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

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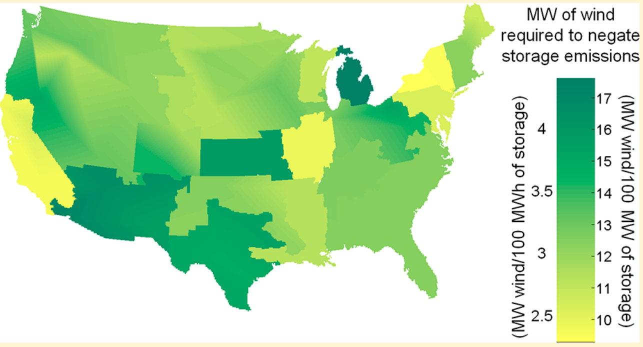
Supporting Information

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 emissions from a 25 MW/100 MWh storage device, depending on location and operational mode. Systems with a realistic combination of renewables and storage will result in net emissions reductions compared with a grid without those systems, but the anticipated reductions are lower than a renewable-only addition.



BACKGROUND

Energy storage is often included in the portfolio of technologies that are needed for deep decarbonization. For example, the Obama Administration's White House report on "United States Mid-Century Strategy for Deep Decarbonization" stated that "on the supply side, energy storage technologies (e.g., batteries, pumped hydropower, compressed-air energy) enable electricity to be generated now and used later, and upgrades in our transmission networks enable larger amounts of electricity to be moved over longer distances".[1] Energy storage may have the potential to reduce emissions when deployed in coordination with renewables, such as wind and solar. Implementing a large-scale deployment of stationary energy storage to accommodate renewable generation is a discussion point in both the renewable energy and energy storage industries, as illustrated through use of the terms like "renewable energy storage".[2] The existence of a robust energy storage industry to complement renewables will likely be critical in the near future and has attracted policy attention, prompting Congressional interest in energy storage tax credits through the proposed Storage Technology for Renewable and Green Energy Act.[3] In 2010, the California Senate passed AB2514 directing the California Public Utilities Commission (CPUC) to determine appropriate requirements for grid energy storage,[4] leading to a mandate that the three major investor-owned utilities in California must collectively add 1.3 GW of storage by 2020.[5] In 2017, Maryland passed a bill to provide tax credits for up to 30% of the cost of residential and commercial storage systems.[6] In each of these policies, environmental benefits were used as an argument in favor of government support for energy storage.

We use the term "bulk energy storage" to refer to large-scale energy storage that charges and discharges over the course of hours, normally located at the transmission level. These high-energy, lower-power storage technologies include pumped hydro, compressed-air energy storage, and some types of chemical energy storage. Bulk energy storage is indeed a complement to renewable energy, enabling increased penetration of wind or solar generation. However, analysis and policy mechanisms often ignore the fact that storage is not a "green" or "renewable" technology per se. The production of energy storage has an environmental footprint, though this has been estimated by Arbabzadeh et al.[7] to be small compared with the operation phase for most energy services. The overall emissions effects of storage operation will depend on which type of generation is used to charge the storage units and which type of generation is being avoided when storage is used.[8,9] In the U.S. electricity system, the addition of bulk energy storage for time-shifting of

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energy will, all else being equal, likely increase system emissions as a result of two effects: first, by enabling greater use of higher-emissions baseload resources to displace cleaner peaking plants (e.g., coal generation displacing natural gas generation), and second, by requiring greater total electricity generation because of losses in the energy storage. In previous work,[8] we showed that the deployment of bulk energy storage tends to increase electricity system emissions of CO_2, NO_x, and SO_2 in most regions across the U.S. Others have come to similar conclusions in research that uses alternative methods or a more focused geographic scope. For example, Fares and Webber[10] assessed the effects of distributed residential photovoltaic coupled with Li-ion battery storage to minimize reliance on utility electricity for 99 homes in Austin, Texas, and also found an overall increase in emissions of CO_2, NO_x, and SO_2. Lin et al.[11] modeled emissions changes due to storage under different grid configurations in IEEE nine- and 30-bus systems using a dispatch model and concluded that net emissions from additional storage increase when nonflexible, high-emission systems provide base load and flexible, low-emission systems meet peak load.

