A marginal damages framework: examples for renewables and storage

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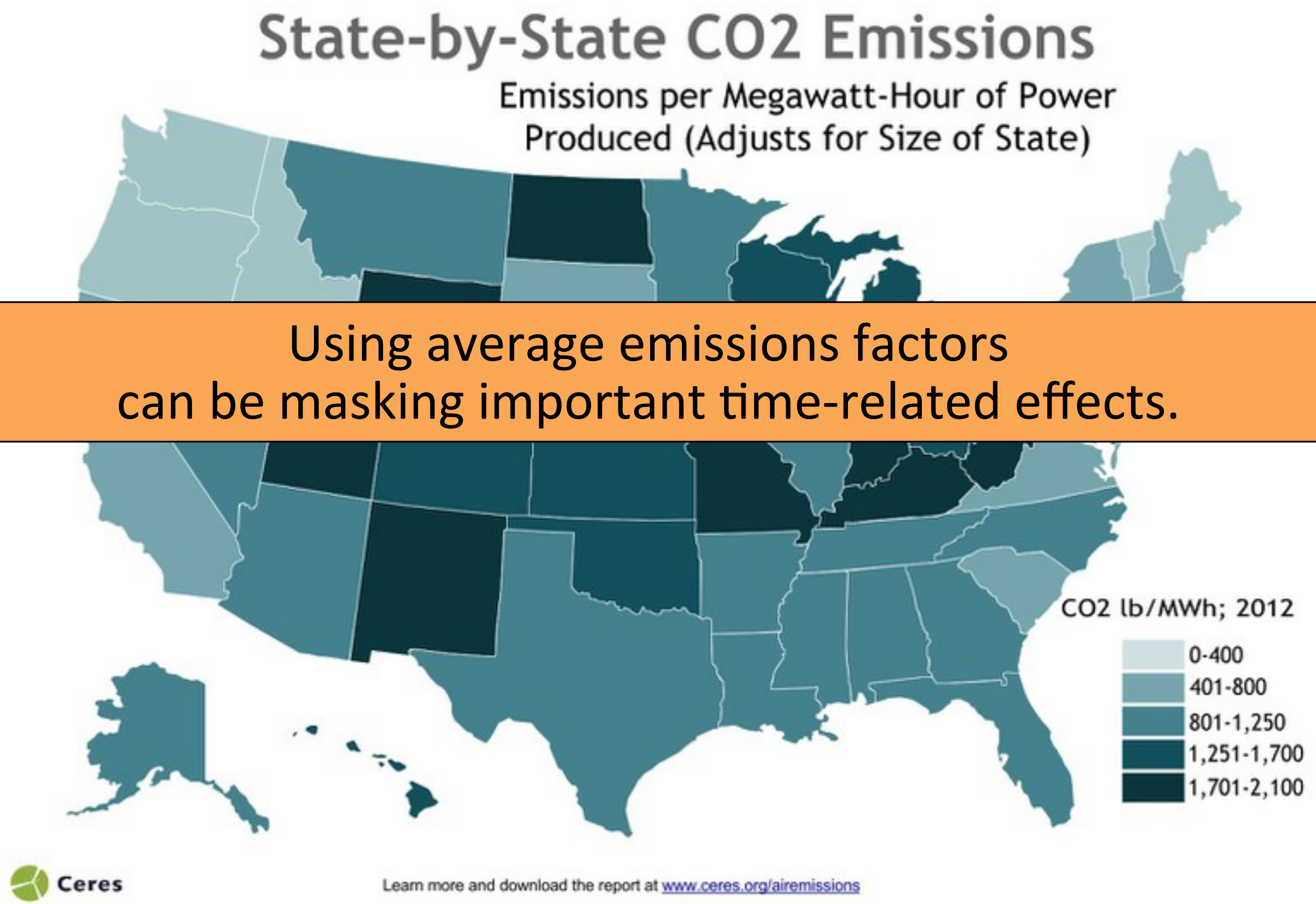
(1) Siler-Evans, K., Azevedo, I.L., Morgan, M.G., Apt, J. 2013, Proceedings of the National Academies of Sciences. "Regional Variations in the Health, Environmental, and Climate Benefits from Wind and Solar Generation; (2) Hittinger, E., Azevedo, I.L., (2015). Bulk Energy Storage Increases US Electricity System Emissions, *Environmental Science & Technology*, 49 (5), 3203-3210.

