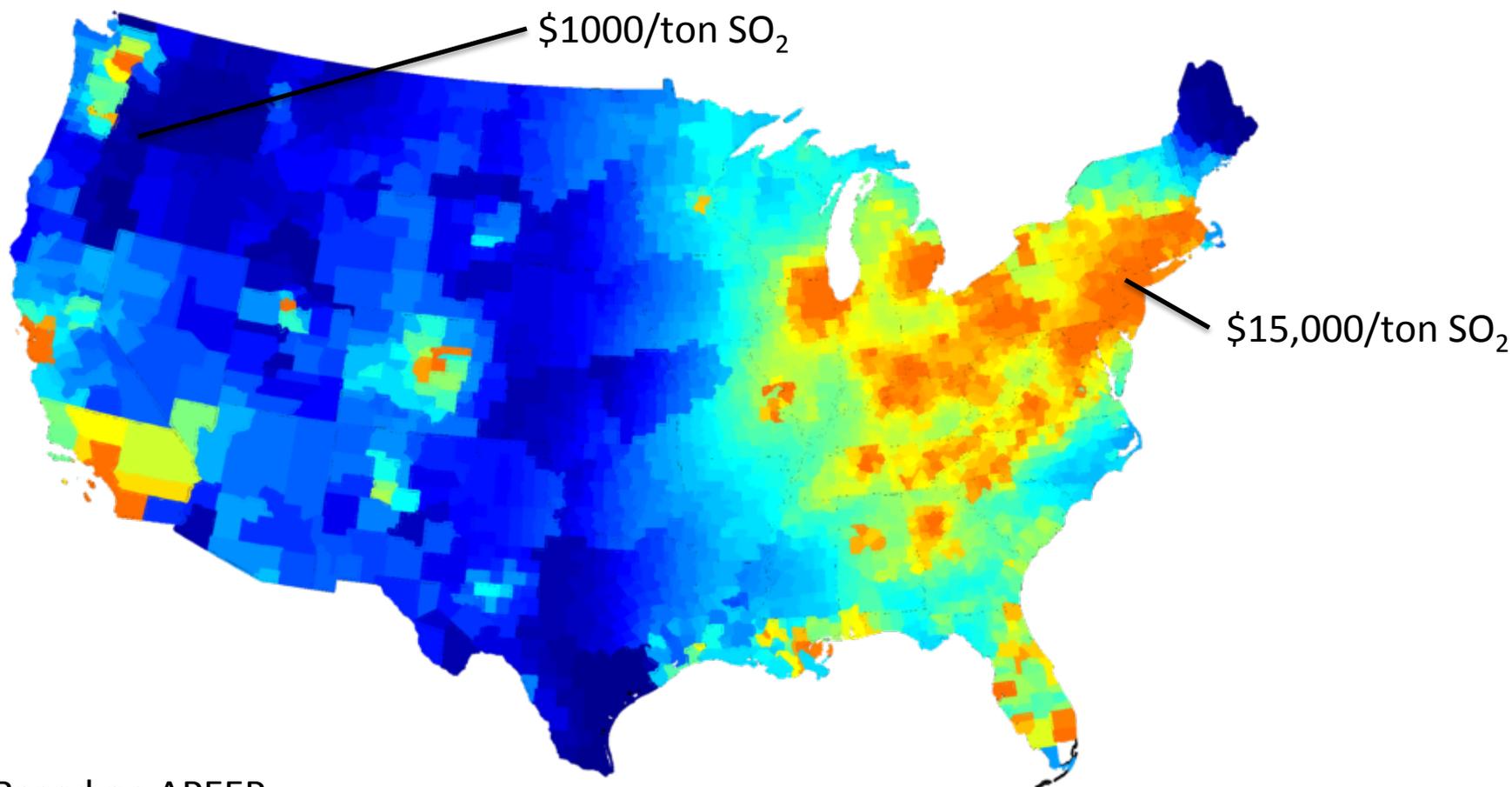
State-by-State CO2 Emissions

Emissions per Megawatt-Hour of Power Produced (Adjusts for Size of State)



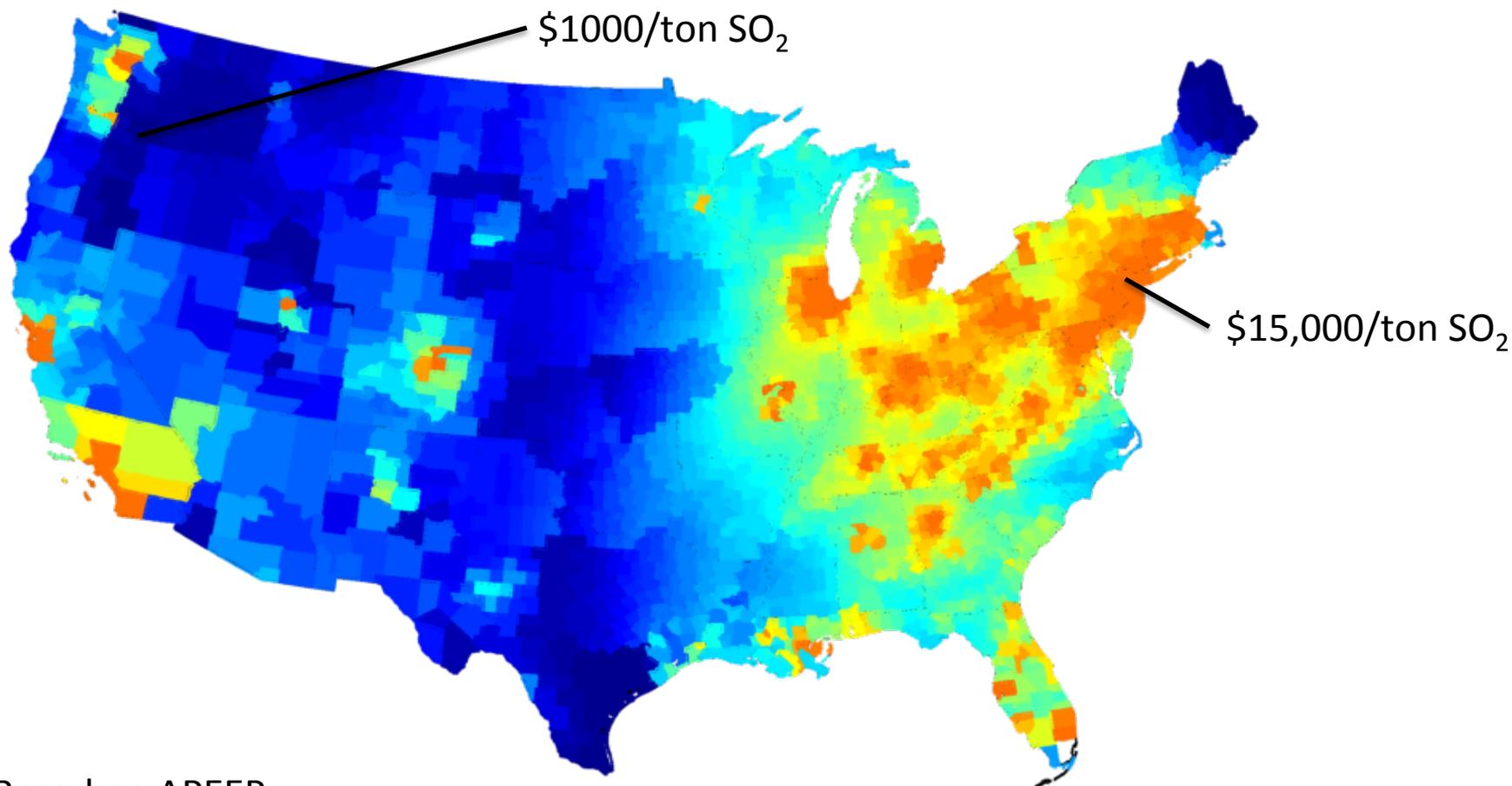
Learn more and download the report at www.ceres.org/airemissions

Damages from criteria air pollutants vary tremendously across the country.



Srouce: Based on APEEP.

When interventions are pursued, the “co-benefits” from reducing health and environmental damages may actually be the **largest benefits**.



Srouce: Based on APEEP.

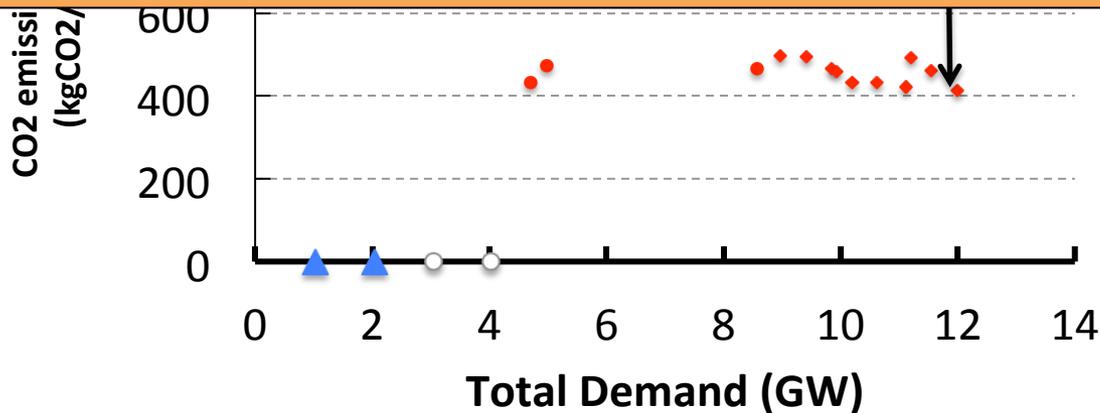
Question:

- When we pursued 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?



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[†]

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

Kyle Siler-Evans[‡], Inês Lima Azevedo^{*,†}, M. Granger Morgan[‡], and Jay Apt^{*,§}

ENVIRONMENTAL
Science & Technology

Article
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Bulk Energy Storage Increases United States Electricity System Emissions

Eric S. Hittinger^{*,†} and Inês M. L. Azevedo[‡]

ENVIRONMENTAL
Science & Technology

Article
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Regional Variability and Uncertainty of Electric Vehicle Life Cycle CO₂ Emissions across the United States

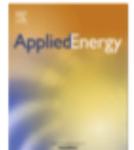
Mili-Ann M. Tamayao,[†] Jeremy J. Michalek,^{*,†,‡} Chris Hendrickson,^{†,§} and Inês M. L. Azevedo[†]



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journal homepage: www.elsevier.com/locate/apenergy



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



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

- We do!
 - The Environmental Protection Agency (EPA) in the United States collects measured data for every single fossil fuel power plant (larger than 25 MW) generation and emissions of CO₂, SO₂ 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 CO₂ 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 CO₂ emissions
- Health and environmental benefits from displaced criteria pollutants: SO₂, 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}

^aEngineering and Public Policy and ^bTepper 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 (CO₂) and criteria air pollutants, which include sulfur dioxide (SO₂), 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 CO₂ emissions by 825 million metric tons by 2030 (1). Valente 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 CO₂ emissions, 13% reduction in NO_x, 8% reduction in SO₂, and an 11% reduction in PM. Lu et al. (3) estimate that the CO₂ 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 CO₂ emissions, and health and environmental benefits from displaced SO₂, 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 CO₂ emissions are monetized using a social cost of \$20 per ton of CO₂. Location-specific damages from SO₂, 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 CO₂ emissions (Fig. 1*B* and *E*); and annual health and environmental benefits from displaced SO₂, 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 CO₂ emissions—kilograms of CO₂ avoided annually and the corresponding social benefits, assuming a social cost of \$20 per ton of CO₂. Wind turbines are most effective at displacing CO₂ emissions when located in the Midwest, where the wind resource is excellent and

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://cedcenter.org/tools-for-cedmins@gmail.com/emissions-factors-repository/>.

¹To whom correspondence should be addressed. E-mail: azevedo@cmu.edu.