Despite the potential increase in emissions associated with storage operations, the deployment of storage is often associated with increased deployment of variable wind and solar generation, either locally (when storage is colocated with the renewable generation to provide more consistent output) or in the market (when the cumulative variability of all renewable generation causes a need for system-level energy storage). In either case, storage may enable more renewable generation, resulting in an indirect reduction in total emissions. This indirect effect, where new storage provides conditions that support the addition of new wind or solar, is complex and hard to quantify. Capacity expansion (and other) models can be used to understand the effects and relationships associated with new storage, but they are complex, dependent on assumptions, and uncertain. Furthermore, these forward-looking models will still have the challenge of not being able to capture unanticipated changes in policies, market conditions, technology, or consumer preferences. Existing research has focused on the marginal economic and emissions effects of new storage. While we do not attempt to quantify the amount of new wind or solar induced by adoption of energy storage, we can estimate how much new renewable generation is required to offset the CO_2 emissions associated with storage deployment, which can be compared to other estimates or policy proposals.

In this work, we investigate the net emissions effect of bulk energy storage and wind/solar, examining 48 wind/storage locations and 936 solar/storage locations across 22 eGRID subregions of the United States. For each location, we determine the proportion of installed storage to renewable wind or solar generation that is required to achieve a zero net increase in system CO_2 emissions, essentially determining the break-even point where increased emissions due to storage are offset by decreased emissions from wind/solar. We then compare these "break-even ratios" across locations, demonstrating how different generation profiles can result in widely different outcomes across the U.S.

■ METHOD AND DATA

We develop an optimization model that identifies the profit-maximizing hourly operation of storage when coupled with or located near wind or solar power at 984 locations (48 wind locations and 936 solar locations) throughout the United States. Because we use location-dependent prices, emissions factors, and wind/solar generation time-series data, our analysis accounts for locational differences in renewable generation and storage patterns.

For each location, we examine two cases: (1) energy storage is operated independently from the output of the wind/solar, simply maximizing revenue from energy arbitrage, and (2) energy storage is used as "storage for renewable energy" that charges only from the colocated wind or solar and sells the stored electricity when market prices are high (in this case, the solar or wind can be sold directly to the grid but storage can never charge from the grid). In both cases, the objective of the storage operation is to maximize revenue, but the first algorithm allows charging from the grid (or local renewables when available) while the second constrains charging to occur only when the colocated renewable energy is producing. The first scenario is generally more realistic, but there are reasons that storage may be constrained to local renewable energy: physical constraints, like a thermal solar plant with thermal storage, or financial benefits, such as gaining the Investment Tax Credit for storage that predominantly charges from local solar.[12] Because the work is focused on emissions effects of storage and renewables, we do not assess capital costs, return on investment, or other metrics of net profitability. Importantly, while these factors affect which storage project will be constructed, they do not affect the optimal operation, annual revenue, or emissions from storage.

The wind power time-series data sets come from the Eastern and Western Wind Data Sets,[13] which provide simulated hourly power output from wind turbines at thousands of sites across the U.S. We chose 48 sites that are relatively accessible to demand centers or transmission with high capacity factors for their region (range: 28% to 56%). Solar data sets are from NREL's Typical Meteorological Year 3,[14] which provides solar irradiation data on an hourly basis for 1020 U.S. locations, with capacity factors ranging from 14% to 26% (maps of the wind and solar locations are section 1 in the Supporting Information (SI)). The real-time wholesale electricity prices for each eGRID region were hourly prices for the year 2015 reported by Horner.[15,16] Horner collected the locational marginal prices (LMPs), averaged within each hour, from the real-time markets at the primary hub or aggregating price note in each state. For the regions in the country governed by independent system operators (ISOs), these data were obtained directly. For the regions of the U.S. that do not fall under an ISO (where generators and utilities generally established bilateral contacts), Horner assumed the LMP of the un/restructured regions that interface with that region. Storage is modeled as a 25 MW/100 MWh plant with a round-trip efficiency of 75%, parameters that represent pumped hydro or compressed-air energy storage, the most established technologies for large-scale energy storage.[17,18] We assume that the storage is connected to the renewable energy through alternating current, which conceptually allows for modeling of electrically proximate (rather than colocated) storage.

