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Bulk Energy Storage Increases United States Electricity System Emissions

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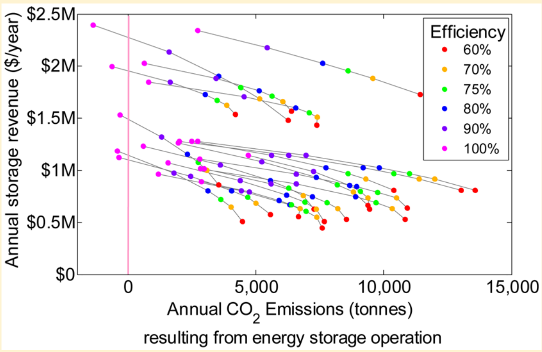
Supporting Information

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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storage tends to charge at night during off-peak hours and discharge during peak afternoon or evening periods. In many areas of the U.S., the marginal electricity generator at night is often a coal plant and the marginal generator during peak periods is a natural gas plant, meaning that storage is effectively displacing cleaner natural gas-generated electricity with coal-generated electricity. Using average emissions factors when assessing the consequences of energy storage would assume no difference between storage charging and discharging times. Second, all storage technologies experience energy losses as they store and recover energy. This inefficiency means that storage effectively loses some of the energy that it handles, requiring the system to generate extra electricity and emissions to account for these losses. These two effects hold whether storage is operated by a revenue-maximizing entity in a deregulated market or operated by a vertically integrated utility attempting to move electricity from low-demand to high-demand periods. Previous work by Siler-Evans et al.[8] provides a framework, which we use here, to characterize the marginal emissions of criteria air pollutants (SO_2, NO_x) and CO_2 that are avoided or generated as interventions are pursued for 20 of the 26 eGRID regions.

Regional Boundaries. Changes in net emissions with a marginal increase in storage are estimated for 20 eGRID regions in the U.S. Electricity systems are widely interconnected, and the emissions intensities of the grid in a particular region will depend heavily on the regional boundary. However, there is no clear choice or standard for the regional boundaries to use in assessments of displaced emissions.[9] For that reason, the Supporting Information (SI) provides a detailed sensitivity analysis, where we show the results for marginal emissions factors produced at the level of North American Electricity Reliability Corporation (NERC) regions, and compare to the base case results.

Storage Operation. We estimate the change in emissions from the operation of storage in 20 sites around the continental U.S. The net emissions from the operation of a bulk energy storage device is determined in two steps. First, the revenue-maximizing operation of storage is determined by using the nearest available hourly electricity market clearing prices. This is calculated under both perfect and imperfect information for 20 locations in the continental U.S. Second, Marginal Emissions Factors (MEFs) are applied to the hourly energy time series to determine the effective net CO_2, SO_2, and NO_x emissions related to storage plant operation.

The 20 energy storage sites are in 20 of the 26 U.S. EPA eGRID subregions[10] and are selected to be close to areas of high wind generation potential as identified through the Eastern Wind Integration and Transmission Study and the Western Wind Data set.[11] The selection of sites is also limited by the availability of nearby market price data. Alaska, Hawaii, and the southeastern U.S. are not represented because they lack native or adjacent electricity markets from which to acquire price data. 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. For example, the Pacific Northwest does not have an hourly wholesale electricity market. The prices used to determine storage operation in this region come from the northern node of the California ISO (Malin, near the Captain Jack interchange, located in southern Oregon). In the SI, we list the location and market data source for each of the 20 sites. All price data are 2012 hly prices.

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.[12] Storage is modeled using a 4-h charge rate, i.e., it will take 4 h to charge or discharge the storage unit at the maximum rate. For comparison, existing pumped hydro facilities listed in the U.S. Department of Energy Storage Database[12] have durations ranging from 4 to 298 h, with a median of 8 h. The base case storage facility is on the low end of this range because new U.S. pumped hydro facilities would tend to have smaller reservoirs due to geographical constraints,[13] and lower cost battery technologies have discharge capabilities around this value.[14] 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. The storage device has a round trip efficiency of 75%, with the inefficiency divided equally between the charge and discharge portions of the cycle.

Storage is operated only as a bulk energy time-shifting device, a service often referred to as energy arbitrage. The vast majority of existing grid energy storage is in the form of pumped hydro storage, which generally operates to provide the energy arbitrage/peak shaving service that we model.[15] Other services that a storage plant could provide, such as frequency regulation, are not included in the model and are outside the scope of this analysis. 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.

