What happens to electricity system emissions when we add energy storage?

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A common narrative about energy storage:

Wind and solar are variable and intermittent and will be unleashed only after we develop and deploy sufficient energy storage.

Thus, cheap and effective energy storage is the “holy grail” of renewable energy.

It also does other things that are useful (but we like it because it is a critical green technology).

This isn’t just a story – it is being written into policy

The “Storage Technology for Renewable and Green Energy Act of 2013 (STORAGE)” was introduced in 2013

California, Arizona, and Massachusetts considering “Clean Peak” standards

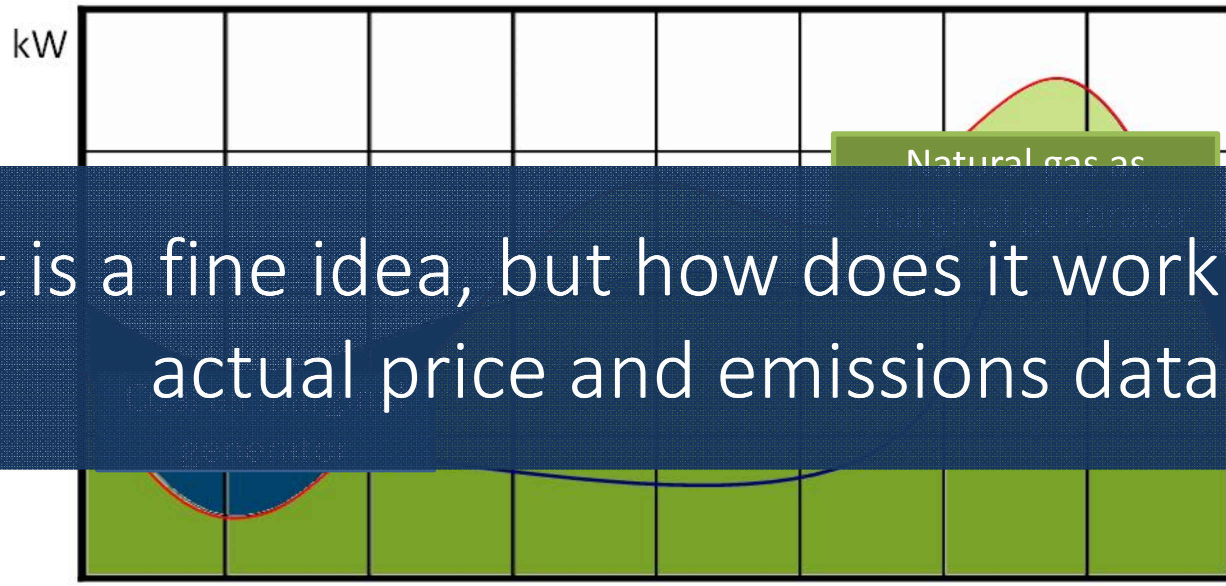
Germany has launched a subsidy program for energy storage linked to residential-level Solar PV

The US Investment Tax Credit will subsidize the addition of storage if that storage mainly charges from solar

https://www.utilitydive.com/news/massachusetts-governor-seeks-clean-peak-standard-with-14b-bond-bill/519254/
http://www.greentechmedia.com/articles/read/Germany-On-The-Verge-Of-A-Subsidy-For-Energy-Storage
http://www.energy.senate.gov/public/index.cfm/democratic-news?ID=de6b4c62-e987-4ba9-933b-d52f82ff0309

However, operation of bulk energy storage has two effects that can increase emissions

1. In many places, "dirty" electricity replaces "clean" electricity.

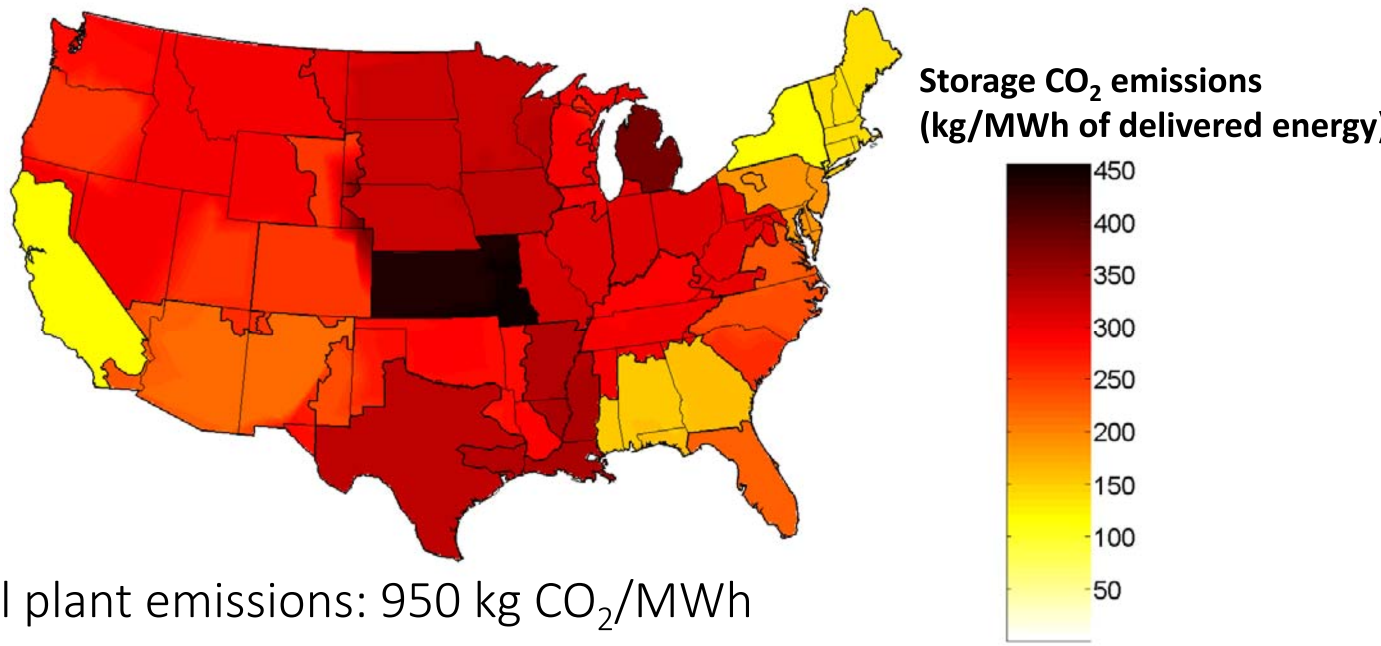


That is a fine idea, but how does it work out using actual price and emissions data?

2. Storage is less than 100% efficient – an energy-consuming device.

[Image: http://greensmith.us.com/applications/peak-shifting/](http://greensmith.us.com/applications/peak-shifting/)

We modeled the operation of energy storage (buy low, sell high) in 20 eGRID regions and compared it to the emissions of the marginal generator in each hour



Average US coal plant emissions: 950 kg CO_2/MWh

Average US natural gas plant emissions: 500 kg CO_2/MWh

Emissions Reference*: Jaramillo et al, Comparative Life-Cycle Air Emissions of Coal, Domestic Natural Gas, LNG, and SNG for Electricity Generation, Environ. Sci. Technol. 2007, 41, 6290-6296*

Importantly, this effect still holds when you charge your storage from renewable energy sources

Scenario A

Solar produces 100 MWh at noon

Scenario B

Solar produces 100 MWh at noon, which is put into storage until 5PM

Thus, storage that always charges from renewables may increase electricity system emissions <u>unless that renewable energy would otherwise be curtailed</u>.