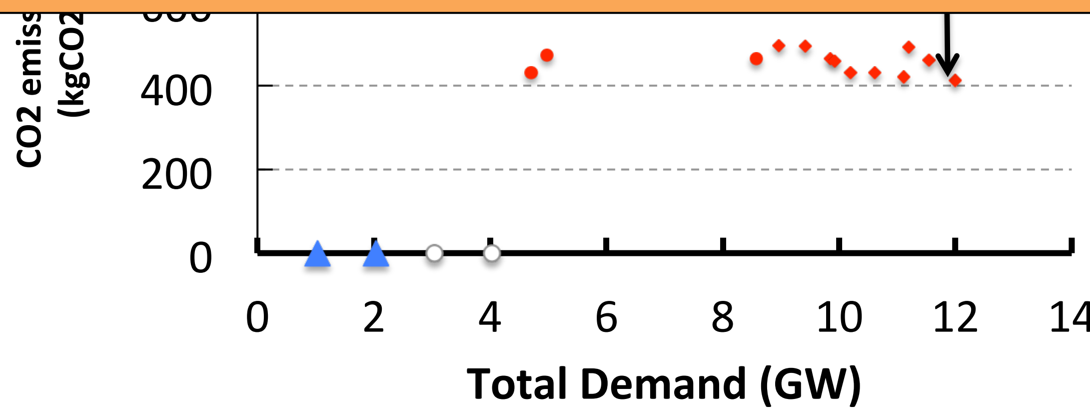
The US grid is diverse in its carbon intensity.



Using average emissions factors
can be masking important time-related effects.

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

Estimating environmental and health benefits

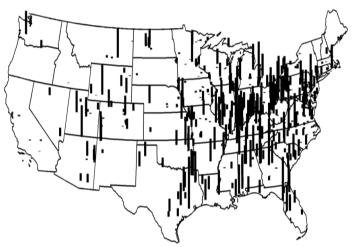
1

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

Data from: APEEP

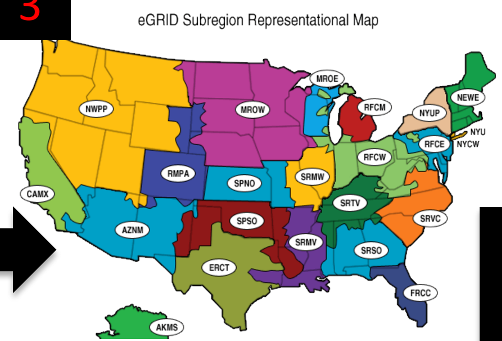
2

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)

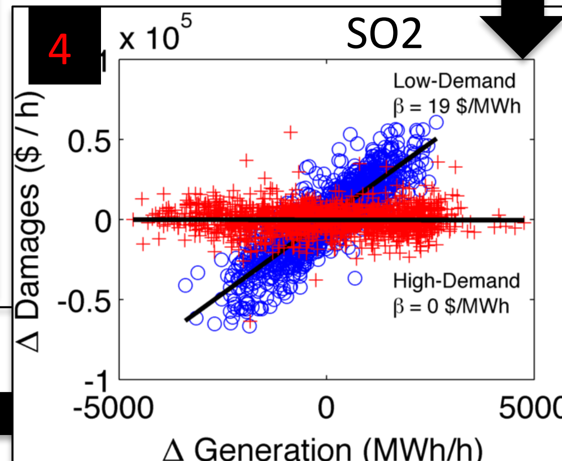
3



For each eGRID sub-region and each pollutant:

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

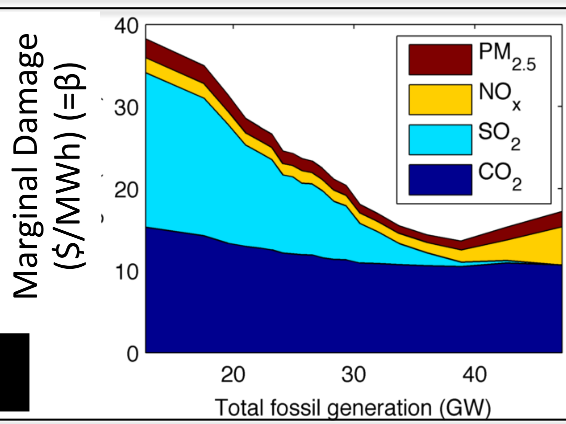
4



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

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

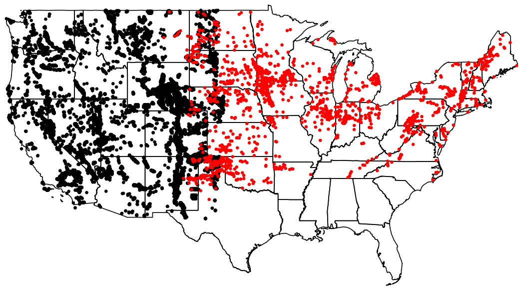
5



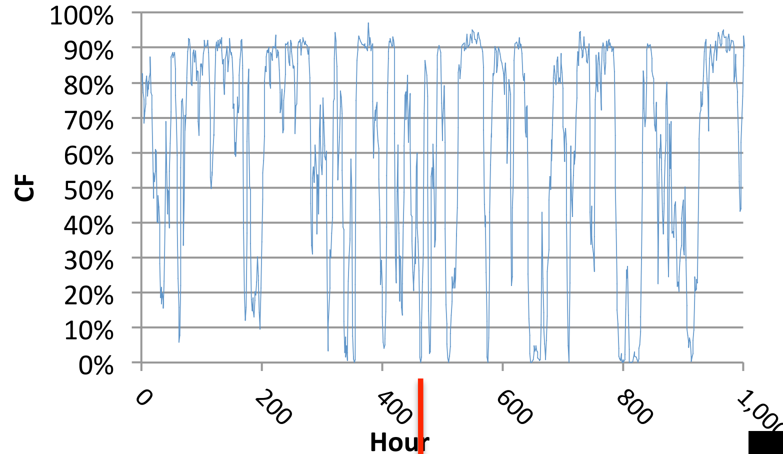
Then we have estimates of marginal damages (\$/MWh) for each demand bin as function of gross generation for each pollutant

Estimating environmental and health benefits

6



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.



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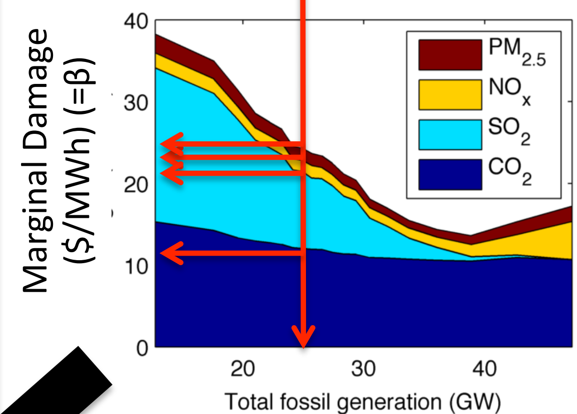
We then Identify the damages associated with gross generation. For each hour, we multiply the associated damages ($/MWh) by the wind/solar output.



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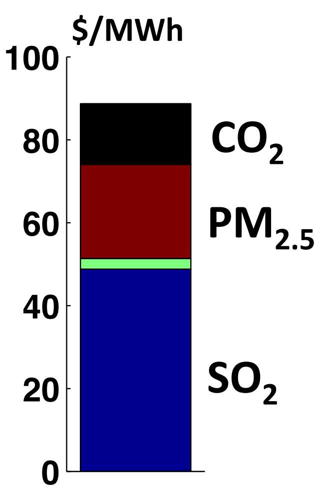
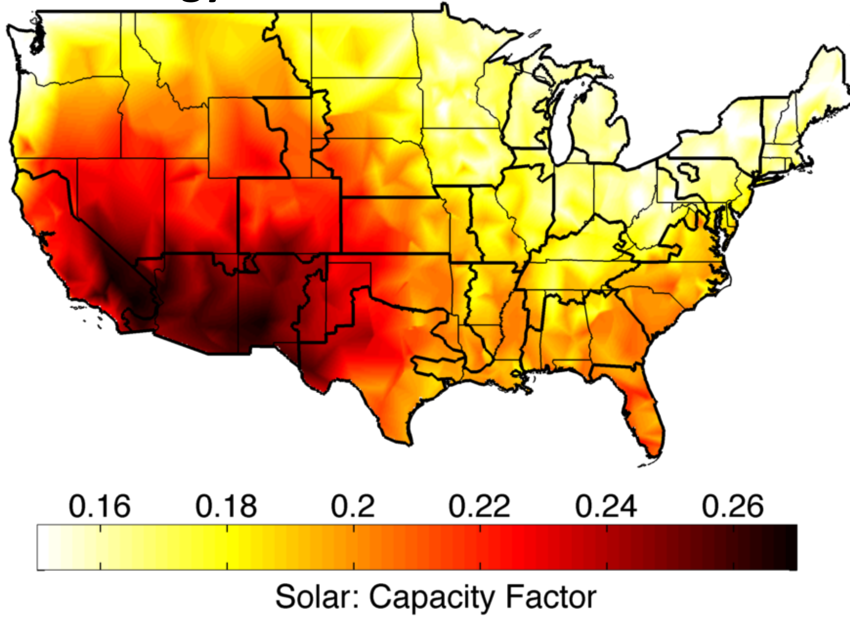