The perfect information model uses a linear programming optimization to maximize revenue within the limitations of storage operation. Equations 1−8 express the optimization objective and constraints. We use an hourly time resolution for all calculations. Prices are exogenous, and we assume storage to be a price taker.

The objective function (eq 1) is to maximize revenue over the year, where P_t and E_t are the electricity price and electrical energy delivered from storage at time t. E_t can be negative, representing the purchase of energy. The initial state of charge for the storage is 50% of maximum (eq 2). Electrical energy into or out of the storage unit is subject to inefficiency, which is divided between the charge and discharge portions of the cycle, assuming equal energy losses during both charge and discharge (eqs 3 and 4), where η_{rt} is the round-trip efficiency. More sophisticated efficiency models (based on state of charge or discharge rate) are often used,[16,17] but these rely on the modeling of a specific rather than a general storage device. S_t represents the state of charge of the storage (in units of energy), S_{max} is the maximum state of charge, and R_{max} is the maximum charge/discharge rate (in units of MW). Finally, the

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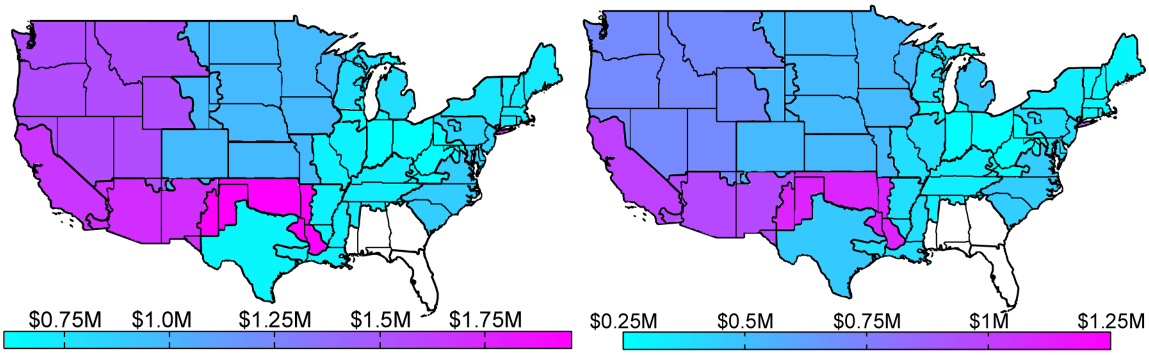

Figure 1. Annual revenue from storage operations in the U.S. under perfect information (left) and imperfect information (right). Note: There is a change in scale between maps.

storage unit has upper and lower capacity limits (eqs 5 and 6) and charge/discharge rate limits (eqs 7 and 8).

$$\max \sum P_t E_t \quad \text{such that} \tag{1}$$

$$S_1 = \frac{S_{\max}}{2} \tag{2}$$

$$S_t = S_{t-1} - \frac{E_{t-1}}{\sqrt{\eta_{\mathrm{rt}}}} \quad \text{if } E_{t-1} \geq 0 \tag{3}$$

$$S_t = S_{t-1} - \sqrt{\eta_{\mathrm{rt}}} \times E_{t-1} \quad \text{if } E_{t-1} < 0 \tag{4}$$

$$\forall\ t,\ S_t \geq 0 \tag{5}$$

$$\forall\ t,\ S_t \leq S_{\max} \tag{6}$$

$$\forall\ t,\ E_t \leq R_{\max} \tag{7}$$

$$\forall\ t,\ E_t \geq -R_{\max} \tag{8}$$

The imperfect information model uses the same storage constraints as the model described above, 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. Given the constraints described by eqs 2–8, the "sell above, buy below" algorithm follows eqs 9–11, where P_{sell} and P_{buy} are the predetermined "sell" and "buy" prices guiding the storage operation.

For all t

$$\text{if } P_t > P_{\mathrm{sell}} \text{ then } \max E_t \tag{9}$$

$$\text{if } P_t < P_{\mathrm{buy}} \text{ then } \min E_t \tag{10}$$

$$\text{otherwise } E_t = 0 \tag{11}$$

The buy and sell prices are determined for each scenario using a simulated annealing optimization that searches for revenue-maximizing values of buy and sell prices. The simulated annealing optimization follows the general algorithm described in Kirkpatrick et al.,[18] using an exponential decay for the temperature drop, and runs the storage time-series model 10 000 times per scenario. The search is relatively straightforward, having only two input variables, and the stochastic search algorithm quickly converges on a solution.