Scenario A

Emissions rate of marginal generator = 500 kg/MWh

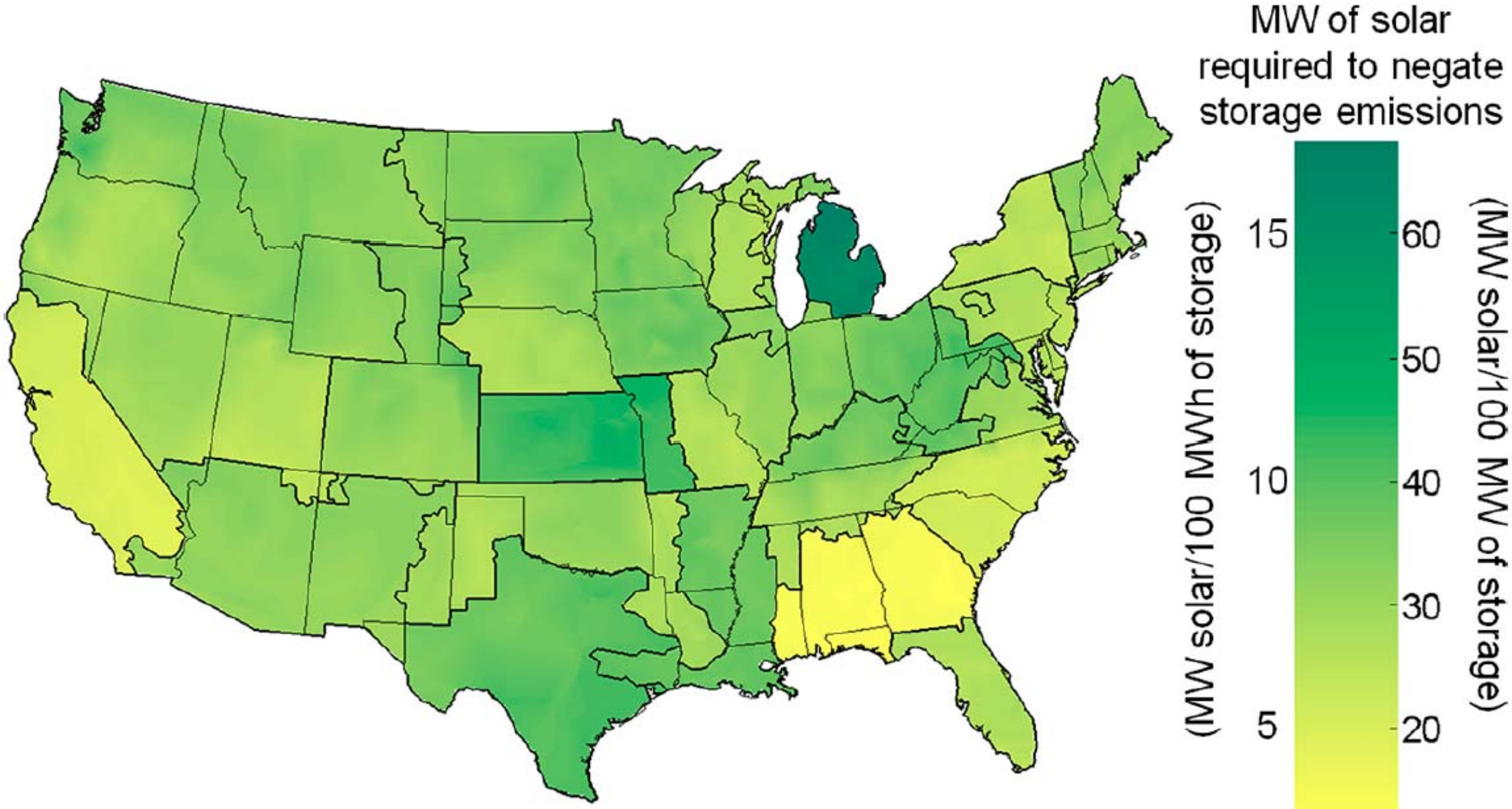
Emissions benefit of solar = 100*500 = **50 tonnes of CO_2**

Scenario B

Emissions rate of marginal generator = 550 kg/MWh

Emissions benefit of stored solar = 80*550 = **44 tonnes of CO_2**

How much new wind/solar do we need to add to offset these storage-induced emissions?



Realistic renewable generation plus storage projects will decrease emissions

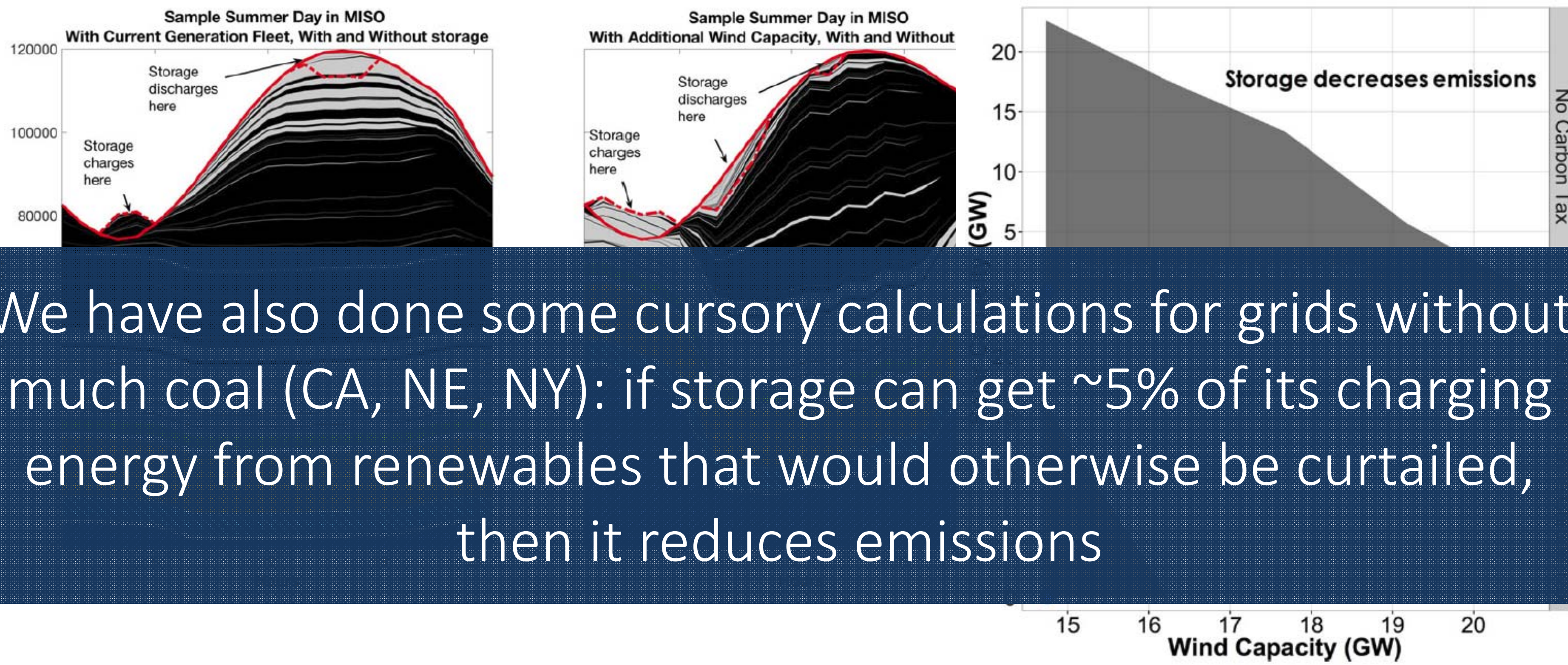
Existing and proposed renewable/storage projects tend to have storage that is small compared to the wind/solar:

- Laurel Mountain: 98 MW Wind & 32 MW (8 MWh) Li-ion
- Solana Generating Station: 280 MW Solar & 280 MW (1680 MWh) thermal storage
- (proposed) Pathfinder Wind: 2.1 GW Wind & 1.2 GW CAES

If Pathfinder Wind was built as proposed, our analysis suggests that the wind+storage project would reduce emissions 93% as much as a wind-only project.