The storage device operates to maximize annual revenue over the year of operation. A linear programming (LP) approach is used to find the maximum revenue (eq 1, where P_t and E_t are the price and net energy out of storage at time t) subject to constraints (eqs 2−9):

$$\max \sum P_t E_t \tag{1}$$

such that

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

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

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

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

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

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

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

$$\forall\, t, \quad E_t \leq \mathrm{RE}_t \tag{9}$$

The storage state of charge is initialized at 50% (eq 2, where $S_{\max}$ represents the energy capacity of the storage), and inefficiency is split geometrically between the charge and discharge portions of the cycle (eqs 3 and 4, where η_{rt} is the round-trip efficiency of storage). In the model, storage is actually permitted to choose the quantity of both charging and discharging during all periods but only ever chooses one at a time because of efficiency losses. Equations 5 and 6 constrain the state of charge to be between zero and the maximum energy capacity, while eqs 7 and 8 constrain the charge/discharge rate to $R_{\max}$, set at a 4 h rate (i.e., one-fourth of the storage energy capacity can be added or removed in 1 h). It should be noted that the use of a 1 h time increment means that the storage power output in a time step (in MW) is always equal to the energy output (in MWh). In the scenario where storage is constrained to charge from colocated wind or solar, eq 9 (where RE_t represents the renewable energy production at time t) is applied. Table 1 gives a list of the variables and their units.

Table 1. List of Variables and Units

variable	symbol	units
electricity price	P_t	\$/MWh
energy discharged from storage	E_t	MWh
storage maximum energy capacity	$S_{\max}$	MWh
storage energy capacity	S_t	MWh
round-trip efficiency	η_{rt}	percent
storage maximum power capacity	$R_{\max}$	MW
available energy from colocated renewable generation	RE_t	MWh
hourly total emissions of a pollutant in an eGRID region	$e_{h,s}$	ton/hour
marginal emission factor	$\beta_{h,s}$	ton/MWh
hourly generation in an eGRID region	g_h	MWh/hour
error term	$\varepsilon_{h,s}$	ton/hour
hour	h	hour
season	s	indicator variable
intercept of the linear regression	$\alpha_{h,s}$	ton/hour
marginal emissions factor (by hour of day and season) and for each region	$\mathrm{MEF}_{\mathrm{h,s}}$	ton/MWh

After the operation of storage has been determined, we assess the net emissions associated with storage in all scenarios as follows: the hourly energy into or out of the storage device is matched with the marginal emissions factors (MEFs) from the grid in that region, time of day, and season. When storage charges, it increases grid generation and emissions of the marginal generator, while periods of discharge reduce generation and associated emissions. Marginal (rather than average) emissions factors are used because they represent the emissions rate of the generator that would increase/decrease output in response to changes in demand. The marginal emissions from the grid are broken down by location, hour of the day, and by season, and calculated for CO_2, NO_x, and SO_2 emissions. We use the MEF estimates developed by Azevedo et al., which are available in a spreadsheet in the SI. The MEFs are the result of a regression approach in which the change in total CO_2 emissions (Δe) from one hour to the next is compared against the total generation (Δg) in that region from one hour to the next using actual data from the EPA's Continuous Emissions Monitoring System (CEMS) database.[19,20] We note that the CEMS includes measured hourly emissions and generation for all of the power plants in operation that are powered by fossil fuels and that are larger than 25 MW in the year of observation. Specifically, we make use of the results from 72 separate regressions of Δe against Δg, where the slope $\beta_{h,s}$ is the MEF estimate (in metric tons of pollutant per megawatt-hour) for hour of day h and season s:

$$\Delta \mathrm{e}_{h,s} = \beta_{h,s}\Delta \mathrm{g}_{h,s} + \alpha_{h,s} + \mathrm{e}_{h,s} \tag{10}$$

where $\alpha_{h,s}$ representes the intercept of linear regression and $\varepsilon_{h,s}$ is the error term.

We apply the same approach as Siler-Evans et al.[19] but use 2014 electricity system data to calculate MEFs. Equation 11 shows that the total annual CO_2 emission is the sum of the hourly net energy consumption times the MEF for the hour of day and season:

$$M_{\mathrm{annual,CO_2}} = \sum_t (-E_t \cdot \mathrm{MEF}_{h,s}) \tag{11}$$

The negative sign is used because power out of storage decreases system emissions and vice versa. The same equation is used to calculate the emissions benefit of wind and solar generation that is needed to estimate the ratio of storage to renewable that results in zero net emissions benefit.