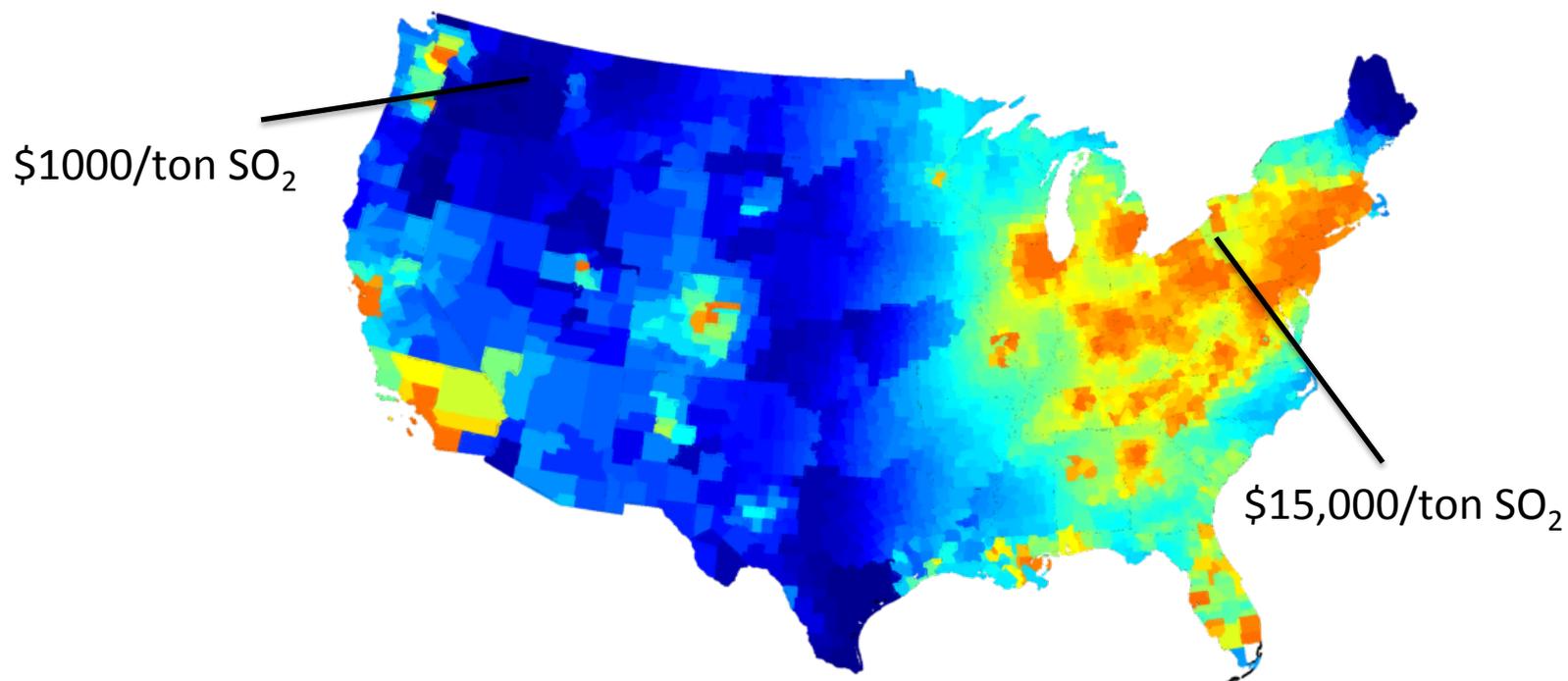
This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1221978110/-DCSupplemental.

Estimating environmental and health benefits



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

Data from: APEEP



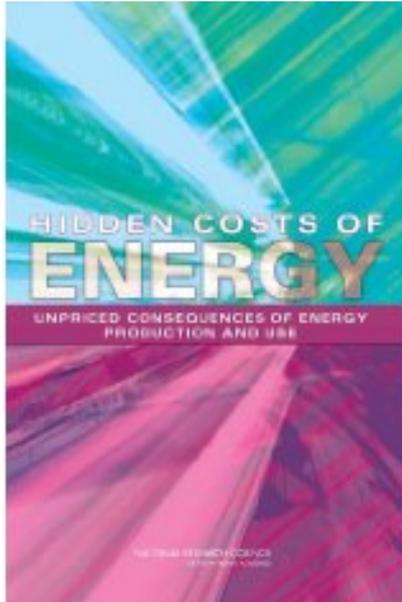
Estimating environmental and health benefits

1



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

Data from: APEEP



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 , $\text{PM}_{2.5}$)

Data from: APEEP

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

For CO_2 , we use \$20/ton CO_2

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

1



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

Data from: APEEP

2

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



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 $\text{PM}_{2.5}$ emissions, stack heights of generators

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

- Plant locations, fuel type

Estimating environmental and health benefits



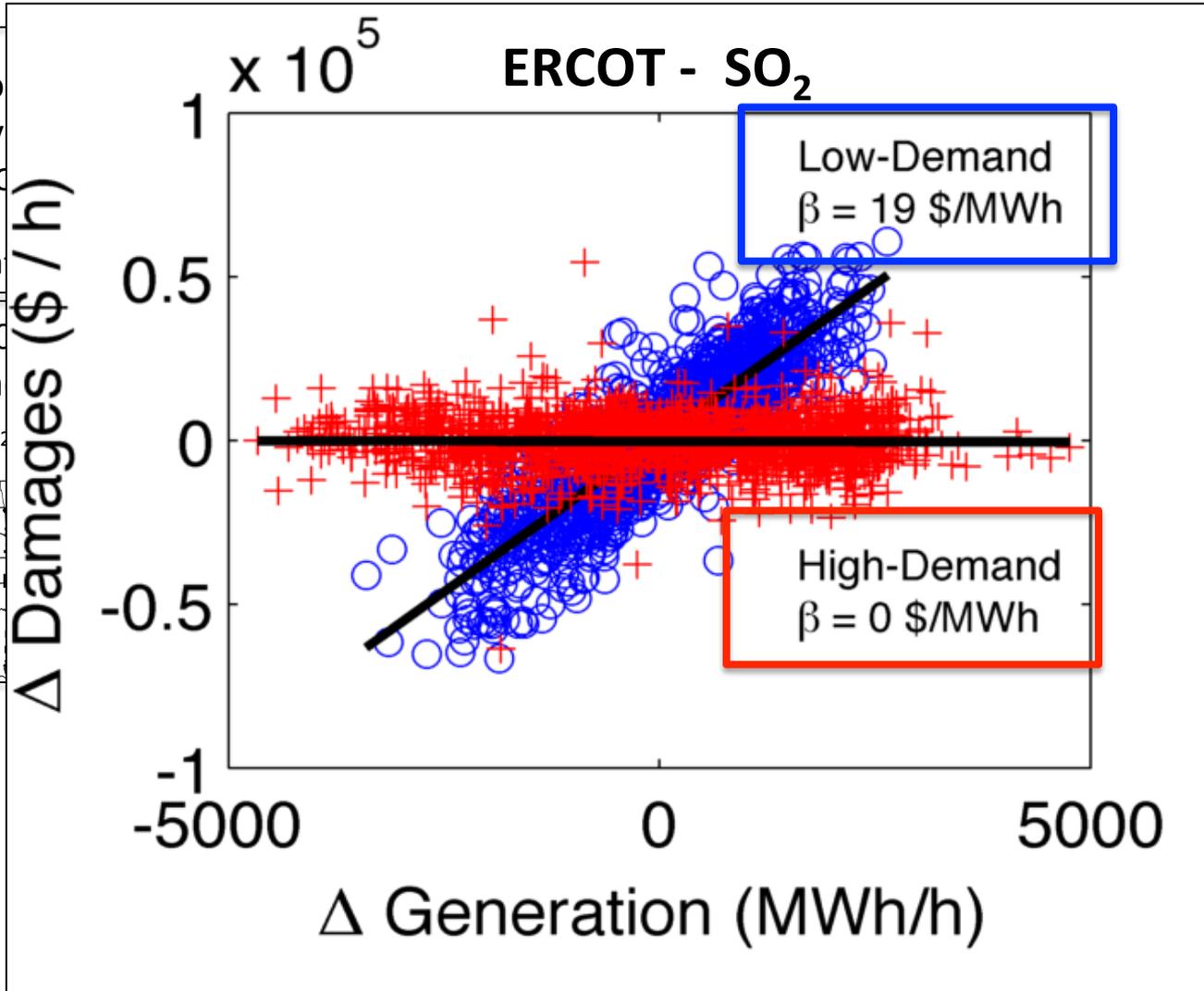
1

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2

For 140
stack h
CO₂, SO₂



ERCOT sub-region
pollutant:

$$\Delta \text{ Damages (\$/h)} = (\text{\$/ton}) \times \text{hourly (ton pollutant/h)}$$

ERCOT sub-region
pollutant, for 20 gross
generation bins:

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

Estimating environmental and health benefits

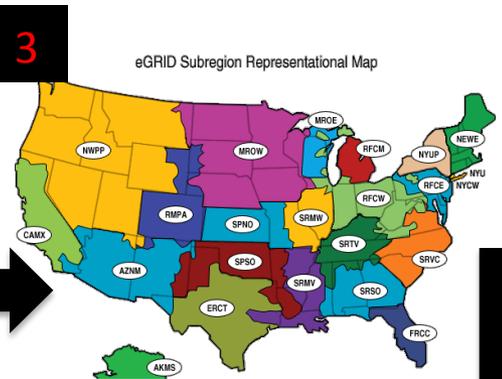
1  For each county: damages (\$/ton) by stack height for each pollutant (SO₂, NO_x, PM_{2.5})

Data from: APEEP

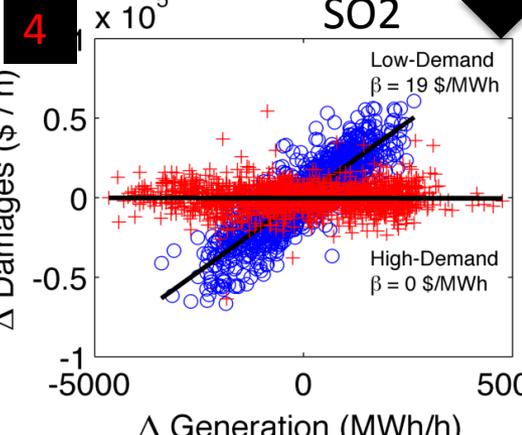
2 For 1400 plants: location, fuel type, stack height and hourly emissions of CO₂, SO₂, NO_x, PM_{2.5}



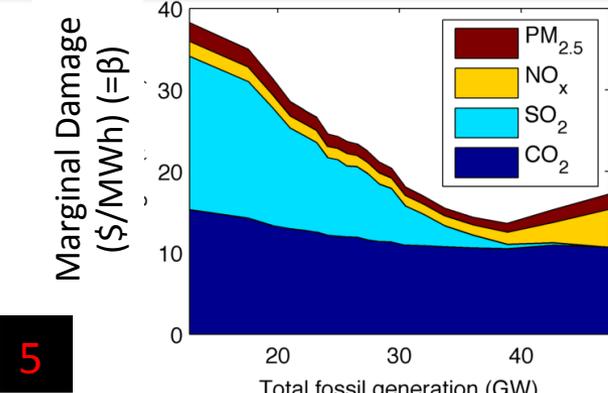
Data from: CEMS (2009-2011), eGRID (2009), NEI (2005)