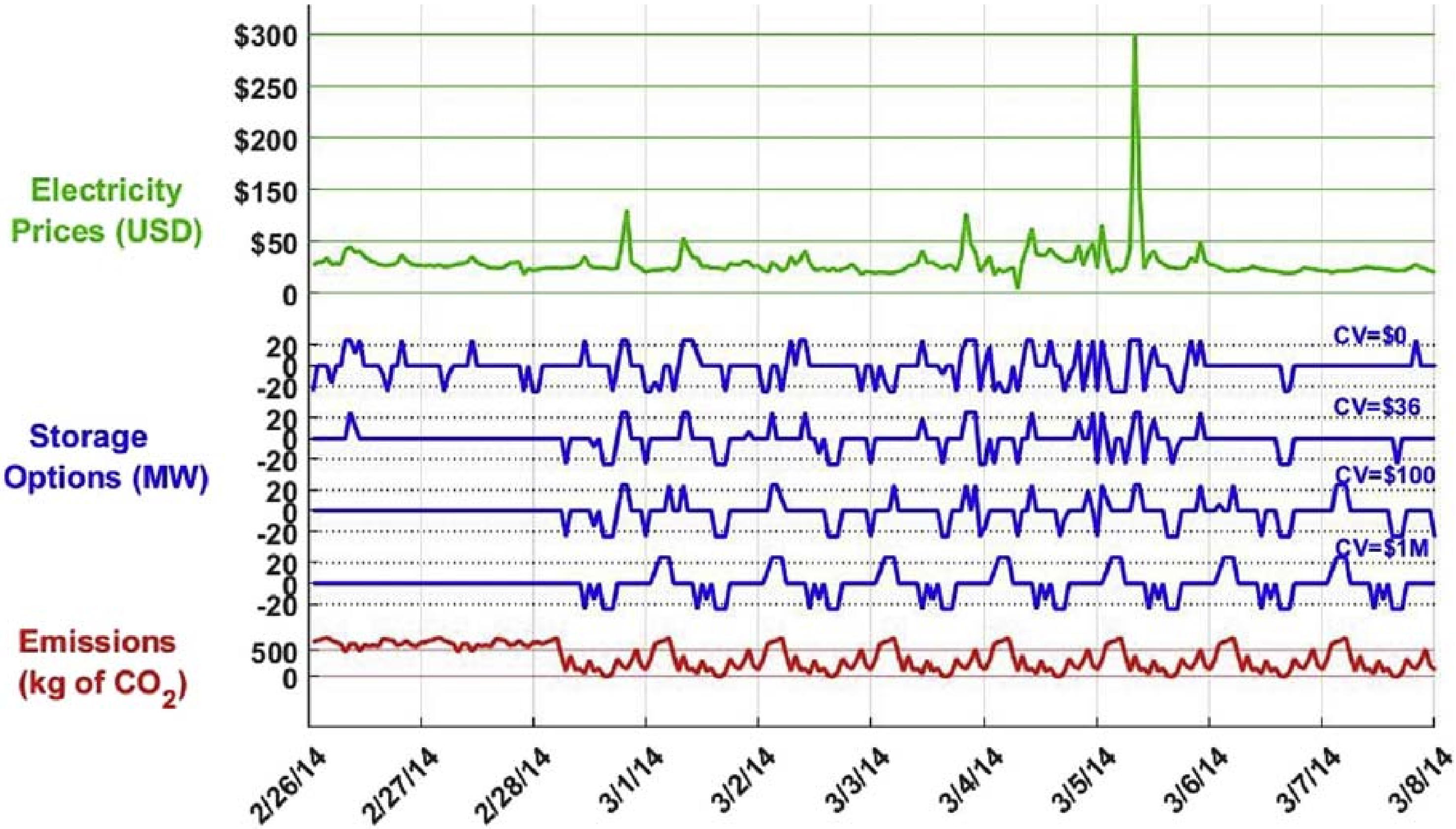
If the CA storage mandate (1.3 GW) induces more than 325 MW of additional solar, then that mandate also has emissions benefits.

If we add enough wind/solar, storage will eventually start reducing emissions. But when does that happen?

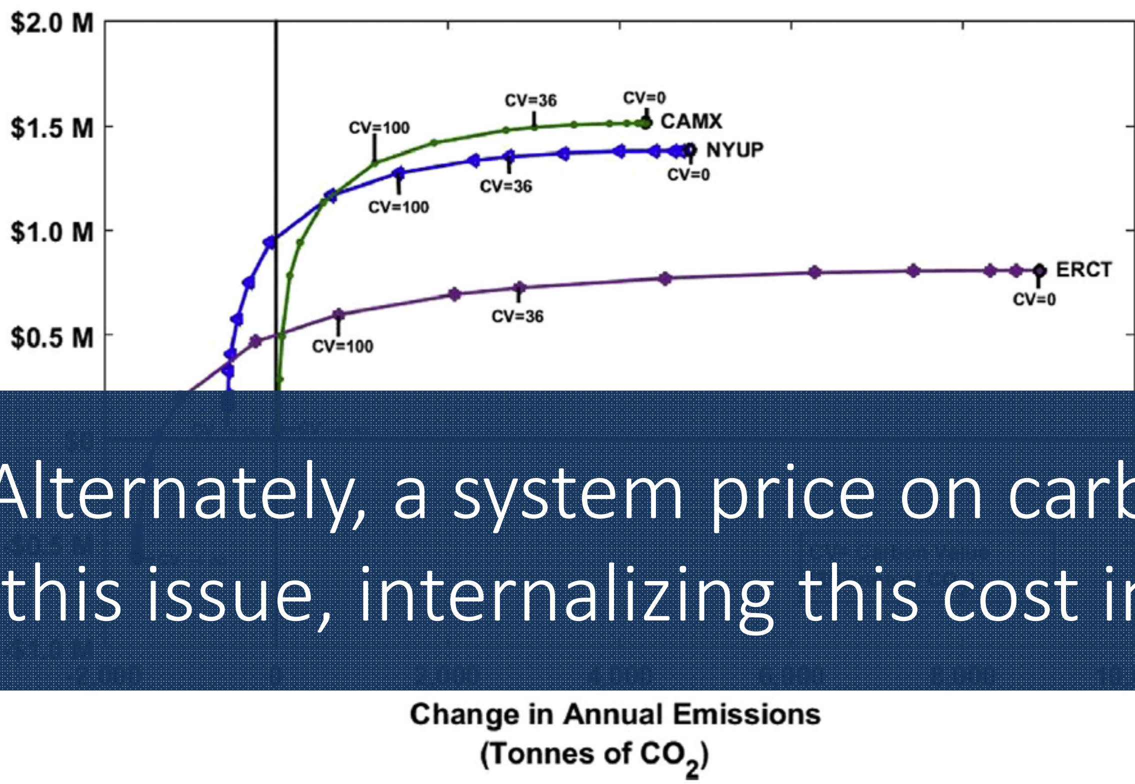


We have also done some cursory calculations for grids without much coal (CA, NE, NY): if storage can get ~5% of its charging energy from renewables that would otherwise be curtailed, then it reduces emissions

Can we eliminate the emissions effect by changing the operational strategy for storage?



By rearranging charging/discharging schedules, the emissions effect of storage can be greatly decreased with little loss of revenue



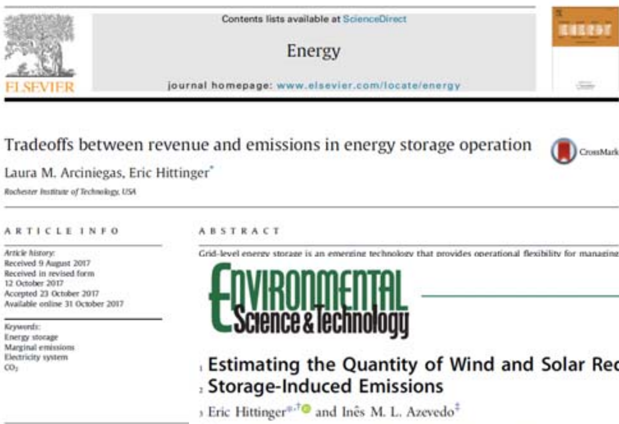
This is an effective cost of about $15/tonne to reduce storage-related emissions by 50% across the US.

Alternately, a system price on carbon would eliminate this issue, internalizing this cost in the energy prices.

What kind of technology is energy storage?

- Energy storage is a valuable technology for improving operational and economic efficiency of electricity systems.
- Energy storage provides flexibility and helps to better utilize whatever resources are available.
- Energy storage is one option among many for integrating wind/solar and achieving other electricity system goals.