When storage is permitted to charge from the grid, calculating the quantity of wind or solar required to offset storage-induced emissions is simple: the net emissions effects of storage and wind/solar are separately calculated using eq 11, and their ratio is calculated. When storage is constrained to charge from colocated wind/solar, the equivalent ratio is determined by iteration. The storage device is fixed in size at 25 MW/100 MWh, and wind/solar is scaled down (from 25 MW) in 5% increments until the net renewable + storage system emissions equals zero. As discussed below, this can get very small because decreasing the size of wind/solar both decreases emissions benefits of renewables and decreases the emissions effect of storage because storage operates less frequently.

Importantly, we note that it is often presumed that storage charged from renewable energy charges "for free" and could not possibly increase emissions, but this is incorrect unless that renewable energy would otherwise be curtailed (which, at least currently, is infrequent in the U.S.). While the marginal cost of renewable energy is essentially zero, energy routed from renewable sources into storage is, logically speaking, neither "free" nor "zero emissions" because of the opportunity cost of charging storage. For example, if 100 MWh of wind energy is produced at night, it could be put directly into the grid, perhaps earning \$2000 (at \$20/MWh) and displacing 80 tons of CO_2 emissions (if the marginal generator has emissions of 800 kg of CO_2/MWh). That wind energy could also be stored until the next day, displacing 75 MWh of peak demand (after storage

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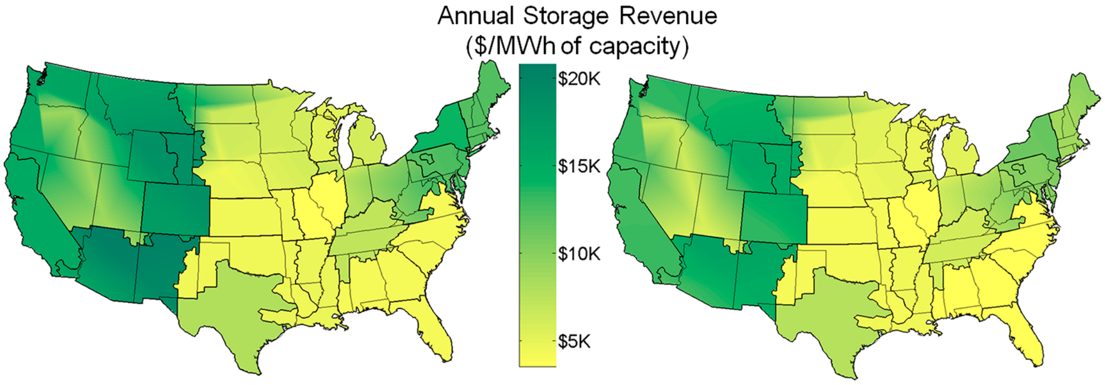

Figure 1. Annual revenue from storage operations ($/MWh of storage capacity) assuming 2014 wholesale electricity prices when storage is unconstrained (left) or constrained to charge from colocated wind with the same capacity (in MW) as the storage (right). The revenue is higher in regions that have larger daily variability in wholesale electricity prices. The variation in revenue is similar when storage is constrained to local wind but an average of 20% lower overall.