Marginal Emissions Factors. The net systems emissions resulting from storage operation are calculated using the Marginal Emissions Factor (MEF) approach from Siler-Evans et al.[8,19] MEFs (in kg of pollutant per MWh) provide the historical emissions intensities of the marginal generators in the system, i.e., the generator that needs to be ramped up or down to meet demand as the system responds to an intervention. We use the outputs from Siler-Evans et al.,[8,19] who provide systematic estimates of MEFs for 22 eGRID regions in the U.S. electricity system. That work used emissions and operation data from 1400 power plants in the U.S. to determine the emissions of the marginal generation unit in different regions of the country. They report the CO_2, SO_2, and NO_x emissions rates for the marginal generator in NERC and eGRID regions in the U.S., separated by hour and season. This approach is used to estimate emissions because it provides a good balance between an average emissions rate approach, which neglects the time dynamics and importance of marginal generators, and a sophisticated dispatch model of each individual electricity system, which would entail a significant effort that is subject to overfitting and sensitivity to assumptions, and for which a systematic representation of the entire U.S. system is not available. The MEF approach is relatively simple, data-driven, and provides time variant estimates of the emissions of marginal generators. The emissions factors used in this work were produced using 2009–2011 emissions data, and are separated into 24 h of operation in three different seasons (summer, winter, and intermediate). In the sensitivity analysis we discuss the implications of using these MEF estimates versus other estimates.

The raw emissions data used in the analysis are from EPA's Continuous Emissions Monitoring System (CEMS), which reports hourly emissions of SO_2, NO_x and CO_2 for every U.S. fossil fuel power plant with capacity more than 25 MW. CEMS does not report $PM_{2.5}$, PM_{10}, or mercury emissions, and hourly emissions data for PM and mercury are currently unavailable. Thus, we present results only for CO_2, SO_2, and NO_x.

Computation of Hourly Emissions Changes for Criteria Air Pollutants and Greenhouse Gas Emissions. We use the hourly energy storage charge/discharge time series, which is produced by the storage operation model, and the hourly/seasonal MEF values for each of the examined eGRID subregions to calculate the emissions displacement of a storage device in each hour of the year. In hours when the storage is charging, this increased demand requires an increase in electricity generation and emissions from a marginal generator, while discharge of storage results in reduced generation and

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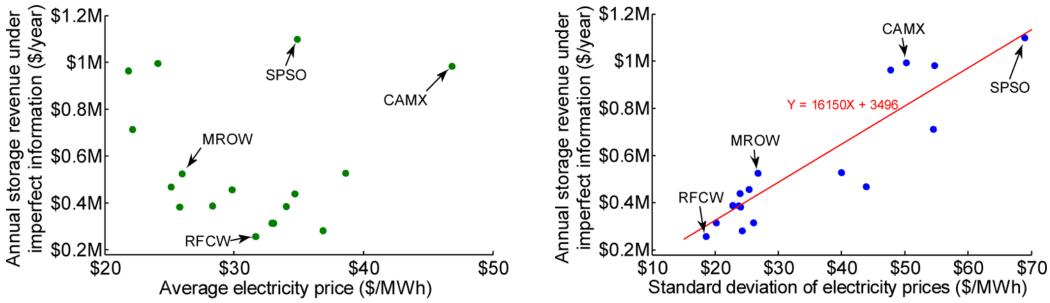

Figure 2. Annual revenue from storage operations versus average (left) and standard deviation (right) of nodal prices at each of the 20 locations, under imperfect information. Because storage both buys and sells electricity, annual revenue is related to variability of electricity prices rather than average prices. Four points are highlighted: RFCW (Ohio), MROW (Minnesota), CAMX (California), and SPSO (West Texas).

emissions. The net system emissions from bulk storage operation are the sum of these increased and displaced emissions over the year. Equation 12 shows how the total emissions are calculated, where $M_{\text{annual, pollutant}}$ is the total annual emissions due to a certain pollutant, E_t is the energy delivered from storage at time t, and $\text{MEF}_{\text{tod, season, pollutant}}$ is the marginal emissions factor for the pollutant during this season and hour in the day. Net emissions are reported as both total emissions from storage and normalized to the delivered energy from the storage device.