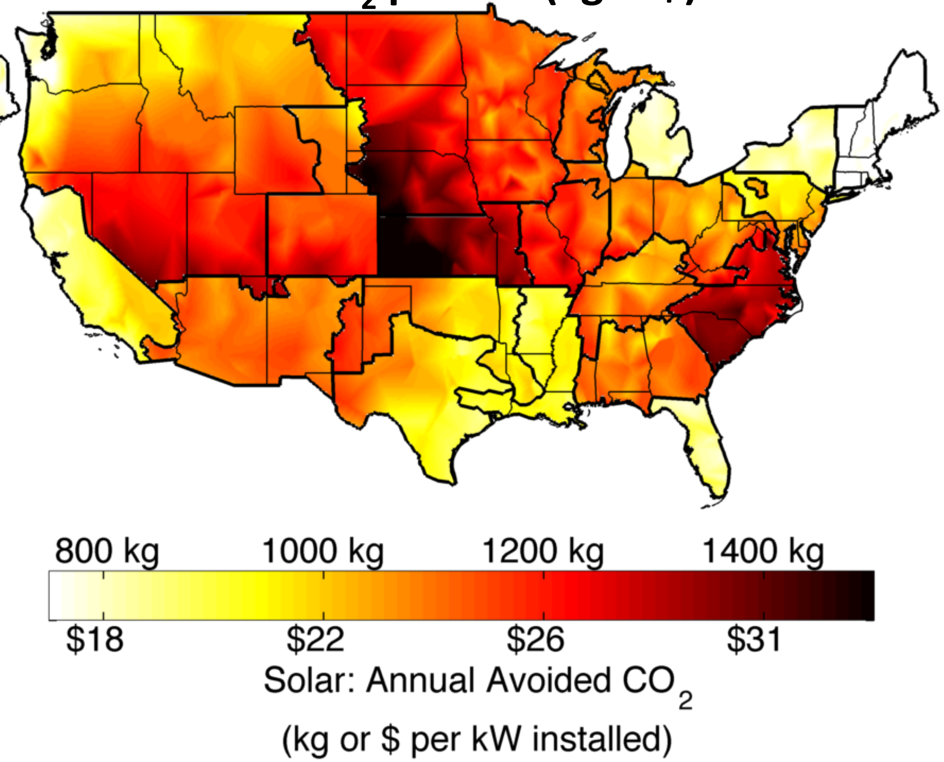
We finally add all damages avoided for each site for all hours of the year and divide by the total generation or capacity installed from wind/solar in each eGRID sub-region, finding the weighted marginal damages for each site