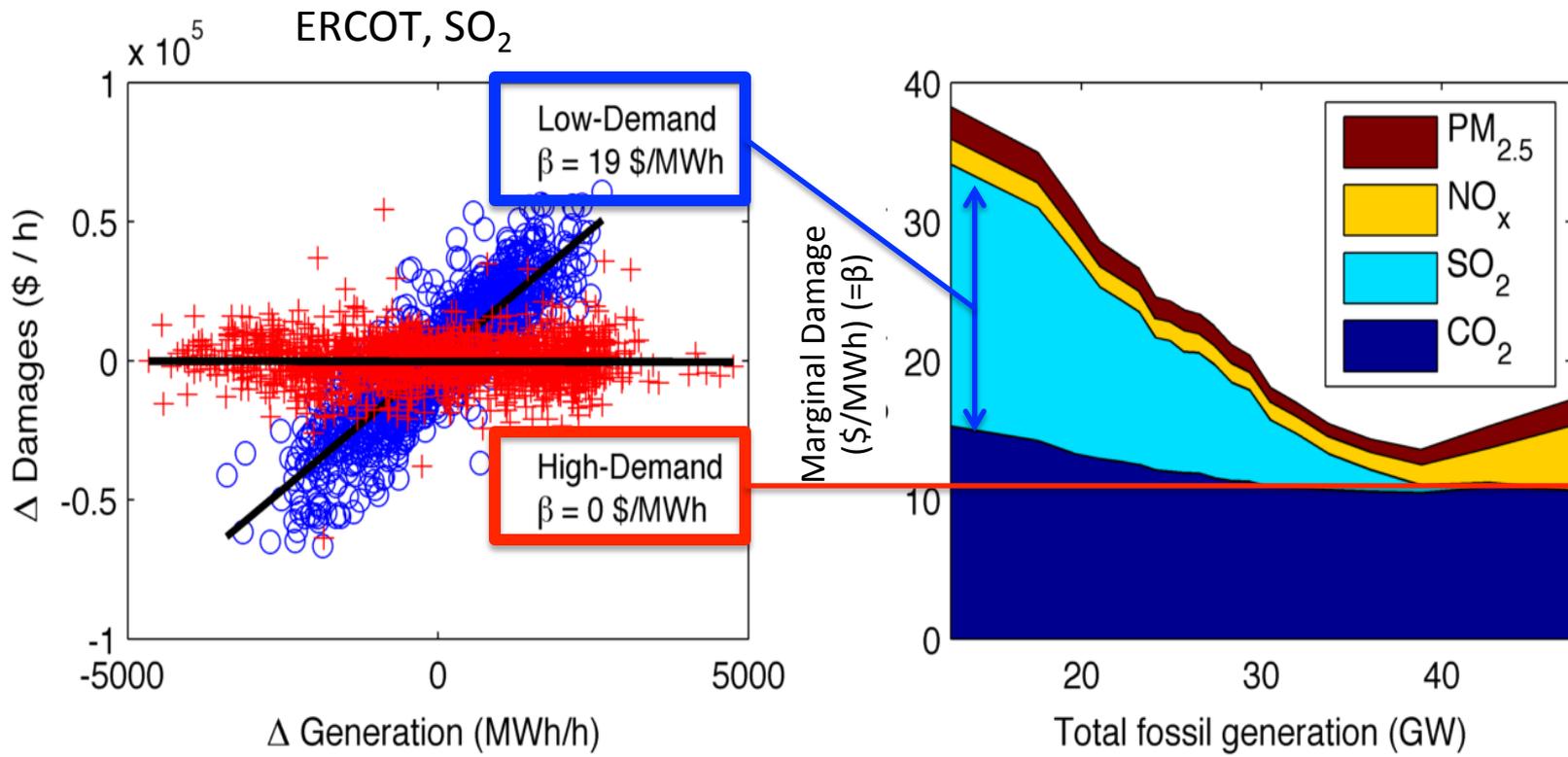
3  For each eGRID sub-region and each pollutant:

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

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

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

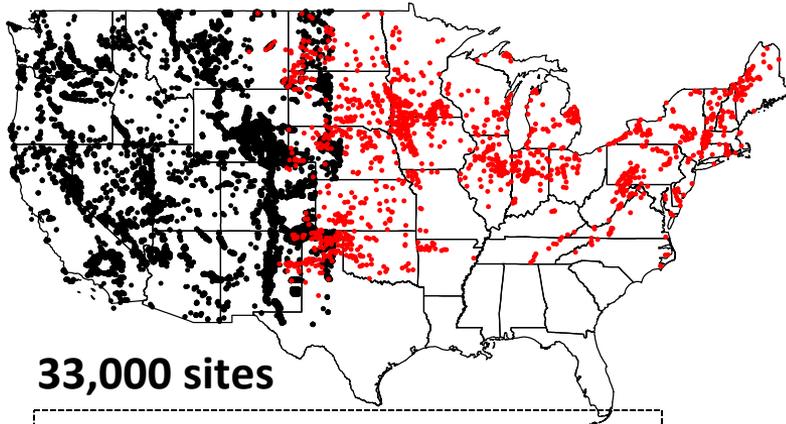
5  Then we have estimates of marginal damages (\$/MWh) for each demand bin as function of gross generation for each pollutant



Estimating environmental and health benefits

6

WIND



33,000 sites

**Eastern Wind Integration and
Transmissions Study (EWITS)**

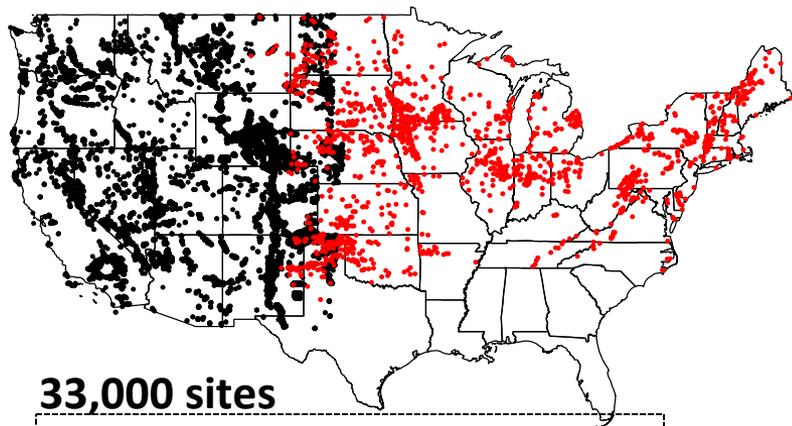
**Western Wind and Solar
Integration Study (WWSIS)**

Hourly wind power output

Estimating environmental and health benefits

6

WIND



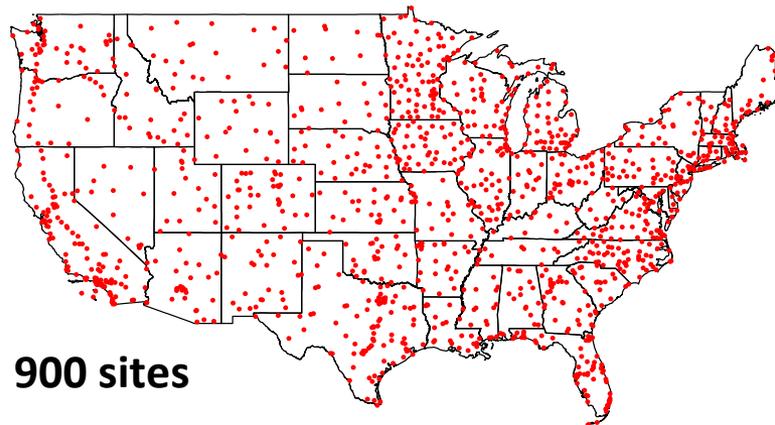
33,000 sites

**Eastern Wind Integration and
Transmissions Study (EWITS)**

**Western Wind and Solar
Integration Study (WWSIS)**

Hourly wind power output

SOLAR

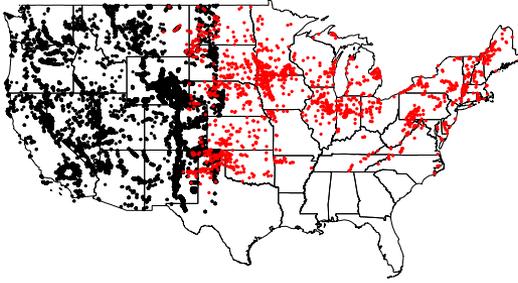


900 sites

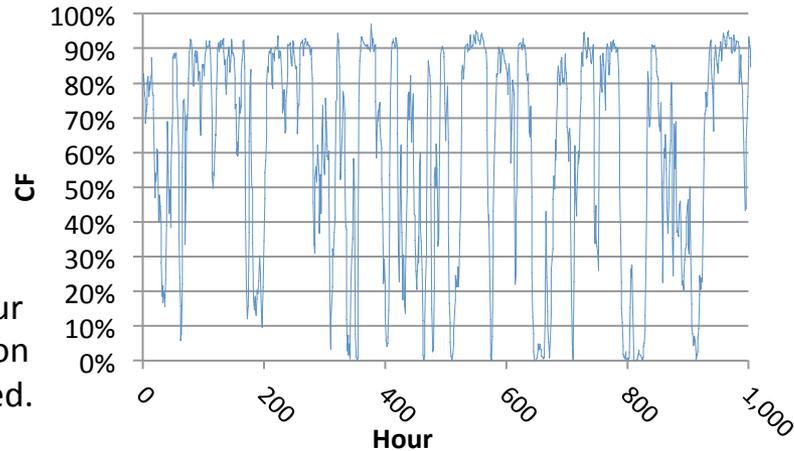
**National Solar Radiation
Database**

Estimating environmental and health benefits

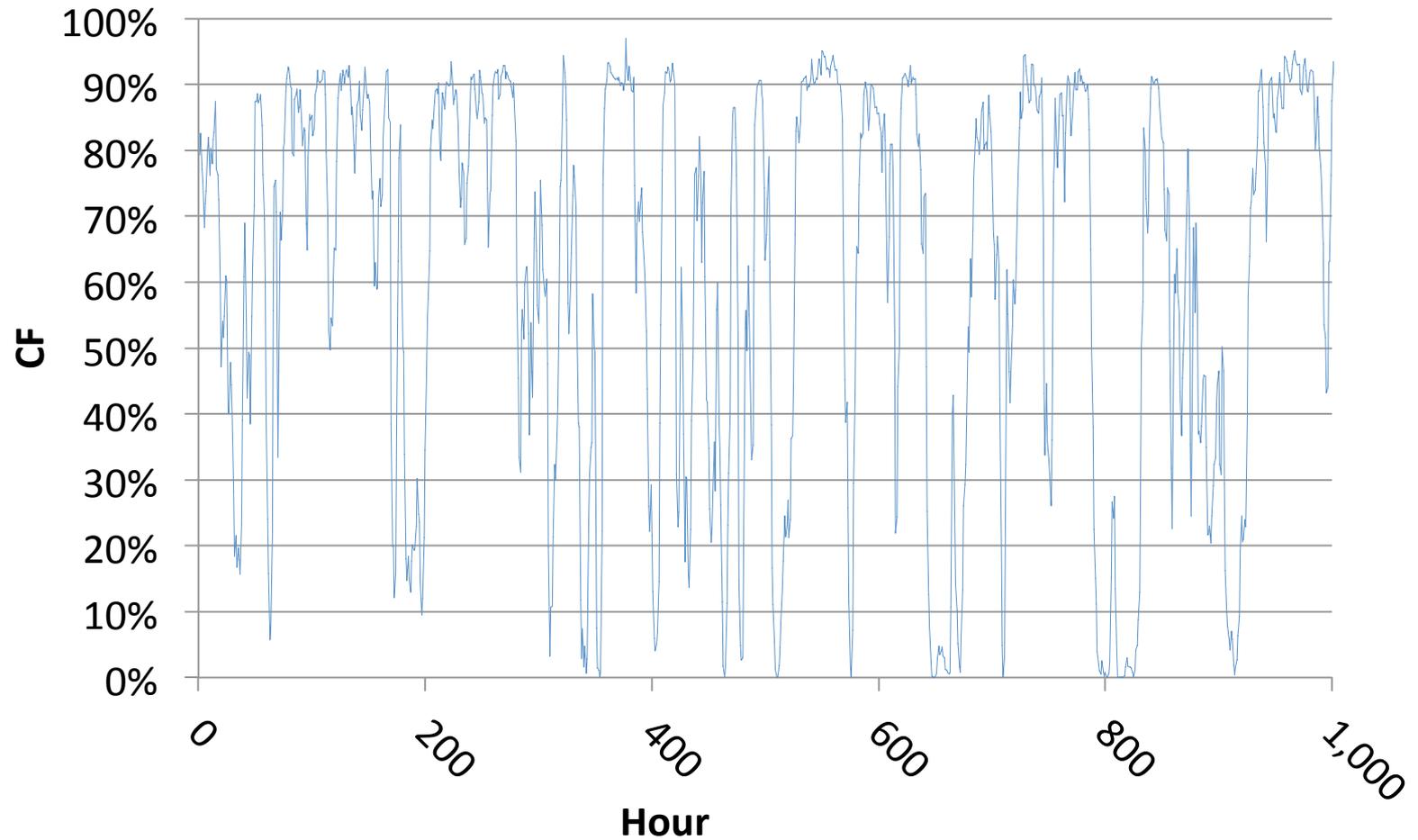
6



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.