$$M_{\text{annual,pollutant}} = \sum_t (-E_t \times \text{MEF}_{\text{tod,season,pollutant}}) \quad (12)$$

■ RESULTS

Storage Revenue Across Locations under Perfect and Imperfect Information. Under perfect information, annual revenue ranged from \$1.95 M in SPSO (West Texas) to \$0.60 M in RFCW (Ohio) (Figure 1, left). Under imperfect information, annual revenue followed the same geographic distribution at a lower magnitude, ranging from \$1.10 M in SPSO (West Texas) to \$0.26 M in RFCW (Ohio) (Figure 1, right). Operating under imperfect information yields between 39% and 70% (mean: 52%) less revenue than perfect information. These significant differences are due to the perfect information model's ability to take advantage of both large spikes and minor variations in price. With perfect knowledge of future electricity prices, the storage device can take advantage of even smaller fluctuations in price and cycles more frequently than in the imperfect information case.

Bulk energy storage providing energy arbitrage is known to be an application that has a large potential market but very low revenue rates.[20,21] Our results confirm that 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 perfect information (\$0.6 to \$1.95 M), the breakeven capital costs of storage range from \$70/kWh to \$225/kWh. These costs are low for existing energy storage devices and only achievable with large pumped hydro or compressed air systems, which are the technologies currently providing this service.[14]

Differences in revenue from storage are mainly driven by variability in prices across different regions. As an illustration, Figure 2 shows the average and standard deviation of hourly 2012 electricity prices plotted against the annual revenue (under imperfect information) for a storage device in each location. Revenues from storage operation are higher in regions where nodal prices are more variable and show no relationship with average electricity prices. In areas with relatively flat prices, such as the Midwest, the revenue generated by storage is lower. In several figures, including Figure 2, we highlight four regions of interest: CAMX, which covers most of California and has the first energy storage mandate in the U.S.; SPSO, which covers West Texas and Oklahoma and demonstrates the highest revenue for storage in most scenarios; MROW, which includes Minnesota, Iowa, Nebraska, and the Dakotas and has the highest storage-related emissions in most scenarios; and RFCW, which includes Indiana, Ohio, West Virginia, and portions of neighboring states and has the lowest revenue and generally high emissions in most scenarios.

Despite the variation in potential revenue, the operation of the storage device is similar across locations. Figure 3 shows the average daily power output of the storage device at the 20 studied locations. This figure illustrates the expected pattern of discharge during the day and charging at night. This illustrates that the general pattern of storage operation is not sensitive to the location of the price data used to generate it.

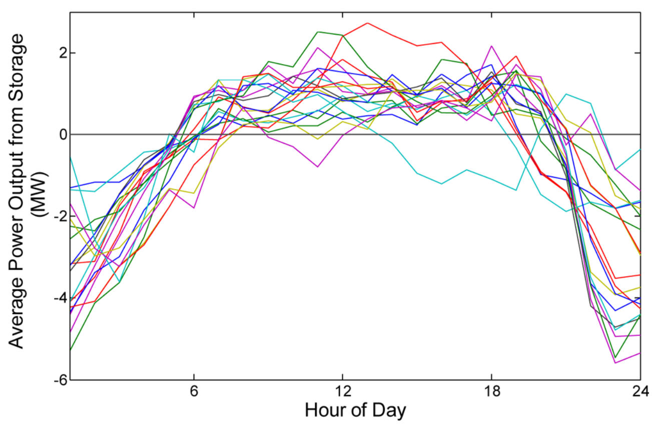

Figure 3. Average daily power output from storage device at the 20 studied locations, under perfect information. Each line shows the average daily charge/discharge pattern for a single location. Each data point is the average for that hour over the year 2012. Positive values represent discharge, and negative values represent charging of the storage.