For the voracious reader, we have four research papers on emissions effects of storage operation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Tradeoffs between revenue and emissions in energy storage operation

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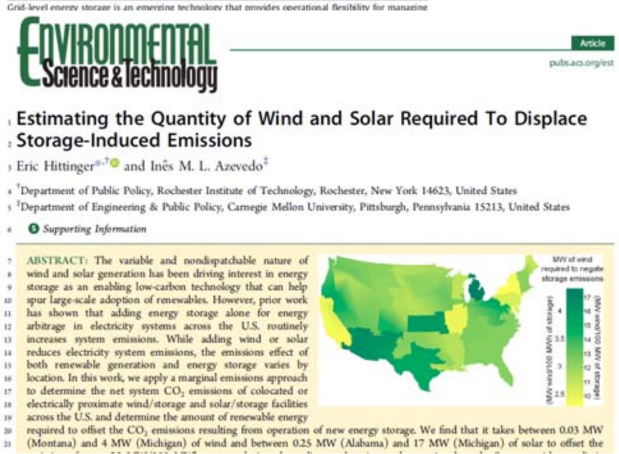
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Article

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Estimating the Quantity of Wind and Solar Required To Displace Storage-Induced Emissions

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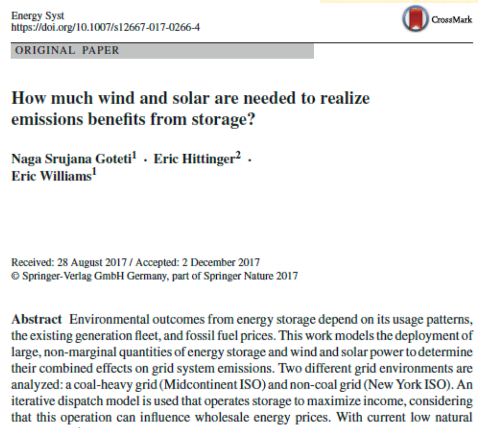
Supporting Information

ABSTRACT: The variable and nondispatchable nature of wind and solar generation has been driving interest in energy storage as an enabling low-carbon technology that can help spur large-scale adoption of renewables. However, prior work has shown that adding energy storage alone for energy arbitrage in electricity systems across the U.S. routinely increases system emissions. While adding wind or solar reduces electricity system emissions, the emissions effect of both renewable generation and energy storage varies by location. In this work, we apply a marginal emissions approach to determine the net system CO_2 emissions of colocated or electrically proximate wind/storage and solar/storage facilities across the U.S. and determine the amount of renewable energy required to offset the CO_2 emissions resulting from operation of new energy storage. We find that it takes between 0.03 MW (Montana) and 4 MW (Michigan) of wind and between 0.25 MW (Alabama) and 17 MW (Michigan) of solar to offset the


Energy Syst
https://doi.org/10.1007/s12667-017-0266-4

ORIGINAL PAPER

How much wind and solar are needed to realize emissions benefits from storage?

Naga Srujana Goteti[1] · Eric Hittinger[2] · Eric Williams[1]

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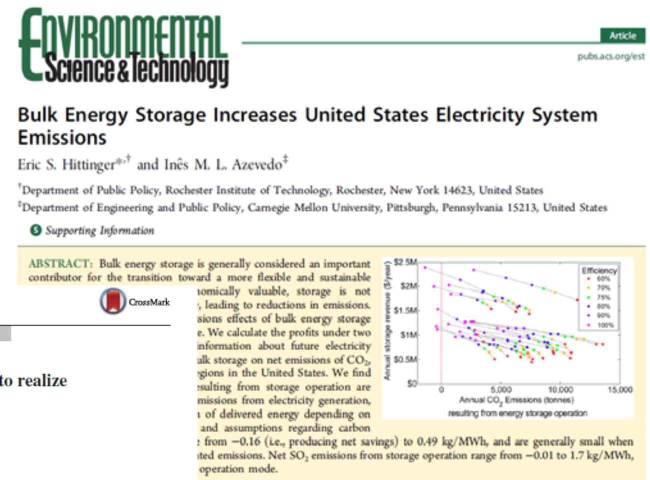
Abstract Environmental outcomes from energy storage depend on its usage patterns, the existing generation fleet, and fossil fuel prices. This work models the deployment of large, non-marginal quantities of energy storage and wind and solar power to determine their combined effects on grid system emissions. Two different grid environments are analyzed: a coal-heavy grid (Midcontinent ISO) and non-coal grid (New York ISO). An iterative dispatch model is used that operates storage to maximize income, considering that this operation can influence wholesale energy prices. With current low natural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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

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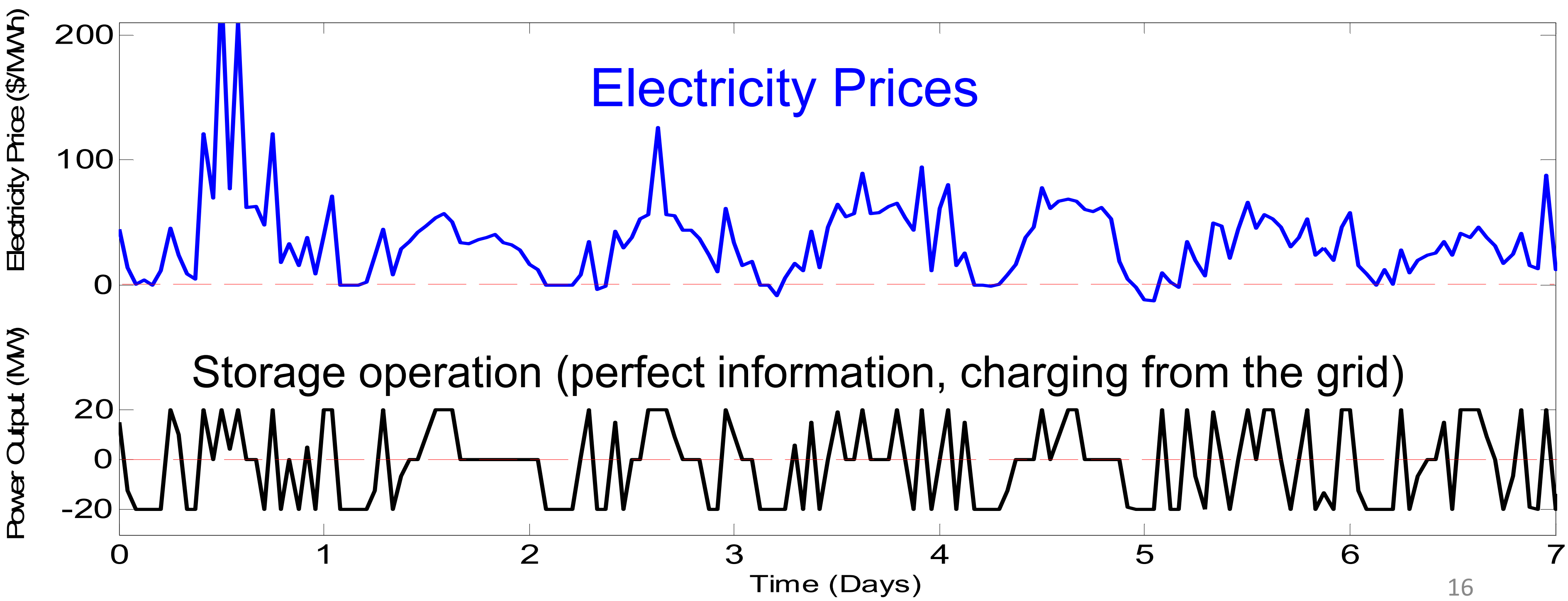
Slide appendix