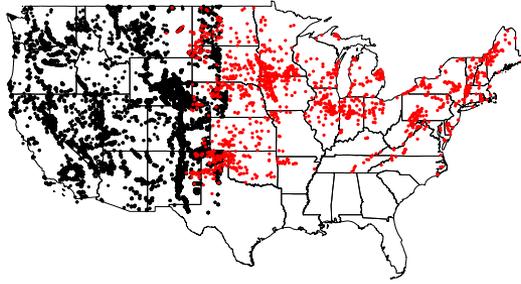


Estimating environmental and health benefits

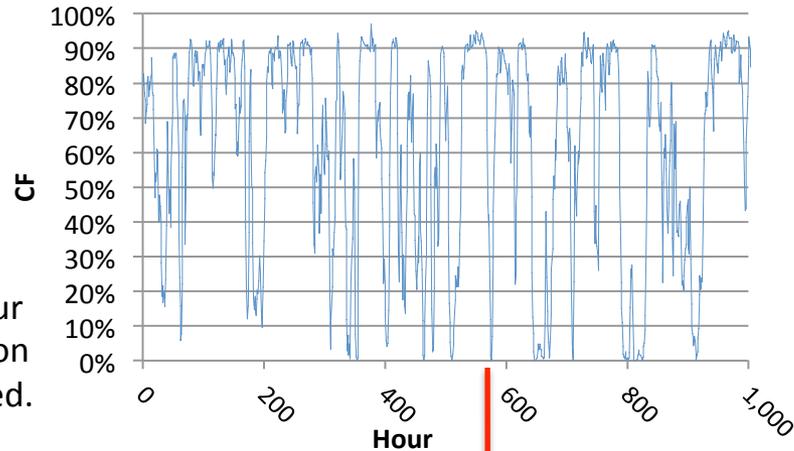


Estimating environmental and health benefits

6



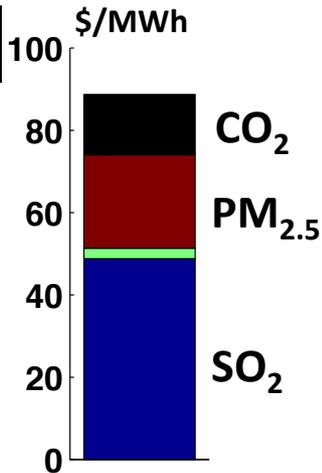
For each wind & solar site and for each hour of the year, we match wind/solar generation with the gross generation that it is displaced.



7

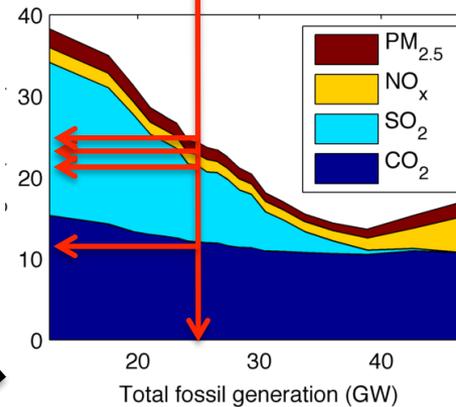
We then identify the damages associated with gross generation. For each hour, we multiply the associated damages (\$/MWh) by the wind/solar output.

8

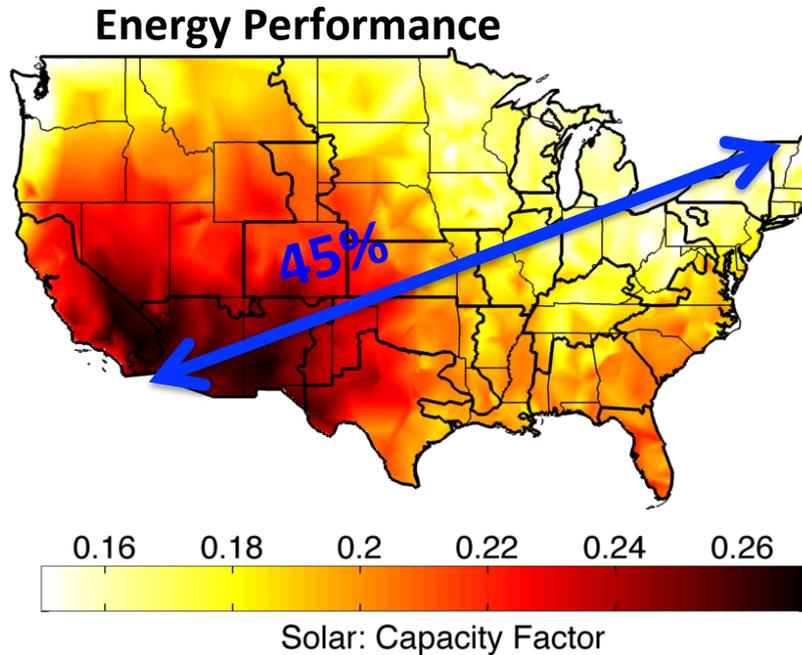


We finally add all damages avoided for each site for all hours of the year and divide by the total generation or capacity installed from wind/solar in each eGRID sub-region, finding the weighted marginal damages for each site

Marginal Damage (\$/MWh) ($=\beta$)



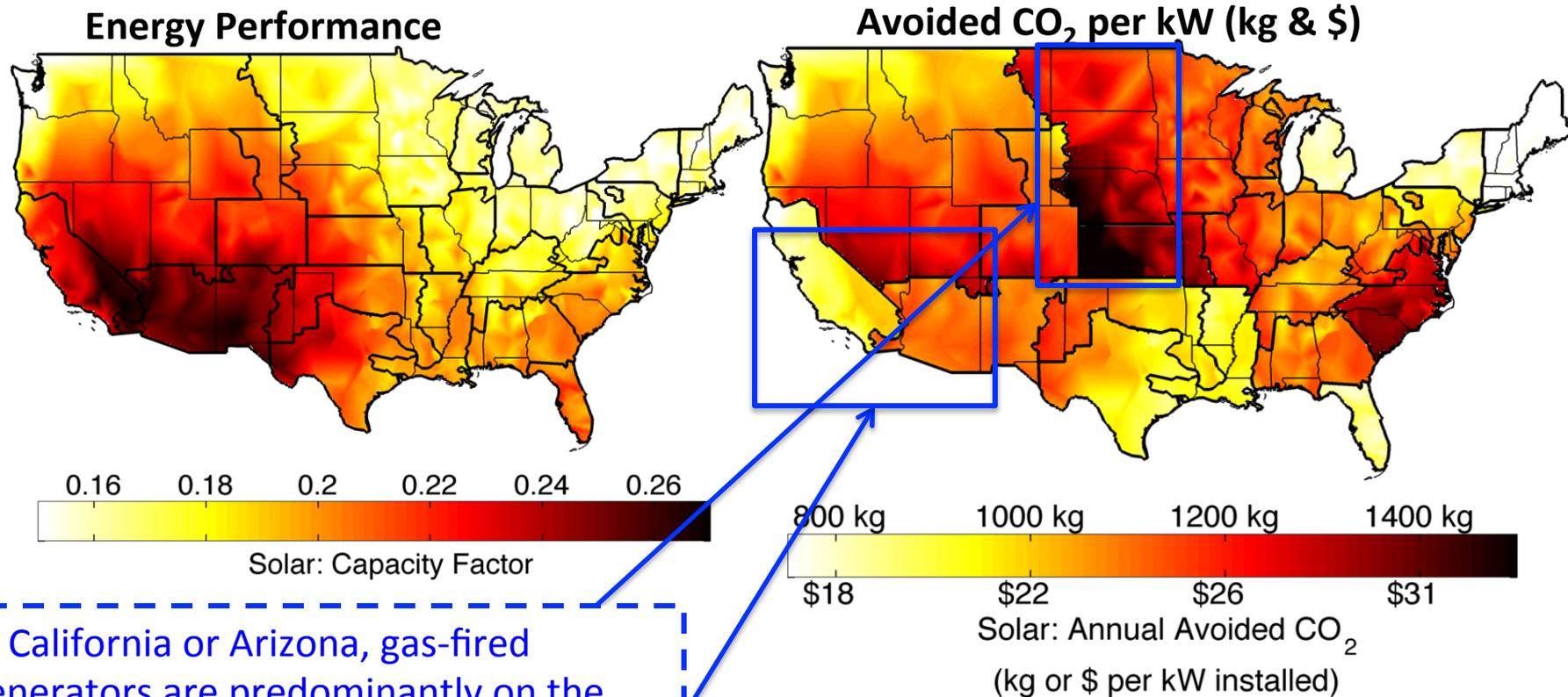
Solar PV: the locations that provide the largest electricity output are not the ones that have the largest climate, health, and environmental benefits.



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.

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

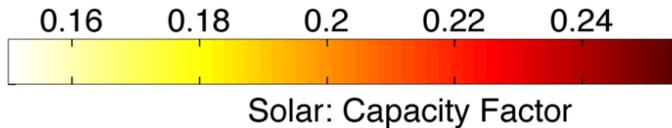
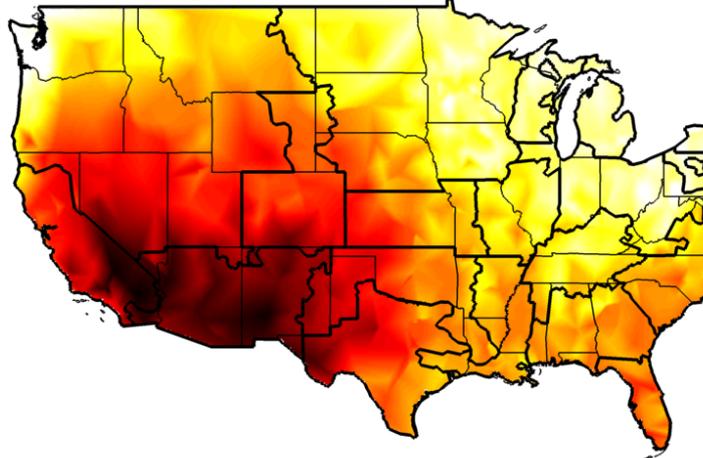


In California or Arizona, gas-fired generators are predominantly on the margin and as a result, solar panels displace relatively little CO₂ emissions.

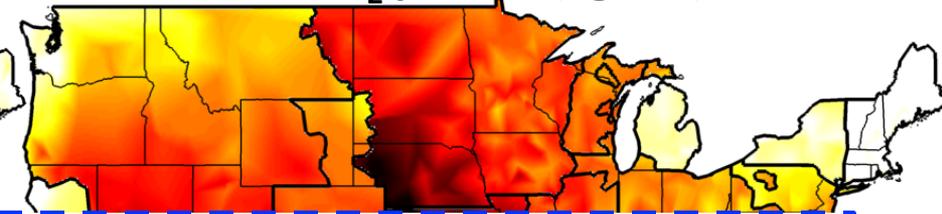
...moderate solar resources, but you're primarily displacing carbon-intensive coal plants.

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

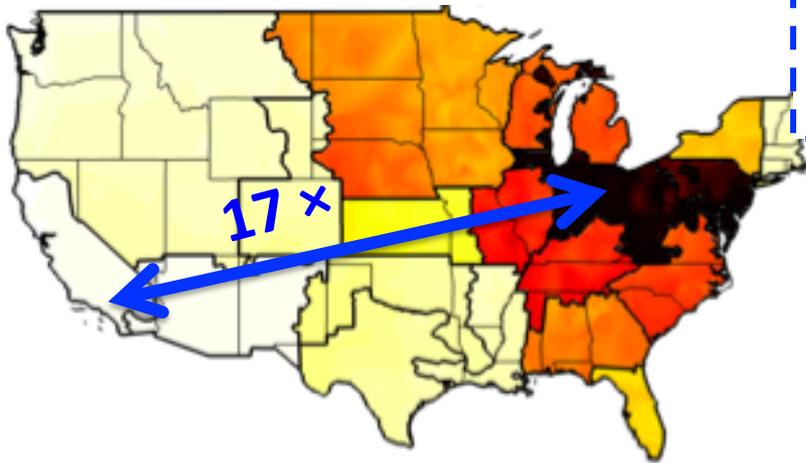


Avoided CO₂ per kW (kg & \$)



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: there are lots of really old, dirty coal plants 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.