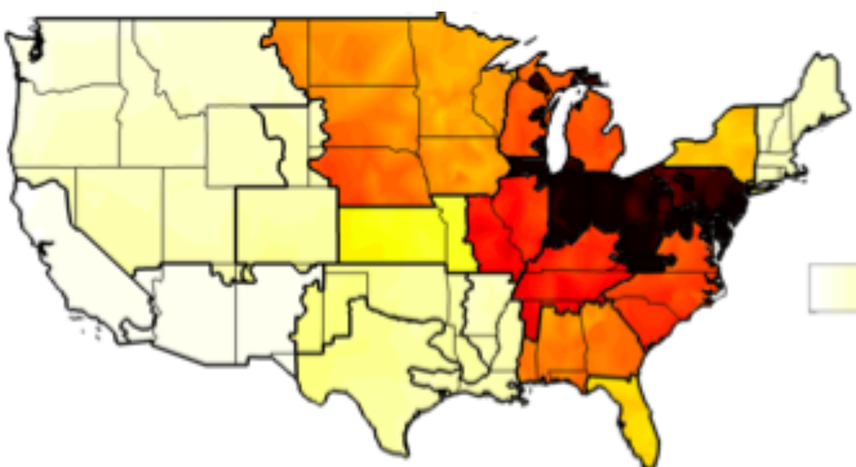
Results for solar

Energy Performance



Avoided CO_2 per kW (kg & $)





Health and environmental benefits

Are we reducing emissions by increasing storage around the country?

Environmental Science & Technology

Article

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Bulk Energy Storage Increases United States Electricity System Emissions

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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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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.

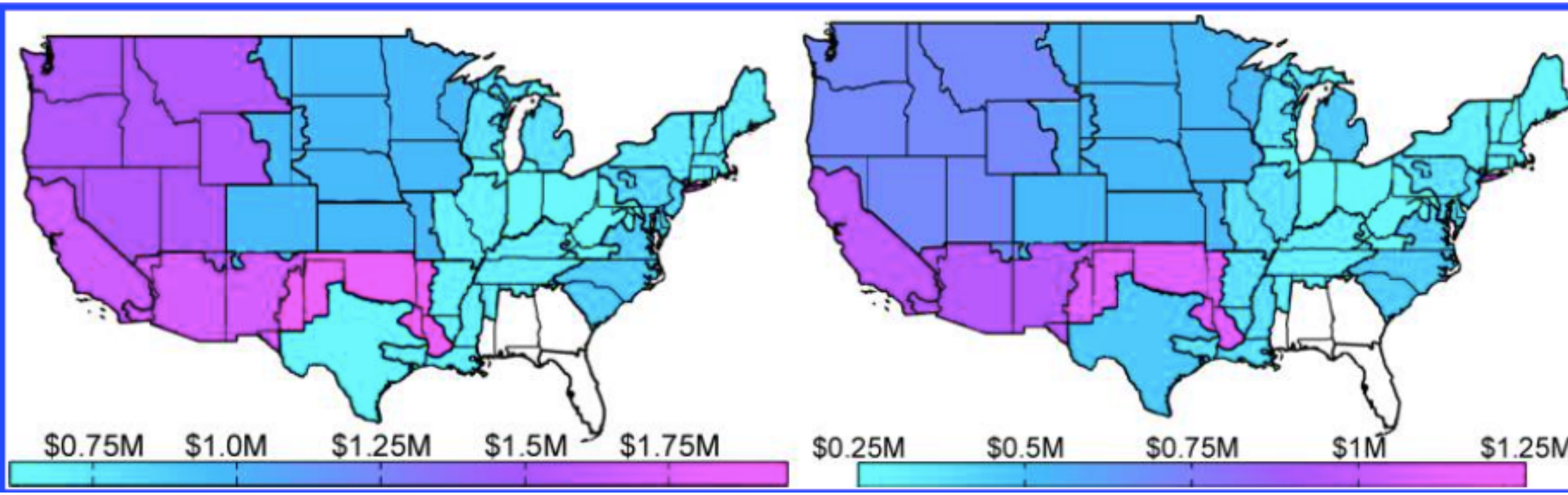
Data & Methods

- 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.

Data & Methods

- The energy storage device is not tied to a particular technology but has attributes of existing or likely bulk storage technologies: pumped hydro, CAES, and some battery technologies.
  - 20 storage sites around the continental U.S.
- Assume revenue-maximizing operation of storage.
  - We consider 2 scenarios: perfect and imperfect information about future electricity prices
  - We use hourly LMP for locations within an Independent System Operator (ISO)
- We use hourly average Marginal Emissions Factors (MEFs) to determine the effective net CO2, SO_2, and NOx emissions related to storage plant operation.
- Round trip efficiency of 75%, with the inefficiency divided equally between the charge and discharge portions of the cycle.