Net Emissions Resulting from Storage Operation. Figure 4 shows the base-case results for net CO_2, NO_x, and SO_2 emissions for 20 eGRID subregions in the U.S., under both perfect and imperfect information models. Emissions are expressed in units of kg per MWh of delivered energy from

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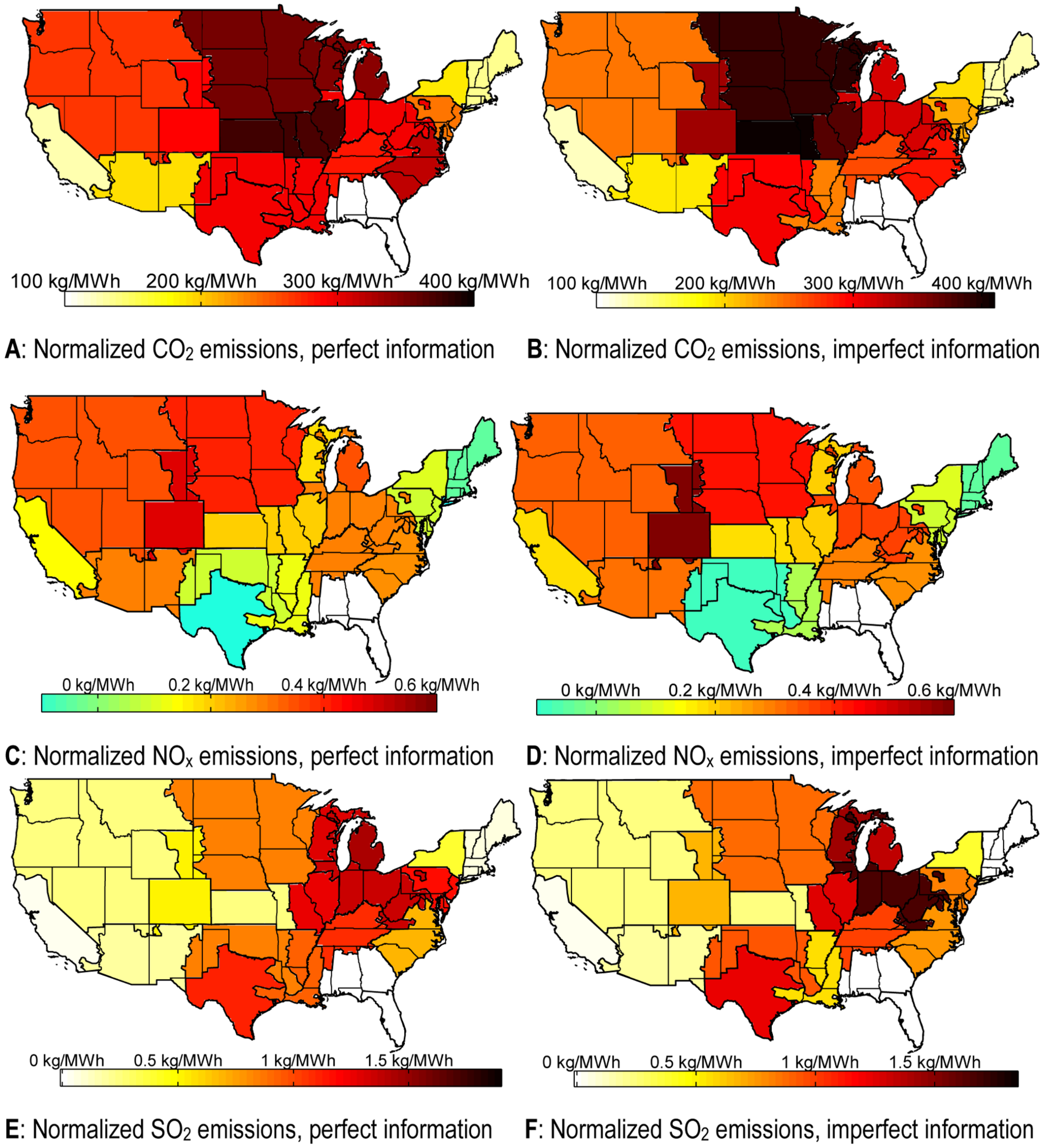

Figure 4. (A) Net CO_2 emissions resulting from the operation of a storage device in 20 eGRID subregions of the U.S., using the perfect information model. (B) Net CO_2 emissions resulting from the operation of a storage device in 20 eGRID subregions of the U.S., using the imperfect information model. (C) Net NO_x emissions resulting from the operation of a storage device in 20 eGRID subregions of the U.S., using the perfect information model. (D) Net NO_x emissions resulting from the operation of a storage device in 20 eGRID subregions of the U.S., using the imperfect information model. (E) Net SO_2 emissions resulting from the operation of a storage device in 20 eGRID subregions of the U.S., using the perfect information model. (F) Net SO_2 emissions resulting from the operation of a storage device in 20 eGRID subregions of the U.S., using the imperfect information model. All emissions are expressed in units of kg per MWh of delivered electricity. There are no data for SRSO (Mississippi and Georgia) or FRCC (Florida); those areas are shown as white.

the storage device. These units are used to facilitate comparison to emissions from electricity generation. Similar figures showing total annual emissions across the U.S., along with tables of the numerical results, are provided in the SI.