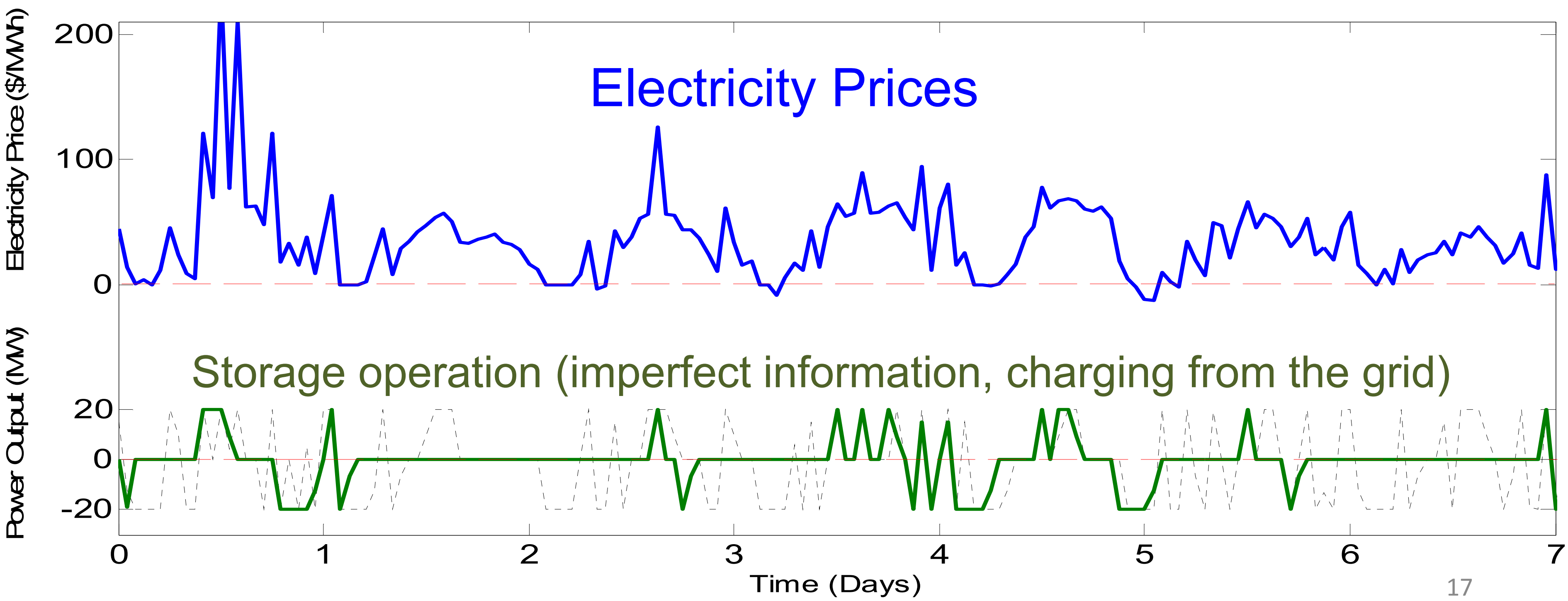
The Approach

- In each location, assume co-located renewable / energy storage system
  - Wind data from NREL Wind Integration National Dataset
  - Solar data from NREL Typical Meteorological Year 3 Dataset
  - Storage modeled as 4-hr discharge, 75% round-trip efficiency
- Using hourly market clearing price data from local or nearest market, determine the revenue-maximizing operation of storage (LP optimization)
  - Both perfect and imperfect price information
  - With and without charging limited to renewables
- Use “marginal emission factors” (MEFs) to determine the net emissions resulting from operating the storage

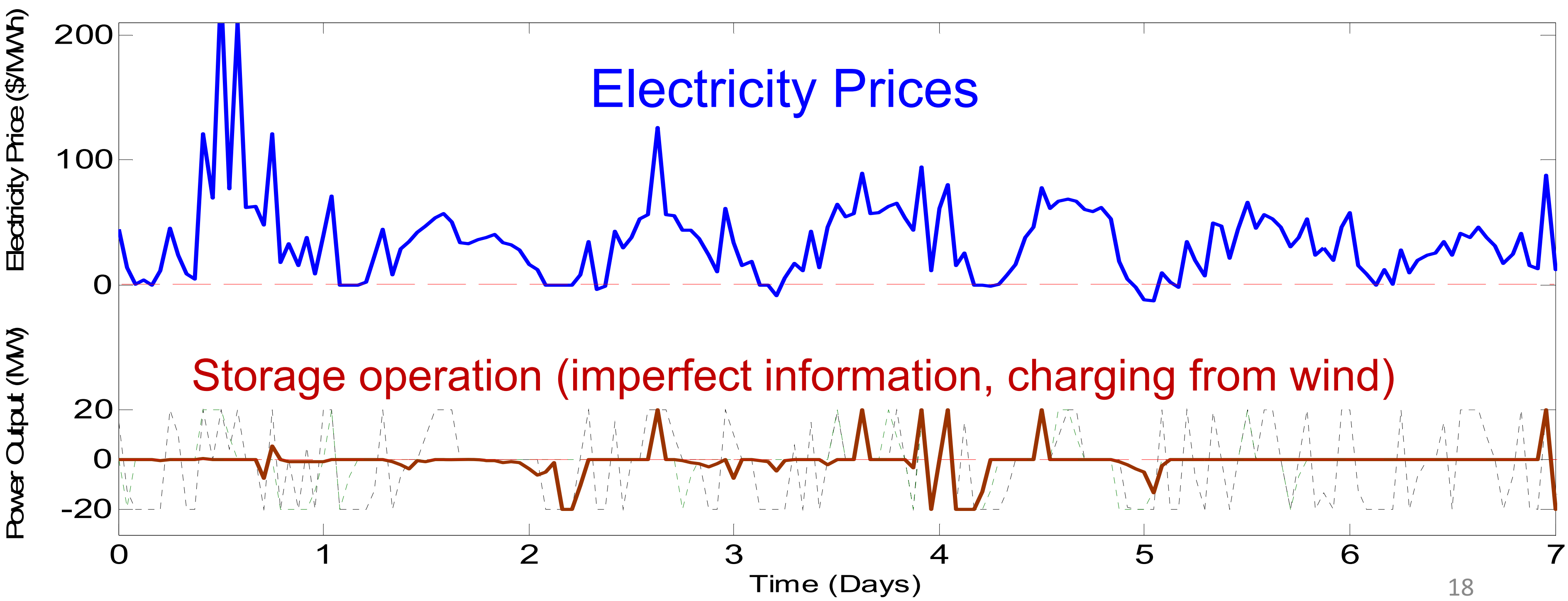
Under perfect information, storage is charging/discharging frequently, taking advantage of every price fluctuation



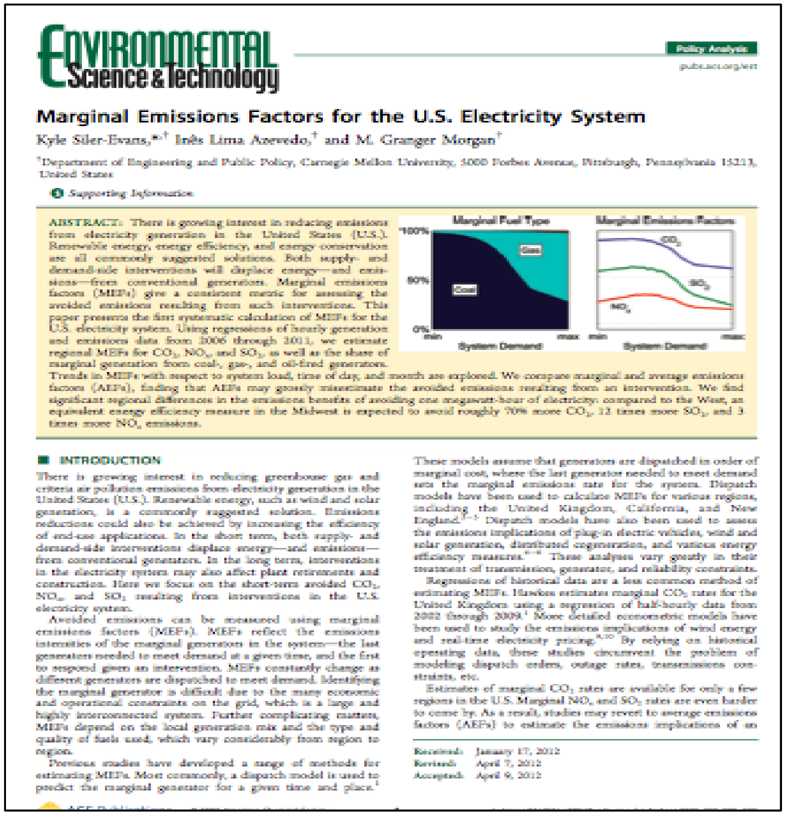
Without knowledge of future energy prices, storage is more conservative and operates less frequently



When storage is also constrained to charge only from wind/solar, this further limits its ability to cycle



Emissions effects are calculated using “Marginal Emissions Factors”



Policy Analysis

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Marginal Emissions Factors for the U.S. Electricity System

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Supporting Information

ABSTRACT: There is growing interest in reducing emissions from electricity generation in the United States (U.S.). Renewable energy, energy efficiency, and energy conservation are all commonly suggested solutions. Both supply- and demand-side interventions will displace energy—and emissions—from conventional generators. Marginal emissions factors (MEFs) give a consistent metric for assessing the avoided emissions resulting from such interventions. This paper presents the first systematic calculation of MEFs for the U.S. electricity system. Using regressions of hourly generation and emissions data from 2006 through 2011, we estimate regional MEFs for CO_2, NO_x, and SO_2, as well as the share of marginal generation from coal-, gas-, and oil-fired generators. Trends in MEFs with respect to system load, time of day, and month are explored. We compare marginal and average emissions factors (AEFs), finding that AEFs may grossly misestimate the avoided emissions resulting from an intervention. We find significant regional differences in the emissions benefits of avoiding one megawatt-hour of electricity: compared to the West, an equivalent energy efficiency measure in the Midwest is expected to avoid roughly 70% more CO_2, 12 times more SO_2, and 3 times more NO_x emissions.