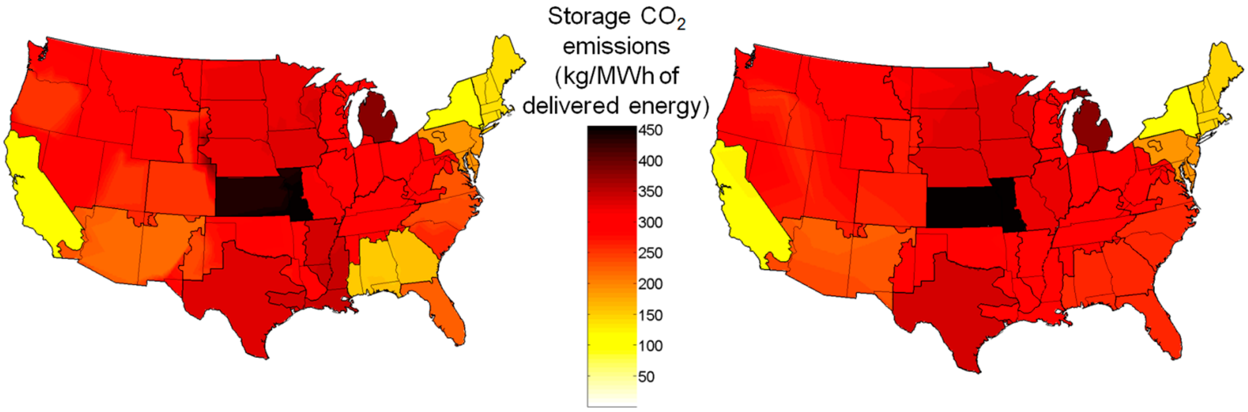

Figure 2. Average net CO_2 emissions resulting from the operation of a storage device at 48 locations in the U.S. under perfect information on future electricity prices when storage is unconstrained (left) or constrained to charge from colocated wind with the same capacity (in MW) as the storage (right). Emissions resulting from storage are highest when there is a large difference between the emission rates of the marginal generator in peak and off-peak periods. Some areas have generation with consistently high or consistently low emissions and demonstrate a smaller emissions effect from storage operations. While the average emissions are very similar between the scenarios, the total emissions are lower when storage is constrained to colocated wind because storage operates less frequently.

losses). That energy would perhaps earn $3750 (at $50/MWh) and displace 37.5 tons of CO_2 (assuming an MEF of 500 kg/MWh). In this example, the financial benefit of storing the wind power is $1750, not $3750, even though the marginal cost of generation was zero. Similarly, storing the wind energy would result in a net increase in CO_2 emissions (of 42.5 tonnes), even though wind power generates no emissions during operation.

■ RESULTS AND DISCUSSION

Revenue from Storage Operations across Locations and Scenarios. We assume that energy storage operates to maximize revenue over the year, with different constraints in each of the two charging scenarios. Within a given scenario, energy storage revenue varies by location, with the highest revenues normally in regions that experience greater daily wholesale price variability. Figure 1 shows the annual revenue for a 25 MW/100 MWh (75% round-trip efficiency) energy storage unit across the continental U.S. when storage is unconstrained (left) or constrained to charge from colocated wind with the same capacity (in MW) as the storage (right). Results for storage constrained to local solar are shown in Figure S4. We observed that revenue is higher in the Western U.S., Mid-Atlantic, and New England regions because of greater price variability.

Unsurprisingly, if we add the constraint that storage must charge only from local wind or solar energy, the revenue that storage can earn decreases. In a system where storage and wind are both scaled to 25 MW and storage is constrained to charge from local wind power, revenue is an average of 20% lower across the 48 locations considered in this work (ranging from 8% lower in Texas to 40% in Utah) than when the same storage device is unconstrained. Similarly, for a system consisting of 25 MW of solar with 25 MW/100 MWh of storage, constraining the storage to charge only from local solar reduces the storage revenue by an average of 42% across the 936 locations (ranging from 18% lower in California to 63% in Iowa). The difference is larger for solar generation because storage is most profitable if it charges at night, when electricity has a lower value, but solar does not produce at night. These large decreases in revenue from constrained-charging storage indicate that "storage for renewable energy" is more profitably operated as "colocated energy storage", suggesting that profit-maximizing firms will prefer to operate bulk energy storage independently from renewable sources, regardless of the initial reason for the energy storage installation.

Emissions Consequences of Storage Operations. Figure 2 shows the CO_2 emissions resulting from the addition of bulk energy storage across the continental U.S. when storage is not

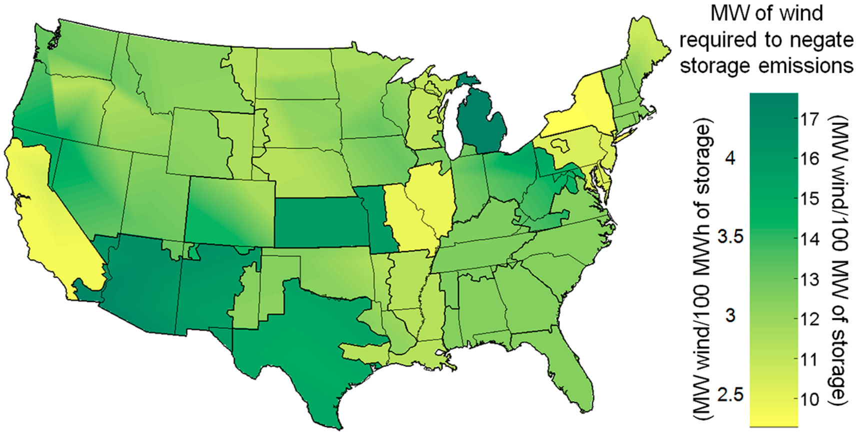

Figure 3. Quantity of wind (in MW) required to negate the CO_2 emissions from 100 MWh (left side of bar) or 100 MW (right side of bar) of storage, assuming storage can charge from the grid. Depending on location, 9−18 MW of wind displaces enough CO_2 to negate the emissions increase associated with 100 MW of storage. Because energy storage is scaled to a 4 h rate, the left and right scales of the color bar are fixed at a 4:1 ratio.