The net CO_2 emissions resulting from the operation of a storage device varies between 104 (in NYCW) and 373 kg/MWh (in SPNO) under perfect information (Figure 4A), and between 113 (in NYCW) and 407 kg/MWh (in SPNO) using the imperfect information model (Figure 4B). The average net CO_2 emission rate across the 20 locations is 262 kg/MWh under perfect information and 264 kg/MWh under imperfect information. The estimates of total annual emissions resulting from operating a storage device have a larger range, from 550 tonnes/yr (in NEWE) to 4090 tonnes/yr (in RFCM), using imperfect information. This larger range is caused by variation in total delivered energy across locations.

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Net NO_x emissions vary between −0.16 (in NYLI) and 0.49 kg/MWh (in RMPA) under perfect information and −0.09 (in ERCT) to 0.59 kg/MWh (in RMPA) under imperfect information. Average net NO_x emissions are 0.17 kg/MWh under perfect information and 0.18 kg/MWh using the imperfect information model. Total annual NO_x emissions resulting from (imperfect information) storage operation range from −750 (in ERCT) to 4800 kg/yr (in RMPA). In several regions (Texas, New England, Long Island), operating storage results in negative net NO_x emissions. This occurs in regions where the marginal off-peak generator has lower NO_x emissions than the marginal peaking plant. NO_x emissions are most damaging in the summer, so seasonality of these emissions is important. Seasonal NO_x emissions results are presented in the SI.

Net SO_2 emissions range from −0.01 (in NYCW) to 1.4 kg/MWh (in RFCM) under perfect information and from −0.03 (in NEWE) to 1.7 kg/MWh (in RFCW) using imperfect information. Average net SO_2 emissions are 0.69 kg/MWh under perfect information and 0.68 kg/MWh under imperfect information. Annual net SO_2 emissions vary between −150 (in NEWE) and 17 000 kg/yr (in RFCM), under imperfect information. As with NO_x emissions, some regions have zero or slightly negative net SO_2 emissions, due to lower SO_2 emissions from marginal off-peak generators.

Sensitivity Analysis. The results above are for base-case assumptions for the storage unit. In this sensitivity analysis, we investigate how changes in round-trip efficiency and energy capacity of the storage unit affect operation, revenue, and net system emissions. We also investigate how assumptions regarding the emissions factors affect the net system emissions in the SI.

Increasing the round-trip efficiency (RTE) of the storage unit allows the storage to profitably arbitrage electrical energy over smaller price differences. Figure 5 shows 3 days of power

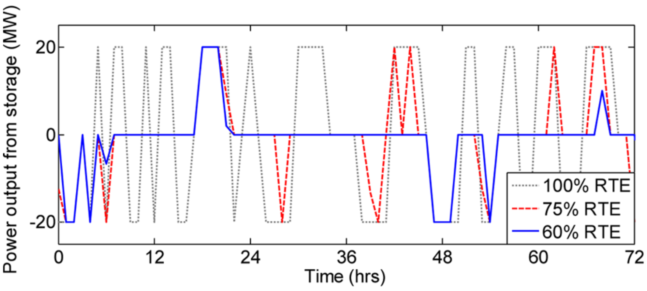

Figure 5. Hourly power delivered from an example storage unit (in New England, imperfect information) over 3 days, at three different round-trip efficiency values. As storage efficiency is increased, the storage operates more frequently.

output from an example storage unit at three different RTE values, under imperfect information. In all three cases, the storage tends to charge at night and discharge in the evening. But increasing the efficiency increases the total amount of charging and discharging of the storage unit. At 100% RTE, the storage is almost always either charging or discharging.