INTRODUCTION

There is growing interest in reducing greenhouse gas and criteria air pollution emissions from electricity generation in the United States (U.S.). Renewable energy, such as wind and solar generation, is a commonly suggested solution. Emissions reductions could also be achieved by increasing the efficiency of end-use applications. In the short term, both supply- and demand-side interventions displace energy—and emissions—from conventional generators. In the long term, interventions in the electricity system may also affect plant retirements and construction. Here we focus on the short-term avoided CO_2, NO_x, and SO_2 resulting from interventions in the U.S. electricity system.

Avoided emissions can be measured using marginal emissions factors (MEFs). MEFs reflect the emissions intensities of the marginal generators in the system—the last generators needed to meet demand at a given time, and the first to respond given an intervention. MEFs constantly change as different generators are dispatched to meet demand. Identifying the marginal generator is difficult due to the many economic and operational constraints on the grid, which is a large and highly interconnected system. Further complicating matters, MEFs depend on the local generation mix and the type and quality of fuels used, which vary considerably from region to region.

Previous studies have developed a range of methods for estimating MEFs. Most commonly, a dispatch model is used to predict the marginal generator for a given time and place.[1] These models assume that generators are dispatched in order of marginal cost, where the last generator needed to meet demand sets the marginal emissions rate for the system. Dispatch models have been used to calculate MEFs for various regions, including the United Kingdom, California, and New England.[1-3] Dispatch models have also been used to assess the emissions implications of plug-in electric vehicles, wind and solar generation, distributed cogeneration, and various energy efficiency measures.[4-8] These analyses vary greatly in their treatment of transmission, generator, and reliability constraints.

Regressions of historical data are a less common method of estimating MEFs. Hawkes estimates marginal CO_2 rates for the United Kingdom using a regression of half-hourly data from 2002 through 2009.[1] More detailed econometric models have been used to study the emissions implications of wind energy and real-time electricity pricing.[9,10] By relying on historical operating data, these studies circumvent the problem of modeling dispatch orders, outage rates, transmissions constraints, etc.

Estimates of marginal CO_2 rates are available for only a few regions in the U.S. Marginal NO_x and SO_2 rates are even harder to come by. As a result, studies may revert to average emissions factors (AEFs) to estimate the emissions implications of an

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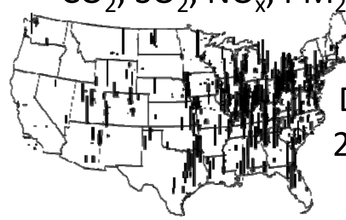
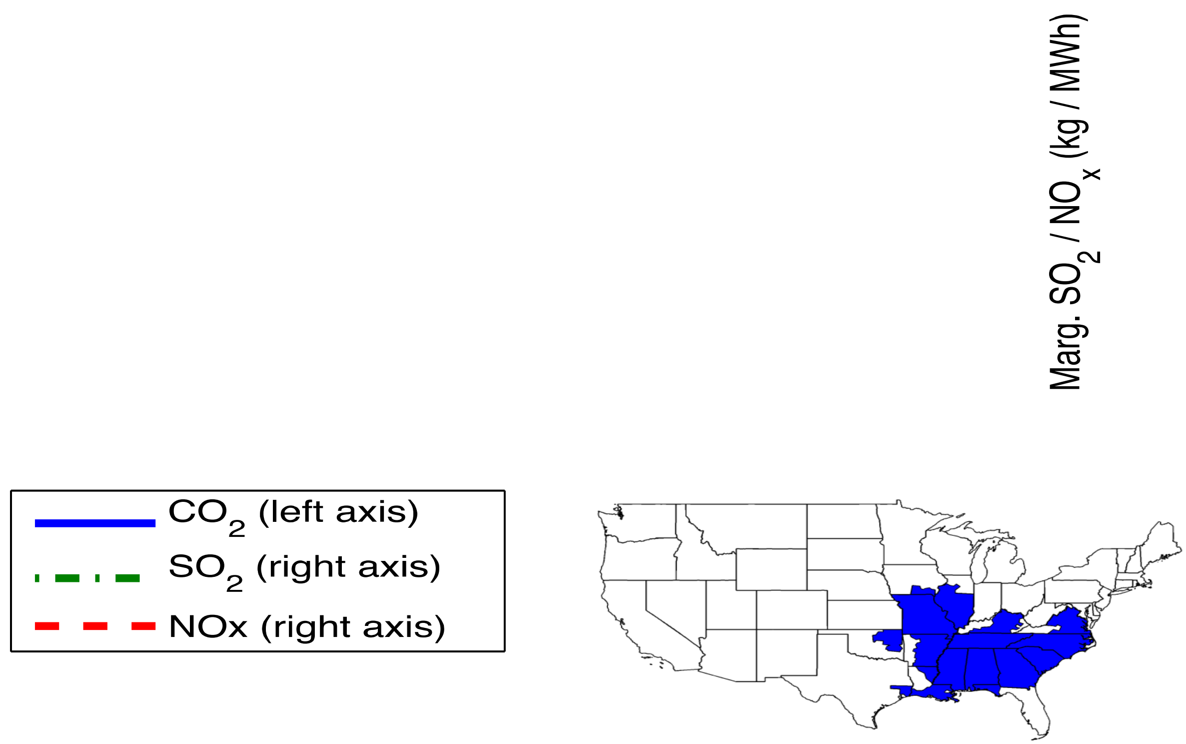
For 1400 plants: location, fuel type, stack height and hourly emissions of CO_2, SO_2, NO_x, $PM_{2.5}$

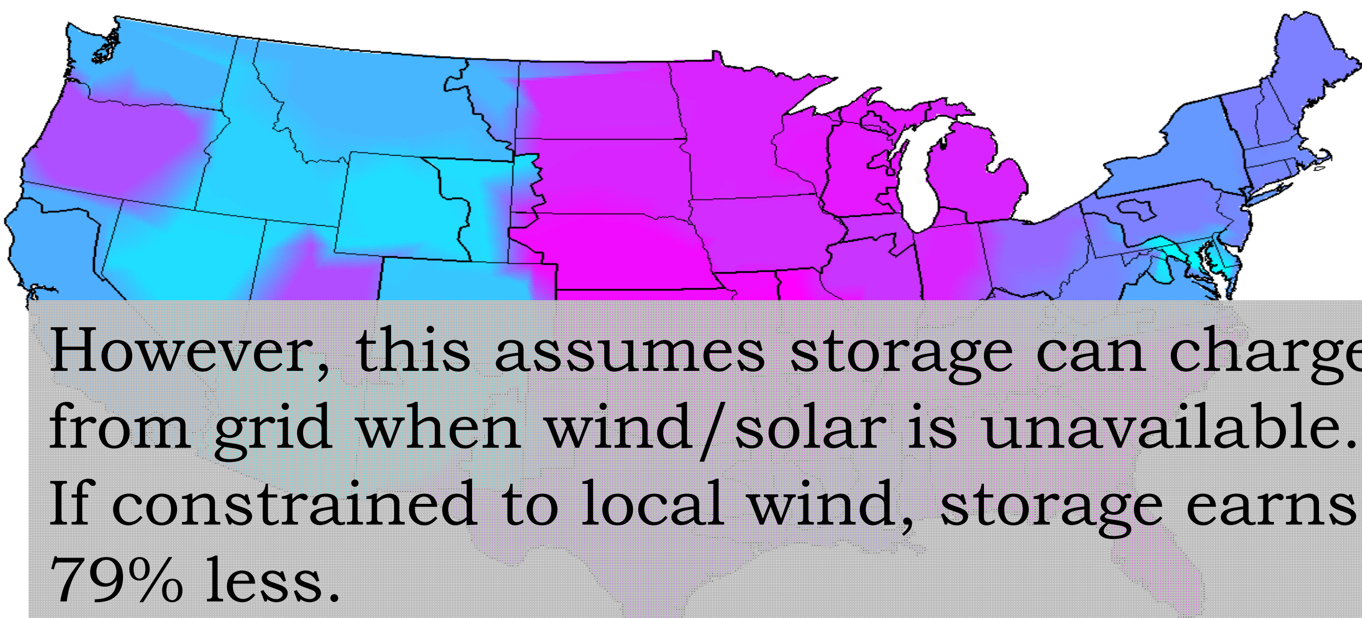


Data from: CEMS (2009-2011), eGRID (2009), NEI (2005)

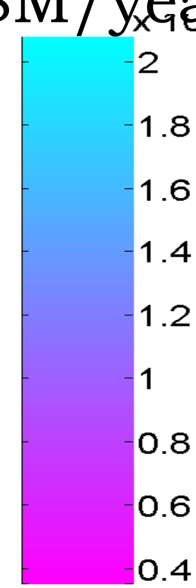


Source: Siler-Evans, Azevedo, Morgan, 2013.