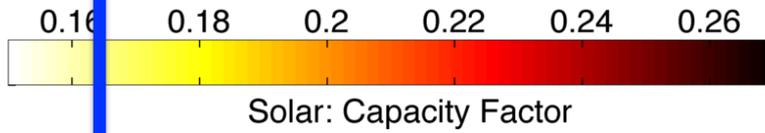
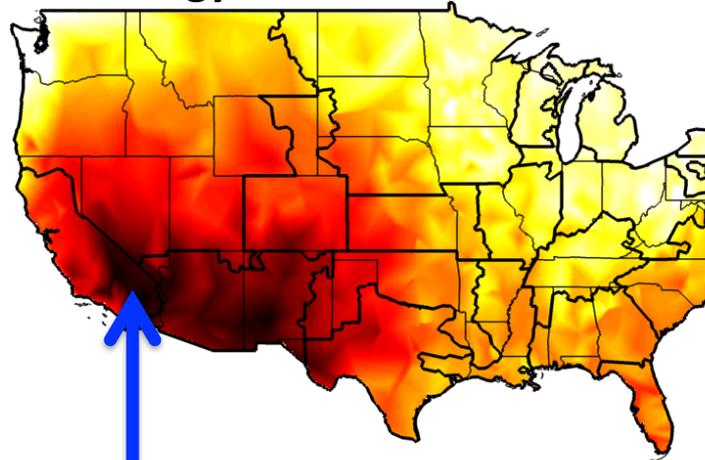
Health and environmental benefits



Solar: Annual Health & Environmental Benefits From Displaced SO₂, NO_x, and PM_{2.5} (\$ per kW installed)

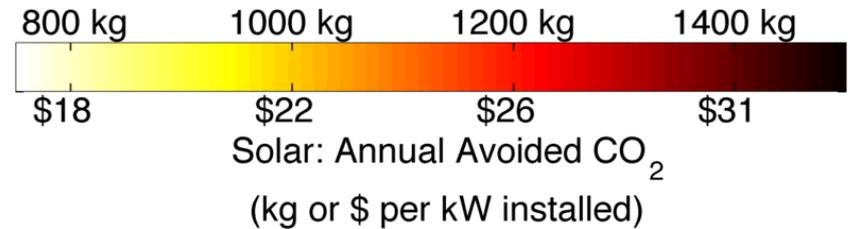
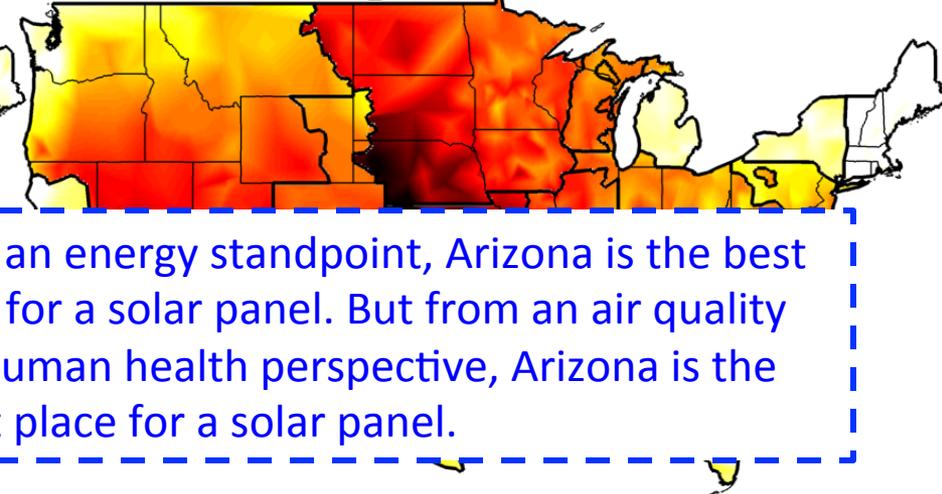
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Energy Performance



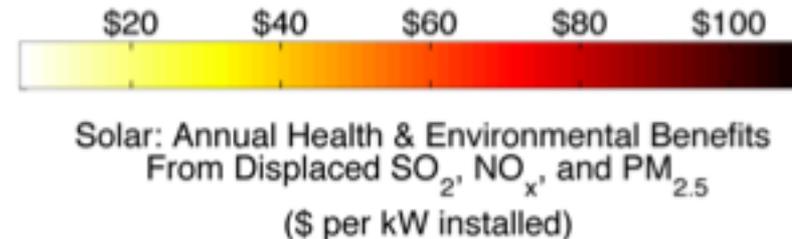
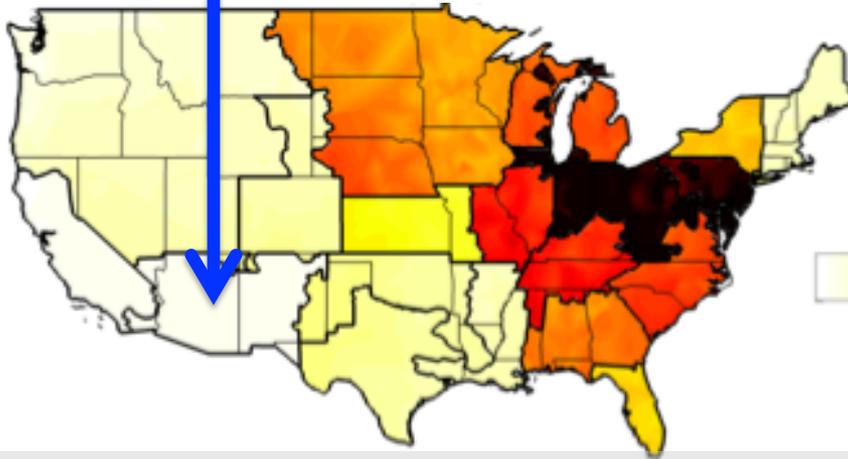
Solar: Capacity Factor

Avoided CO₂ per kW (kg & \$)

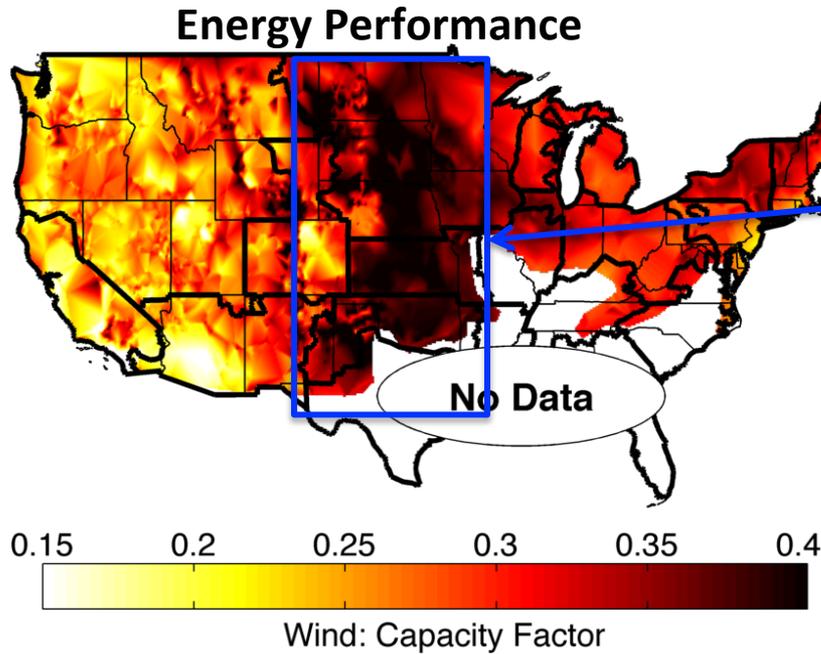


From an energy standpoint, Arizona is the best place for a solar panel. But from an air quality and human health perspective, Arizona is the worst place for a solar panel.

Health and environmental benefits



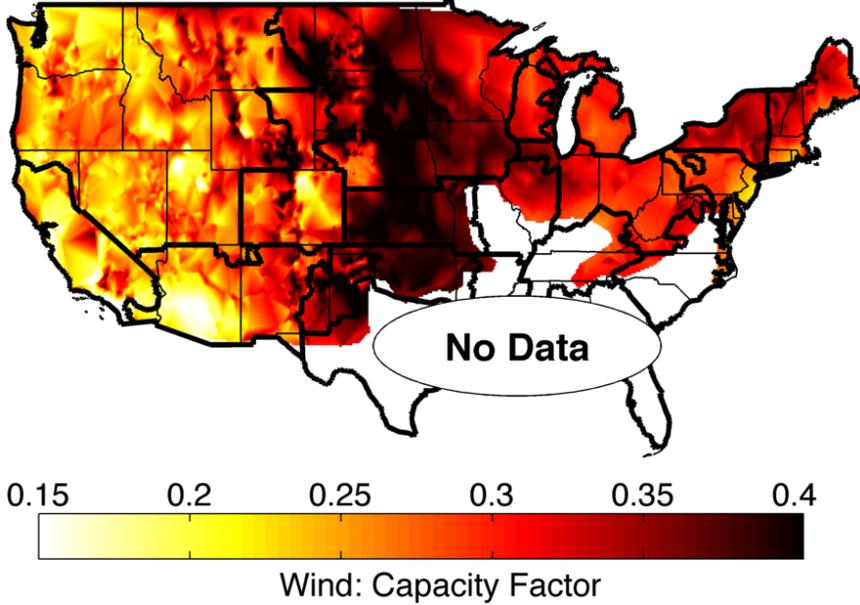
Wind: the locations that provide the largest electricity output align with the locations that provide the largest CO₂ savings, but not criteria air pollutant savings.



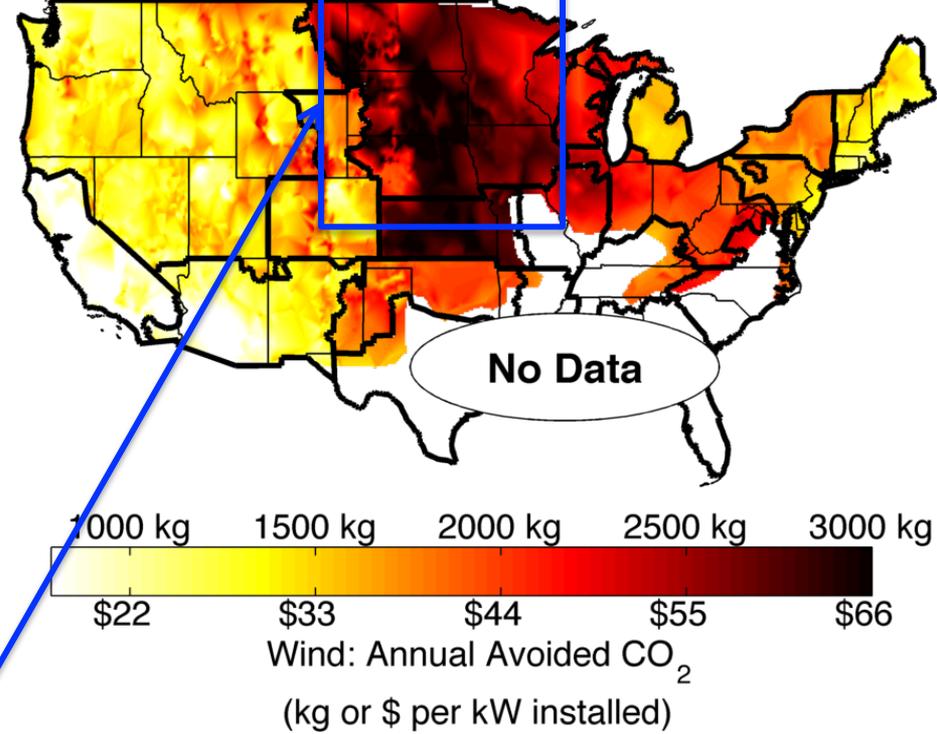
From an energy standpoint, wind turbines perform best in the Great Plains through West Texas, where capacity factors can reach 40%.