As the storage RTE is increased, the delivered electrical energy from storage increases significantly. But, because the storage is pursuing smaller price differentials with the additional cycling, the revenue increases by a smaller margin. For operation under imperfect information, going from 60% to 100% RTE increases the delivered electricity from storage an average of 191% across the 20 locations, but only increases revenue by an average of 44%.

Improving the round-trip efficiency of the storage unit has a strong influence on overall CO_2 emissions (Figure 6).

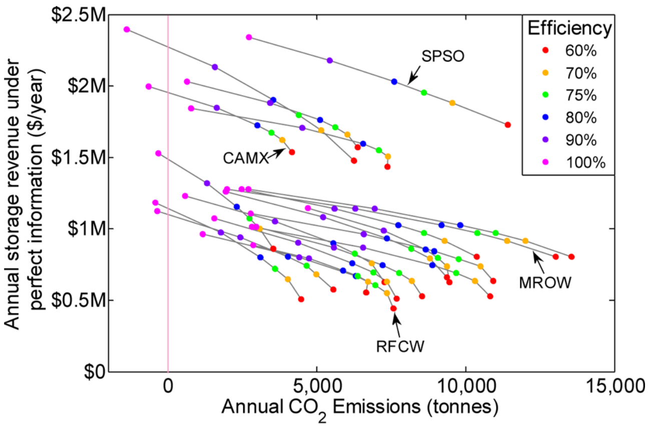

Figure 6. Net annual CO_2 emissions versus storage revenue at different round-trip efficiencies for storage (perfect information). Positive values mean that emissions increase with the addition of storage. Storage is modeled under base-case assumptions except for round-trip efficiency which is varied from the base value of 75%. As efficiency is increased, revenue increases and emissions decrease substantially. Each line represents one of the 20 investigated locations. Four locations are highlighted: RFCW (Ohio), MROW (Minnesota), CAMX (California), and SPSO (West Texas).

However, even at a RTE of 100%, most regions will see an increase in emissions from storage operation used for price arbitrage under a profit maximization framework. Going from 60% to 100% RTE decreases net emissions from storage operation from an average of 8200 to 1500 tonnes/yr, with some locations experiencing negative net emissions at 100% RTE. These locations are subregions where the marginal off-peak generator has lower emissions than the marginal peak generator (for example, combined cycle natural gas turbines displacing peaker natural gas turbines). The same trends are observed under imperfect information and when looking at normalized instead of annual emissions (figures provided in the SI).

■ DISCUSSION

Grid energy storage provides many valuable services, such as reliability, fast-responding frequency regulation, and the ability to integrate renewables. Though energy storage technologies do not directly produce emissions during their operation, the addition of new bulk storage devices can shift the operation of existing generation resources and cause changes in system emissions. The results presented in this paper show that the addition of a marginal energy storage unit performing energy arbitrage in the U.S. will increase system emissions of the existing generation fleet, assuming economics and emissions patterns similar to those of the 2010−2012 time period.

The net system emissions resulting from storage operation are nontrivial when compared to the emissions from electricity generation. Under base-case assumptions, net CO_2 emissions resulting from the operation of a storage device varies between 104 and 407 kg/MWh (mean: 264 kg/MWh) of delivered energy depending on location and operational mode for the storage device. These values are the same order of magnitude as

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the emissions rates from producing electricity: approximately 500 kg/MWh for U.S. natural gas plants and 950 kg/MWh for U.S. coal plants.[22]

For NO_x, net emissions range from −0.16 to 0.49 kg/MWh (mean: 0.18 kg/MWh). These values are small compared with average generation-related emissions of 2.5 kg/MWh for coal plants and 1.2 kg/MWh for natural gas plants. SO_2 emissions are more comparable to those of fossil fuel generation: we find that SO_2 emissions range from −0.01 to 1.7 kg/MWh (mean: 0.68 kg/MWh), which is less than U.S. coal plant emissions (6 kg/MWh), but of the same magnitude as U.S. natural gas emissions (0.25 kg/MWh).

In the eastern U.S., NO_x and SO_2 are regulated under cap-and-trade programs, suggesting that total emissions are fixed at the cap. However, in recent years, due to policy uncertainty, the allowance prices have been extremely low, which leads to a nonbinding cap.[23,24] If pollution caps are binding, total emissions from the power sector will remain fixed: in that case the operation of the storage could affect the "tightness" of the cap, putting upward pressure on emissions prices. If storage were operated in a revenue maximizing way and increased local emissions, an equivalent amount would need to be decreased elsewhere.