Storage revenue varies as a function of electricity price variability



Storage Revenue ($M/year)



However, this assumes storage can charge from grid when wind/solar is unavailable.
If constrained to local wind, storage earns 79% less.
If constrained to local solar, storage earns 83% less.

Renewables+storage emissions: Some Good News and Some Bad News

The Approach

For each US EPA eGRID subregion:

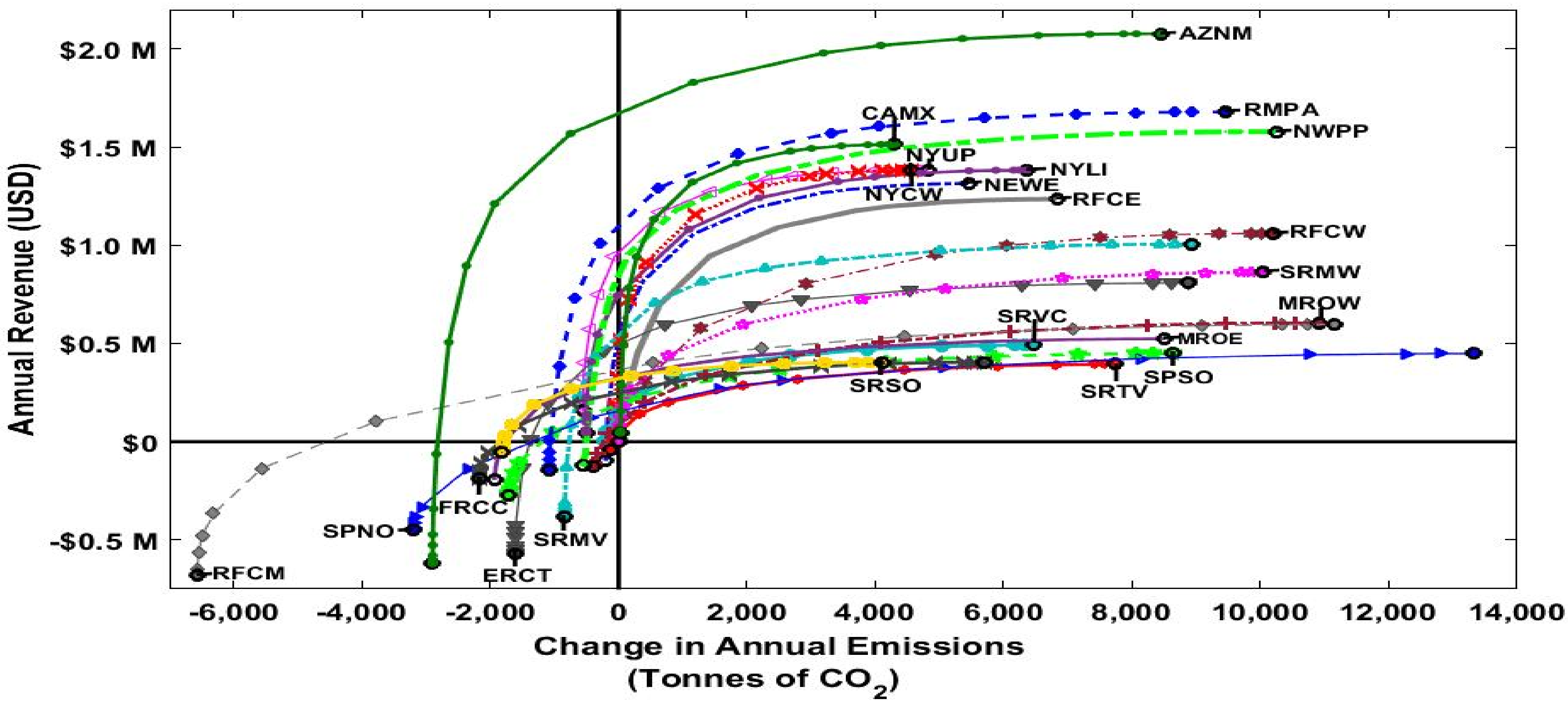
Get hourly market clearing price data[1] and time-varying marginal emissions data[2] (converted to hourly)

Use a linear programming (LP) optimization to determine optimal storage operation, at different levels of "carbon value"

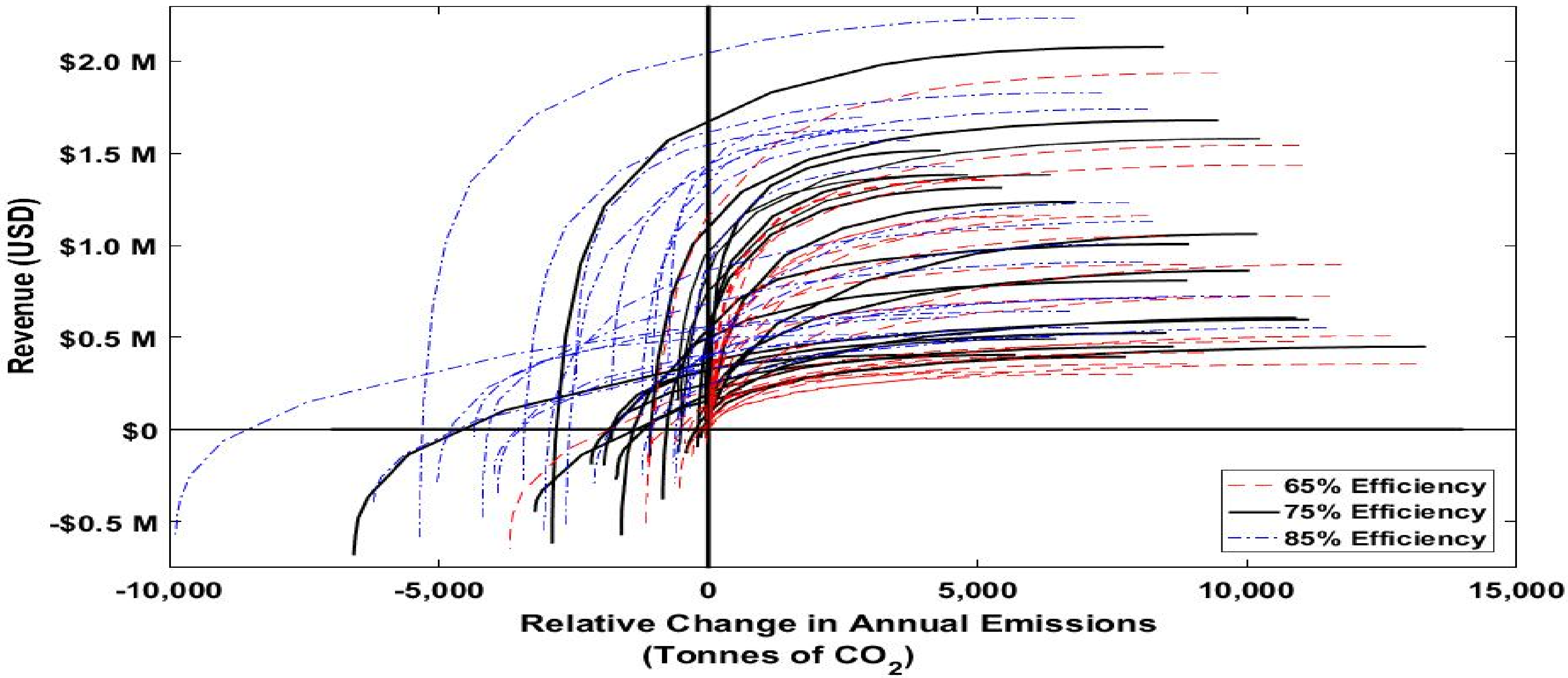
Collect and compare the net storage revenue and emissions at different locations and with different level of carbon value