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Energy Performance



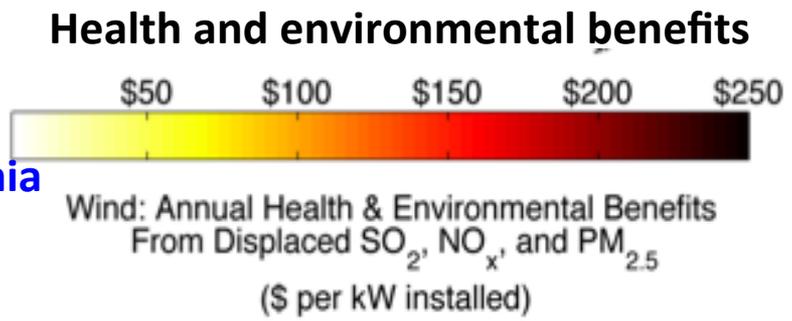
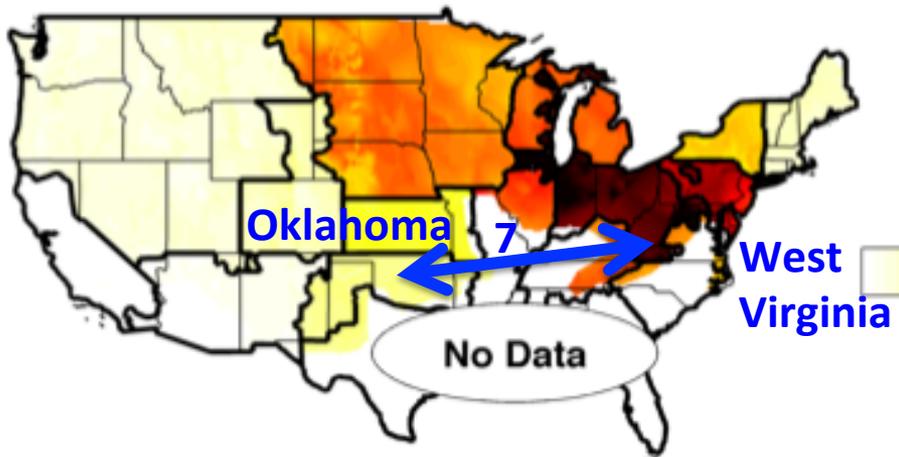
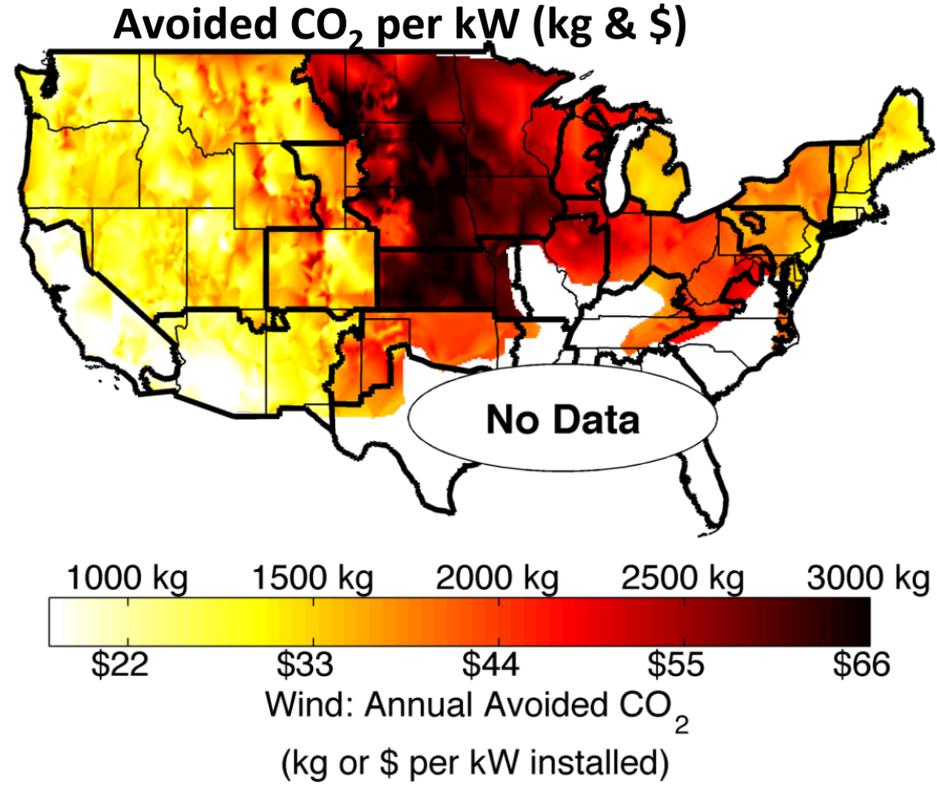
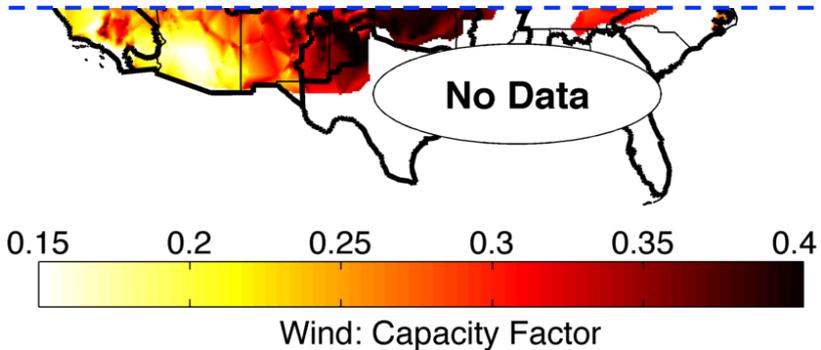
Avoided CO₂ per kW (kg & \$)



Wind turbines are most effective at displacing CO₂ emissions when located in Midwest, where the wind resource is excellent and wind energy primarily displaces coal-fired generators.

Wind: the locations that provide the largest electricity output align with the locations that provide the largest CO₂ savings, but not criteria air pollutant savings.

A wind turbine in West Virginia displaces \$230 in health and environmental damages per kilowatt per year (\$82/MWh) — 7x more than a wind turbine in Oklahoma and 27x more than a wind turbine in California.



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. 31

Are we reducing emissions by increase storage around the country?

Bulk Energy Storage Increases United States Electricity System Emissions

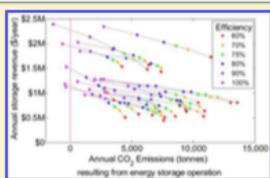
Eric S. Hittinger^{1,†} and Inês M. L. Azevedo²

¹Department of Public Policy, Rochester Institute of Technology, Rochester, New York 14623, United States

²Department 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 CO₂, SO₂, and NO_x for 20 eGRID subregions in the United States. We find that net system CO₂ 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 SO₂ 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 CO₂, NO_x, and SO₂ 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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With Eric Hittinger

Bulk Energy Storage (BES)

- BES is generally considered an important contributor for the transition toward a more flexible and sustainable electricity system.

.... But, is it?

Policy Question:

Should policies incentivize an increase in the share of storage in our electric grid?

Is storage “green”?

- 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.
 - 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.
 - 2010: The CA Senate passed AB2514, directing the California Public Utilities Commission (CPUC) to determine appropriate requirements for grid energy storage.
 - 2013. CPUC mandated that the 3 major investor-owned utilities in California must collectively add 1.3 GW of storage by 2020.

Why will storage potentially increase emissions

1. Storage tends to charge at night during off-peak hours (coal at the margin) and discharge during peak afternoon or evening periods (natural gas at the margin).
 - Using average emissions factors implies no difference between storage charging and discharging times.
2. Second, all storage technologies experience energy losses as they store and recover energy.
 - This inefficiency means the system needs to generate extra electricity and emissions to account for these losses.

Framework

Let's assess the trade-offs in storage deployment across the country:

- How does the **economics** look like?
 - We estimate the annualized profits
- What do the **emissions** look like?

Two scenarios for storage operation: perfect and imperfect information about future electricity prices.

Using Simulation and Optimization

Storage Operation:

1. We consider 20 sites around the continental U.S.
2. We determine the **revenue-maximizing** operation of storage by using the nearest available hourly electricity market clearing prices.
3. We consider 2 scenarios: **perfect** and **imperfect information**
4. We use Marginal Emissions Factors (MEFs) the hourly energy time series to determine the effective net CO₂, SO₂, and NO_x emissions related to storage plant operation.

Price data

- We use hourly LMP for locations within an Independent System Operator (ISO)
 - The nearest node to the location is used for the hourly price data, acquired from the grid operator for that region.
 - For sites located in regions without an hourly electricity market, we use the price data from the nearest node in the most closely linked electricity market.

Modelling Storage

- The base-case modeling of the energy storage device is not tied to a particular technology but has attributes of existing or likely bulk storage technologies: pumped hydro, compressed air energy storage, and some battery technologies.
- We use a 4 h charge rate (i.e., it takes 4 h to charge or discharge the storage unit at the maximum rate).
- The storage is modeled as a 20 MW/80 MWh system in the base case, with the energy capacity of the storage device varied in sensitivity analysis.
- The scale of storage does not affect the results because there are no economies of scale in the applied storage model.
- Round trip efficiency of 75%, with the inefficiency divided equally between the charge and discharge portions of the cycle.

Storage operations

- Storage is operated only as a **bulk energy time-shifting device**, a service often referred to as **energy arbitrage**.
 - This is what pumped hydro storage does nowadays
- Other services that a storage plant could provide, such as frequency regulation, are not included in the model.
- We assume that the storage system is small enough that it displaces only the marginal generator and has no effect on market prices or marginal system emissions.

- The operation of the storage plant is considered under **both perfect** and **imperfect information** about **future electricity prices**.
- In either case, the storage owner pursues a strategy of **maximizing** annual revenue from the storage device.
- The perfect and imperfect information cases act as **bounds** to the actual operation and revenue of energy storage systems.
- A real storage plant **cannot** exceed the revenue found in the perfect information case, but should be able to earn more revenue than the simple imperfect information model, if operated with a reasonably sophisticated algorithm.

Scenarios

Perfect Information

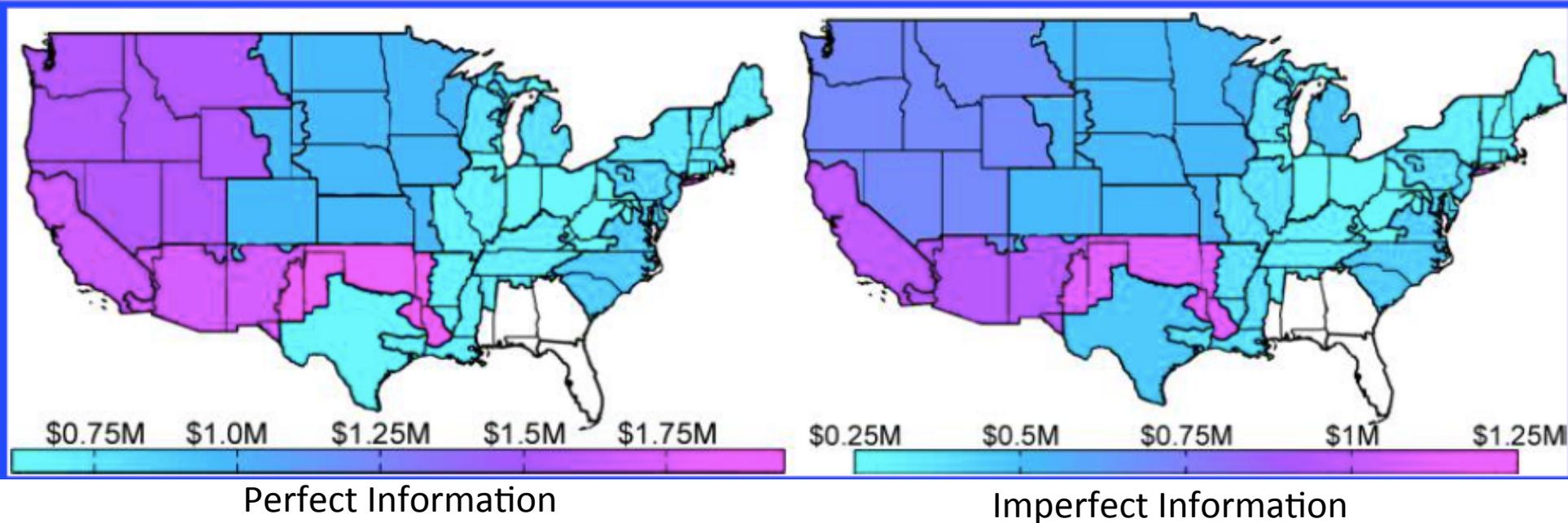
- The perfect information model uses a linear programming optimization to maximize revenue within the limitations of storage operation.
- We use an hourly time resolution for all calculations. Prices are exogenous, and we assume storage to be a price taker.