The results that we present are calculated for a marginal additional storage unit operating in an electricity grid with similar generation resources as the current system. However, we believe that the general conclusions will hold for both more significant deployments of storage and moderate changes in the generation mix. Adding significant amounts of bulk energy storage to a system would tend to flatten out electricity prices, reward baseload and low-marginal cost generators, and cause difficulty for peaking plants. This would tend to decrease the total amount of natural gas generation, at least from single-cycle turbines, and increase utilization of baseload resources. Whereas this situation would improve the economics of wind power, it also improves the economics of baseload coal plants and disincentivizes natural gas generation. However, given lower natural gas prices, increasing usage of grid storage may find relatively efficient combined cycle gas plants as the marginal off-peak generator, which would tend to reverse the trend we observe. The effects that large quantities of bulk storage would have on generator dispatch are uncertain, though storage inefficiency demands that off-peak generators have 25% fewer emissions than peak generation to observe overall emissions reductions.

Improving the efficiency of the storage unit consistently decreases the net emissions resulting from storage operation (both total and normalized—though the storage operation would still lead to increased emissions over a no-storage scenario), but has a smaller effect on revenue to the storage owner. This suggests that the social value of increased efficiency of bulk storage may be nontrivial relative to the direct benefit to the storage operator. For example, when averaged across the 20 locations, improving the round-trip efficiency of the storage unit from 70% to 80% decreases annual CO_2 emissions by 600 tonnes/yr, NO_x emissions by 650 kg/yr, SO_2 emissions by 1000 kg/yr, and increases revenue by \$50,000/yr. Assuming emissions damages of \$25/tonne for CO_2, \$5000/tonne for NO_x, and \$35,000/tonne for SO_2,[25] the social value of the emissions reduction from this efficiency improvement is \$53,000/yr. This is the same order of magnitude as the direct benefit to the owner, and may be large enough to warrant policies that promote the use of more efficient grid-level storage. Furthermore, addition of bulk storage will have other unaccounted benefits, such as reducing line losses, which are highest during peak electricity periods.[26]

In our analysis, we do not include direct emissions of $PM_{2.5}$. The data sources for $PM_{2.5}$ report emissions on an annual basis only (i.e., in the National Emission Inventory, or NEI). To use proxies of emissions on an hourly basis to account for variability of emissions, one could use a strategy similar to what we have done in Siler-Evans et al.,[8,19] where $PM_{2.5}$ are assumed to be correlated with gross power production. However, since direct $PM_{2.5}$ emissions constitute a small contribution to overall health and environmental damages,[19] and because of the strong assumptions necessary to downscale the emissions to an hourly basis, we decided to not include these in the analysis. Similarly, mercury emissions are only available in national annual inventories, and thus are not included in the analysis. These are important data gaps worth mentioning: while some years back the eGRID data set reported mercury emissions, these have not been reported in recent years. Annual emissions of mercury from power plants are reported in NEI.

Our work in this paper focuses on estimating emissions from storage operation. However, for policy and for decision-making, the consequences of those emissions in terms of health and environmental effects have to be assessed. Future work should estimate the health and environmental effects associated with storage operations, including PM2.5 and mercury emissions (and how these are likely to change as changes in grid operations and infrastructure occur).

In the coming years, the U.S. electricity grid will likely see increased natural gas and wind generation along with a slow and steady decline in coal generation,[27] which would decrease total emissions. However, our results are dependent on the emissions of marginal rather than average generators. To see a notable change in these conclusions would require a situation where the marginal off-peak generator has significantly lower emissions than the marginal peaking plant. This may occur with increased use of combined-cycle natural gas generators for baseload or, in the long term, eventual replacement of coal with wind, hydro, or nuclear as the marginal off-peak generator. Alternately, a change in relative marginal emissions may result from the EPA's Clean Power Plan Proposed Rule, which would require a reduction in CO_2 emissions from existing power plants.[28] Although the effects of adding bulk energy storage may eventually diverge from our estimates, policy makers and grid operators should be cognizant of the issues raised by this work when considering the value of additional grid energy storage.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Annualized net emissions resulting from storage operation, extended sensitivity analysis, list of the locations and price data used in this work, and results under NERC region-level MEFs. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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