1. N. C. Horner, "Powering the Information Age: Metrics, Social Cost Optimization Strategies, and Indirect Effects Related to Data Center Energy Use," Carnegie Mellon University, 2016.
2. From Carnegie Mellon: https://cedm.shinyapps.io/MarginalFactors/

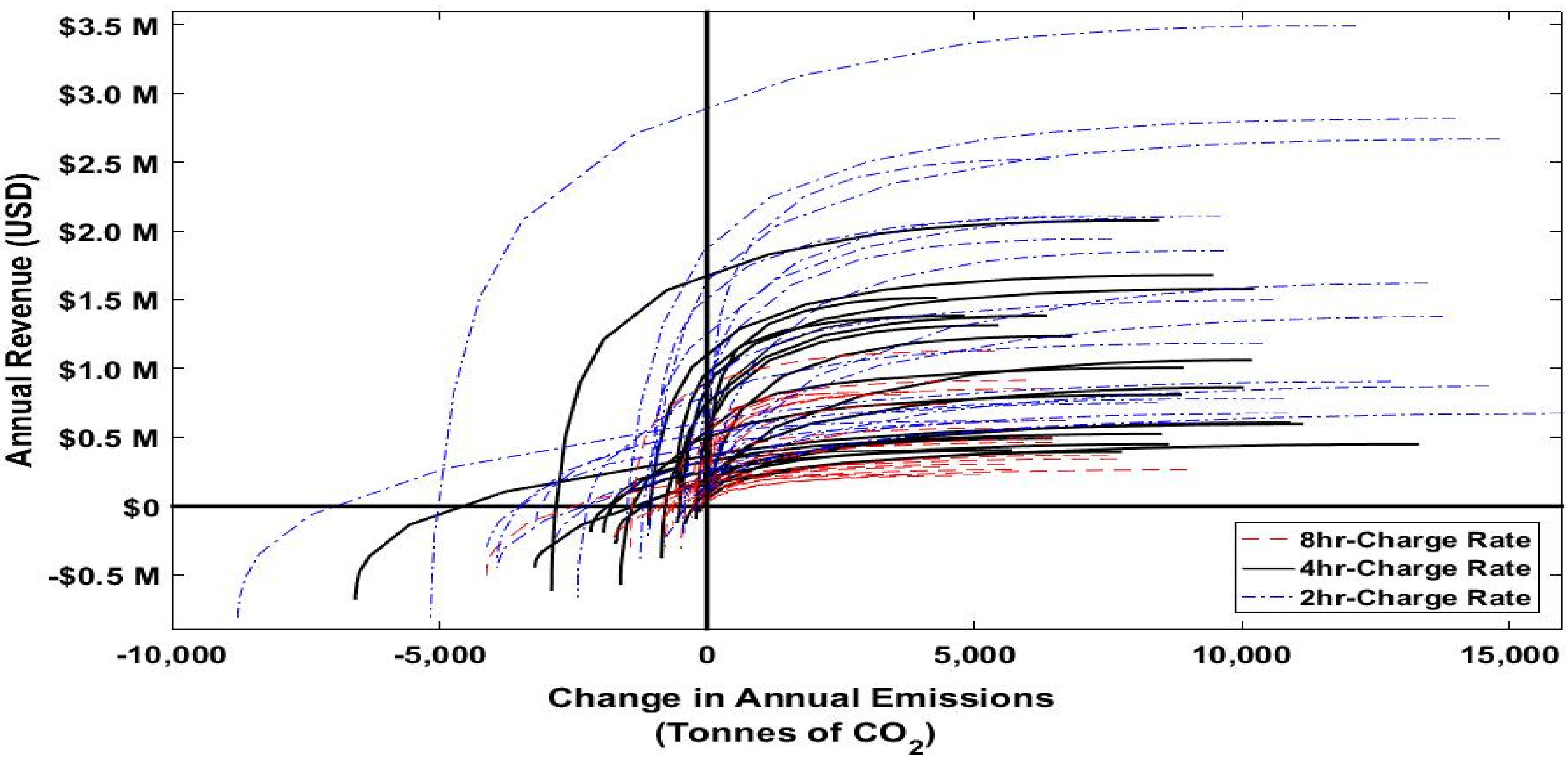
The trend is qualitatively similar across the US, though significant regional variation exists



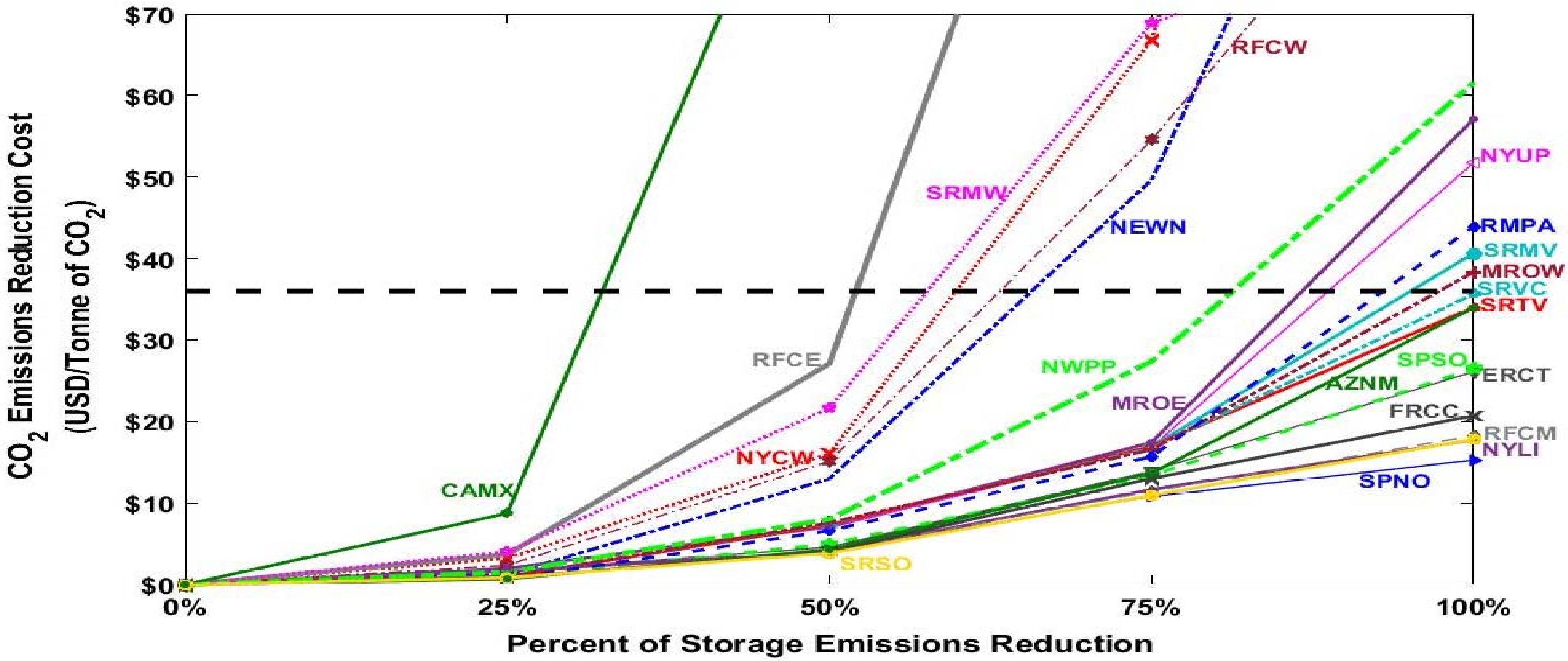
Improved storage efficiency increases revenue, but has a more beneficial effect on emissions



Improving the charge/discharge rate of storage tends to exaggerate existing revenue and emissions effects



The "cost" of emissions reductions through alternative storage operation is low



Takehome Thoughts

While profit-maximizing storage operation consistently increases US grid emissions, this is not a necessary result of storage adoption and operation.

Even without any changes to electricity system structure or operation, alternative operational patterns for storage can reduce induced emissions at a low "cost of carbon".

However, the implementation of this in policy or market rules is challenging and problematic.

Regions with significant variability in both prices and emissions can most easily reduce storage-related emissions at low cost