Scenarios

Imperfect Information

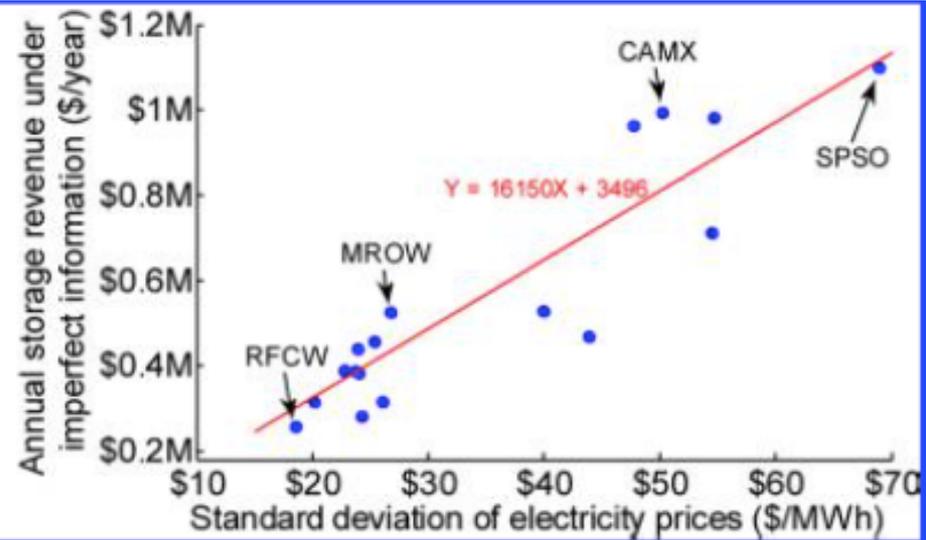
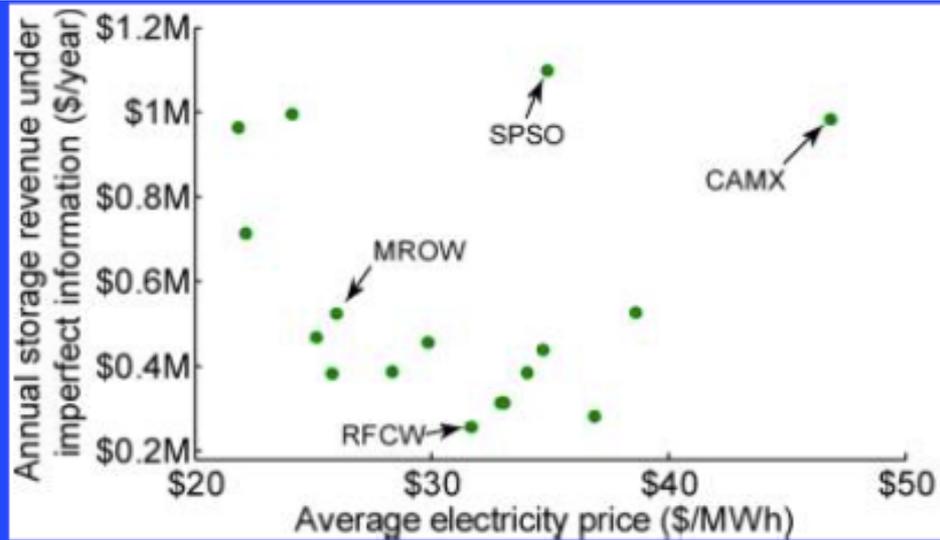
- The imperfect information model uses the same storage constraints before, but applies a simple “**sell above, buy below**” algorithm to determine when to charge or discharge.
- Storage is charged whenever the market clearing price is below a fixed “buy price”, and discharged whenever the energy price is above a fixed “sell price”.
- Between the buy and sell prices, the storage unit does nothing.
- This algorithm relies on neither past nor future electricity prices for operational decision making.
- The buy and sell prices are determined using a simulated annealing optimization that searches for revenue-maximizing values of buy and sell prices (following the algorithm from Kirkpatrick et al.).

Revenue

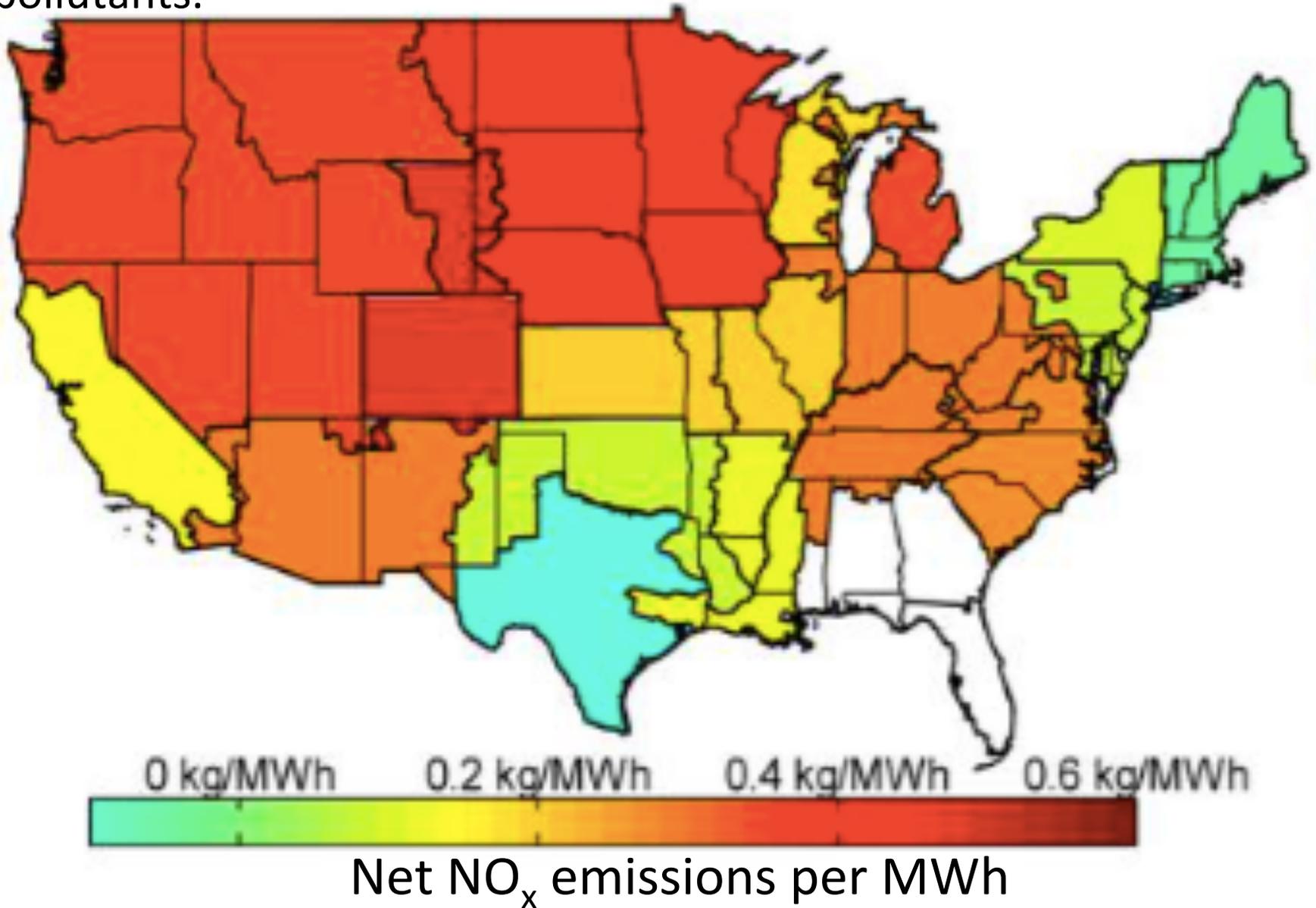


- Large large potential market, but very low revenue rates.
- Only the most inexpensive storage technologies could produce a profit in this market.
 - For example, assuming a 15-year life and a 7% cost of capital, the upfront cost of the storage device would have to be less than \$115/kWh in order to create a profit from an annual revenue of \$1 M per year.
 - For the annual revenue calculated under PI (\$0.6 to \$1.95 M), the breakeven capital costs of storage range from \$70/kWh to \$225/kWh -> most energy storage devices cost more (perhaps large pumped hydro or compressed air systems would do)

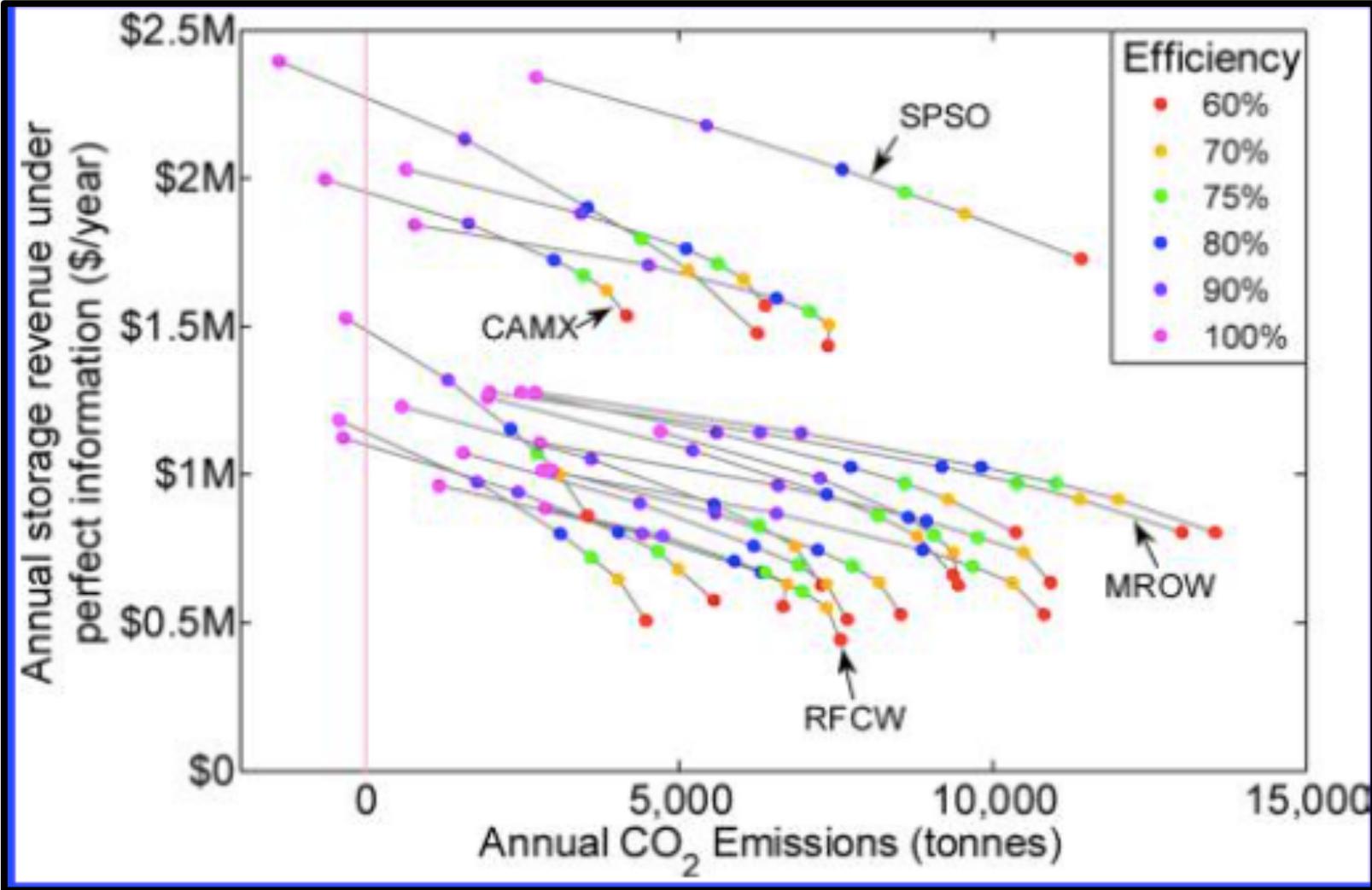
Revenue under imperfect information



Storage: for most locations across the country, using storage for energy arbitrage will increase emissions of CO₂ and of criteria air pollutants.



Sensitivity Analysis



Electrified vehicles:

Regional Variability and Uncertainty of Electric Vehicle Life Cycle CO₂ Emissions across the United States

Mili-Ann M. Tamayao,[†] Jeremy J. Michalek,^{*,†,‡} Chris Hendrickson,^{†,§} and Inês M. L. Azevedo[†]

[†]Department of Engineering and Public Policy, Carnegie Mellon University, 129 Baker Hall, Pittsburgh, Pennsylvania 15213, United States

[‡]Department of Mechanical Engineering, Carnegie Mellon University, 324 Scaife Hall, Pittsburgh, Pennsylvania 15213, United States

[§]Department of Civil and Environmental Engineering, Carnegie Mellon University, 119 Porter Hall, Pittsburgh, Pennsylvania 15213, United States

Supporting Information

ABSTRACT: We characterize regionally specific life cycle CO₂ emissions per mile traveled for plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) across the United States under alternative assumptions for regional electricity emission factors, regional boundaries, and charging schemes. We find that estimates based on marginal vs average grid emission factors differ by as much as 50% (using National Electricity Reliability Commission (NERC) regional boundaries). Use of state boundaries versus NERC region boundaries results in estimates that differ by as much as 120% for the same location (using average emission factors). We argue that consumption-based marginal emission factors are conceptually appropriate for evaluating the emissions implications of policies that increase electric vehicle sales or use in a region. We also examine generation-based marginal emission factors to assess robustness. Using these two estimates of NERC region marginal emission factors, we find the following: (1) delayed charging (i.e., starting at midnight) leads to higher emissions in most cases due largely to increased coal in the marginal generation mix at night; (2) the Chevrolet Volt has higher expected life cycle emissions than the Toyota Prius hybrid electric vehicle (the most efficient U.S. gasoline vehicle) across the U.S. in nearly all scenarios; (3) the Nissan Leaf BEV has lower life cycle emissions than the Prius in the western U.S. and in Texas, but the Prius has lower emissions in the northern Midwest regardless of assumed charging scheme and marginal emissions estimation method; (4) in other regions the lowest emitting vehicle depends on charge timing and emission factor estimation assumptions.