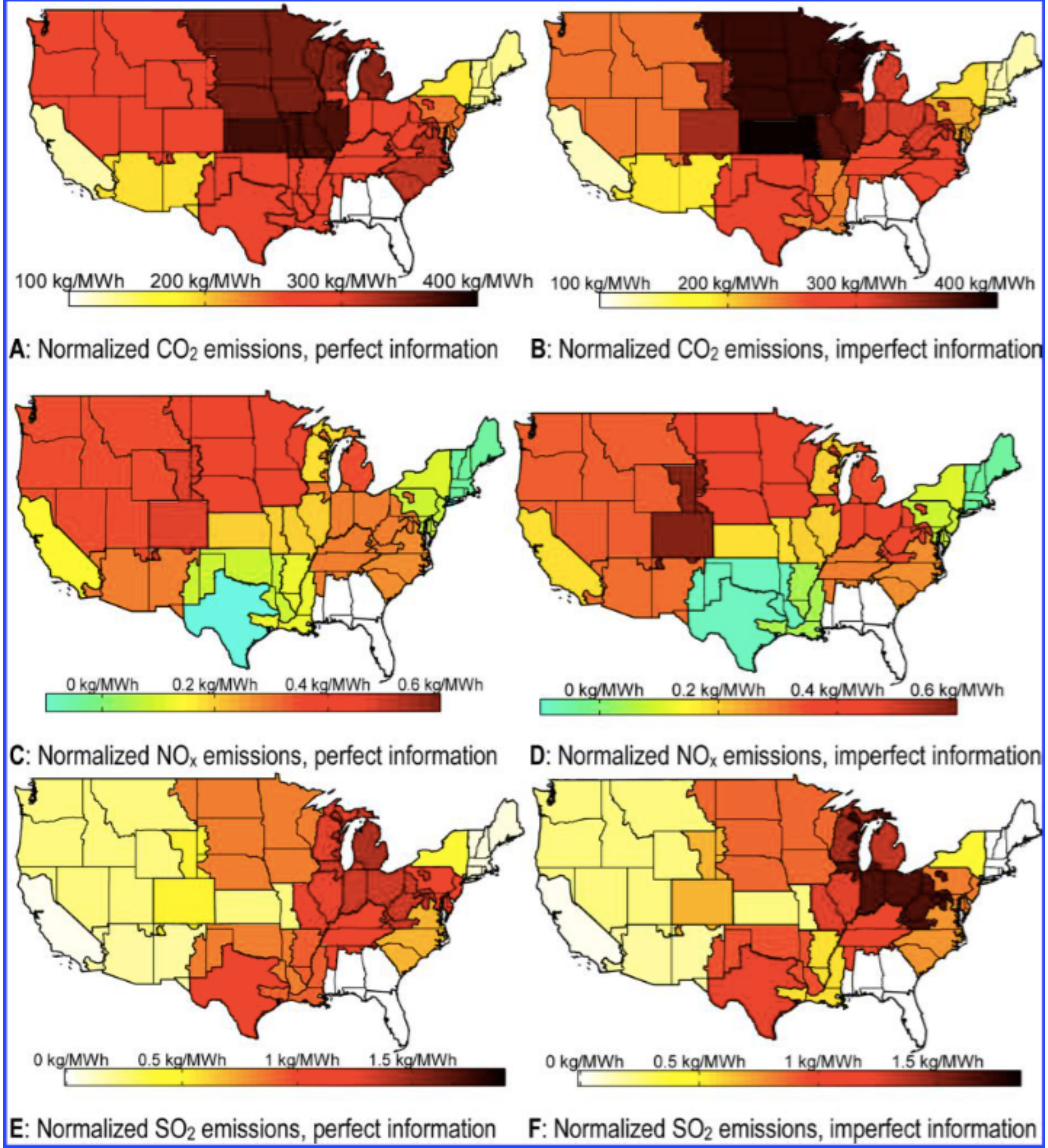
Revenue



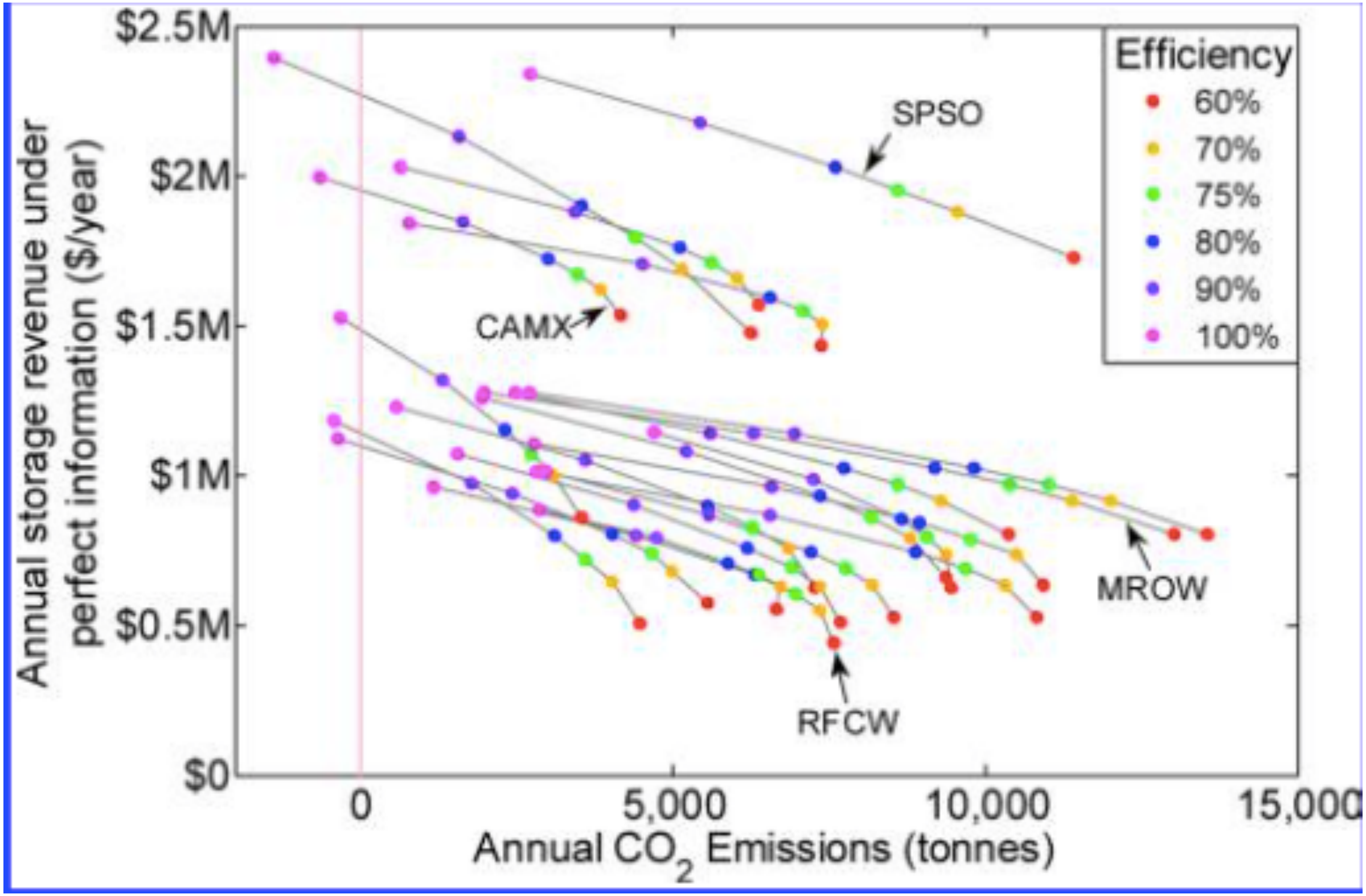
Perfect Information

Imperfect Information

- 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)


100 kg/MWh 200 kg/MWh 300 kg/MWh 400 kg/MWh
A: Normalized CO_2 emissions, perfect information
100 kg/MWh 200 kg/MWh 300 kg/MWh 400 kg/MWh
B: Normalized CO_2 emissions, imperfect information
0 kg/MWh 0.2 kg/MWh 0.4 kg/MWh 0.6 kg/MWh
C: Normalized NO_x emissions, perfect information
0 kg/MWh 0.2 kg/MWh 0.4 kg/MWh 0.6 kg/MWh
D: Normalized NO_x emissions, imperfect information
0 kg/MWh 0.5 kg/MWh 1 kg/MWh 1.5 kg/MWh
E: Normalized SO_2 emissions, perfect information
0 kg/MWh 0.5 kg/MWh 1 kg/MWh 1.5 kg/MWh
F: Normalized SO_2 emissions, imperfect information

Sensitivity Analysis



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