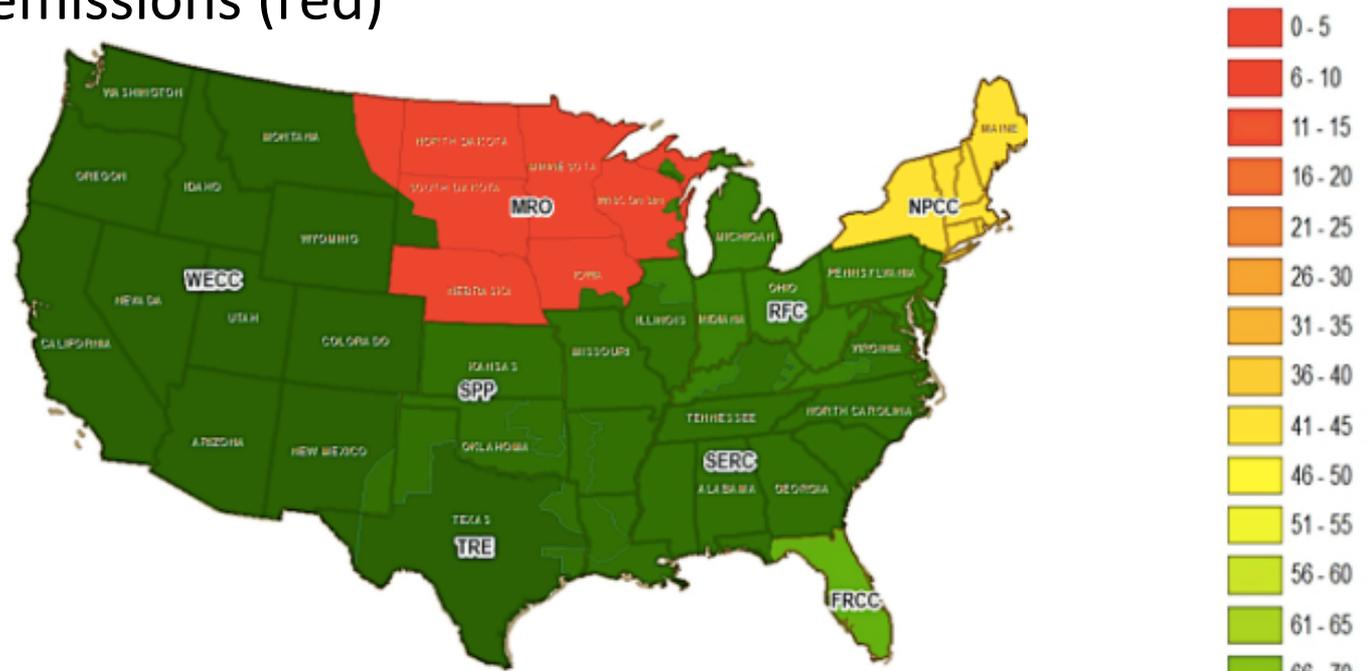
1. INTRODUCTION

To address climate change, move toward more sustainable energy systems, and improve the security of energy supply, new technologies and strategies are needed in the transportation sector. In the United States, transportation accounted for about 28% of U.S. greenhouse gas (GHG) emissions¹ and about 28% of total U.S. primary energy consumption² in 2012. Vehicle electrification has been proposed as a way to reduce emissions, and much attention has been paid to comparisons of life cycle GHG emissions between plug-in electric vehicles (PEVs) and

In Table 1 we summarize recent studies that have focused on a regional comparative analysis of electric and gasoline vehicle CO₂ emissions in the U.S. For illustrative purposes, in the Supporting Information (SI) we provide a set of maps that highlight differences in two of these analyses. These studies vary in life cycle scope, vehicle assumptions, regional boundaries, and grid emission factors. In particular, variation in grid emission factors and regional boundaries are key drivers of differences in the estimates of regional PEV benefits.

We examine how the regional variation in emissions from electrified vehicles differ depending on the assumptions

Electrified vehicles: there is no one size fits all: the Nissan Leaf has lower CO₂ emissions than gasoline (ICEV or Toyota Prius hybrid) in parts of the country (green) where in other parts, the Prius or ICEV have lower emissions (red)

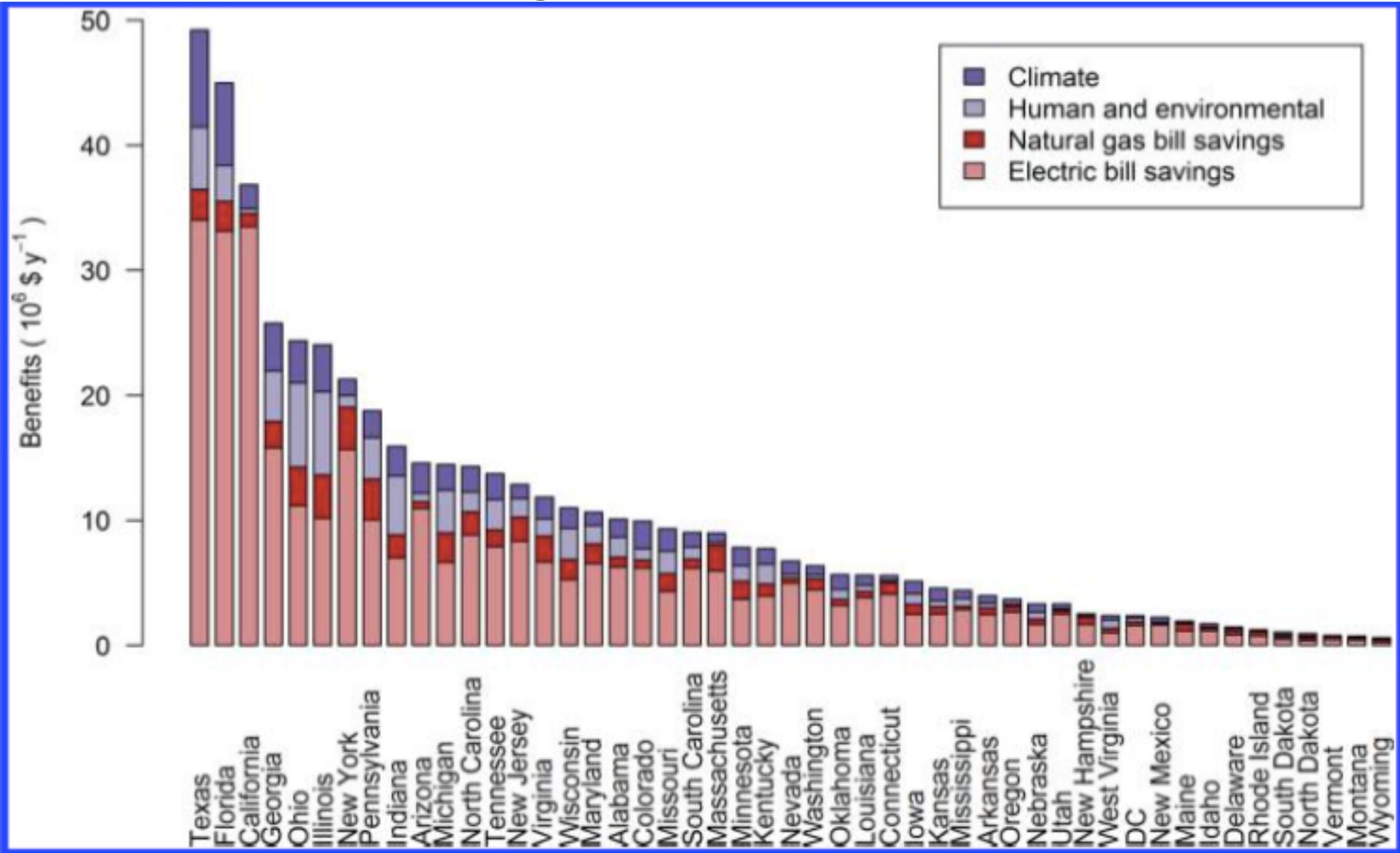


a) Consumption-based, Convenience Charging

Probability that CO₂ emissions from Nissan Leaf < gasoline vehicle (Toyota Prius Hybrid or sales-weighted ICEV)



Building codes: moving to ASHRAE 90.1–2010 relative to a baseline building code
 ASHRAE 90.1–2007 have 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 transition to low-carbon, environmentally sustainable, and socially desirable energy systems will require a major transition in our energy system.
- During this transition, we want to focus on strategies and interventions that provide the intended emissions savings.
- Focusing on both greenhouse gases and criteria air pollutants together makes sure we select strategies that have the largest climate, environmental and health benefits.
- Data for other countries!

I am working on an online tool

- With a group of 6 PhD students, we are developing a tool that downloads the most recent CEMS data and transforms it in a usable dataset; run the regressions for different years, seasons, regions; use different assumption for the damages
 - We hope to make this publicly available online sometime this Fall.

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;
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3. Hittinger, E., Azevedo, I.L., (2015). Bulk Energy Storage Increases US Electricity System Emissions, *Environmental Science & Technology*, 49 (5), 3203-3210;
4. Tamayao, M., Michalek, J., Hendrickson, C., Azevedo I.L., (2015). Regional variability and uncertainty of electric vehicle life cycle CO₂ emissions across the United States, accepted to *ES&T* in May 2015;
5. Gilbraith, N., Azevedo, I.L., Jaramillo, P., (2014). Regional energy and GHG savings from building codes across the United States, *Environmental Science & Technology*;
6. Min, J., Azevedo, I.L.* , Hakkarainen, P., (2015). Net carbon emissions savings and energy reductions from lighting energy efficiency measures when accounting for changes in heating and cooling demands: a regional comparison, *Applied Energy*, [Volume 141](#), 1, 12–18.

De-carbonizing the electricity sector in the United States: what big data analytics can tell us about sustainable transitions.

Inês M.L. Azevedo
iazevedo@cmu.edu

This presentations & paper can be found at:

[https://www.dropbox.com/sh/9skgog59wdd3m4x/
AAQzsPhamXaRmGOIOhyz7Dpa?dl=0](https://www.dropbox.com/sh/9skgog59wdd3m4x/AAQzsPhamXaRmGOIOhyz7Dpa?dl=0)

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- 08:30 – 09:15 Overview of >25 years of HDGC, CDMC and CEDM – Granger Morgan
- 09:15 – 10:00 Uncertainty in energy efficiency, Part 1: technologies, strategies, behavior and policy – Inês Azevedo
- 10:00 – 10:30 Uncertainty in energy efficiency, Part 2: technologies, strategies, behavior and policy – Alex Davis
- 10:45 – 11:15 **Coffee break**
- 11:15 – 11:45 Decision support for implementing the EPA Clean Power Plan Proposed Rule – Jeff Anderson
- 11:45 – 12:30 Marginal emissions factors, health and climate change co-benefits and trade-offs - Inês Azevedo
- 12:30 – 13:30 **Lunch break**
- 13:30 – 13:55 Insights from twenty years of work on expert elicitation and projections – Granger Morgan
- 13:55 – 14:05 Transitioning to a low carbon economy, Part 1: Insights from the RenewElec Project – Granger Morgan
- 14:05 – 14:30 Transitioning to a low carbon economy, Part 2: Insights from ITC and BC’s Climate Policy – Hadi Dowlatabadi
- 14:30 – 15:10 Strategies for supporting investment decisions about large energy infrastructure in the face of regulatory and other uncertainty – Dalia Patiño
- 15:10 – 15:40 **Coffee break**
- 15:40 – 16:00 Reflections on Research and Governance wrt Albedo Modification – Granger Morgan
- 16:00 – 16:45 Insights From Our Experience in Building and Using ICAMs – Hadi Dowlatabadi
- 17:45 – 17:00 Muddling through on climate policy: good, but not good enough to avoid the risk of dead ends – Granger Morgan
- 17:00 – 17:30 Discussion and round table on what investigators in CEDM might best work on in the next several years to be most useful to the IA and energy modeling communities.