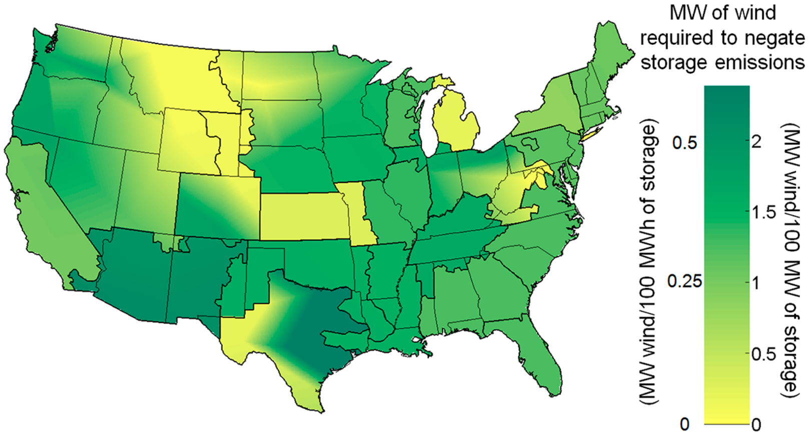

Figure 4. Quantity of wind (in MW) required to negate the CO_2 emissions from 100 MWh (left side of bar) or 100 MW (right side of bar) of storage, assuming storage can charge only from colocated wind generation. Depending on location, 0.1−2.5 MW of wind displaces enough CO_2 to negate the emissions increase associated with the colocated 100 MW of storage. Because energy storage is scaled to a 4 h rate, the left and right scales of the color bar are fixed at a 4:1 ratio.

constrained to local wind/solar sources (left) and when it is required to charge from local wind generation (right). Annual (rather than average) emissions results are shown in section 3 in the SI. Figure 2 gives emissions in units of kg of CO_2 per megawatt-hour of delivered energy from the storage. We find that in many U.S. regions, the carbon intensity of moving electricity with storage is comparable to other electricity generation technologies: the average U.S. natural gas plant has an emissions rate of 500 kg of CO_2/MWh, while the average U.S. coal plant produces 950 kg of CO_2/MWh.[21]

Locational variations are due to regional differences between the emission rates of the average peak versus off-peak generator. Throughout the Midwest and much of the Western U.S., coal is normally on the margin at night while natural gas is used to meet peak generation. In California and New England, there is much less coal generation, and it is rarely the marginal generator, with natural gas units on the margin for most of the year. Because storage is a net consumer of electricity, greater utilization of the same storage device resulted in higher total system emissions in our model (see section 3 in the SI) but had little effect on average emissions.

As with revenue, constraining storage to charge only from colocated wind/solar will reduce total emissions because the storage is used less frequently. A 25 MW wind/25 MW (100 MWh) storage installation that charges only from colocated wind has CO_2 emissions that are 30% lower (range: 19−43% over 48 locations) than the same storage plant that is permitted to charge from the grid. For a similar 25 MW solar/25 MW storage installation, emissions are 62% lower (range: 35−83% over 936 locations) than those observed for an unconstrained plant. The solar/storage plant shows a larger change when constrained to local renewables because solar has fewer possible periods in which to charge storage and because solar produces primarily during mid-day, when electricity prices are relatively high and arbitrage opportunities are less frequent and profitable. Emissions benefits results for renewables-only additions are provided in section 4 in the SI.

In the scenario where storage is colocated with wind generation but can charge from the grid when the local wind is not producing, Figure 3 shows the quantity of new wind generation (in MW) required to offset the CO_2 emissions from energy storage. Across the continental U.S., the quantity of wind required to offset emissions from 100 MW of energy storage varies between 9 and 18 MW (of nameplate capacity). This means, for example, that if a wind/storage installation has 100 MW of wind generation and 100 MW of storage, the CO_2

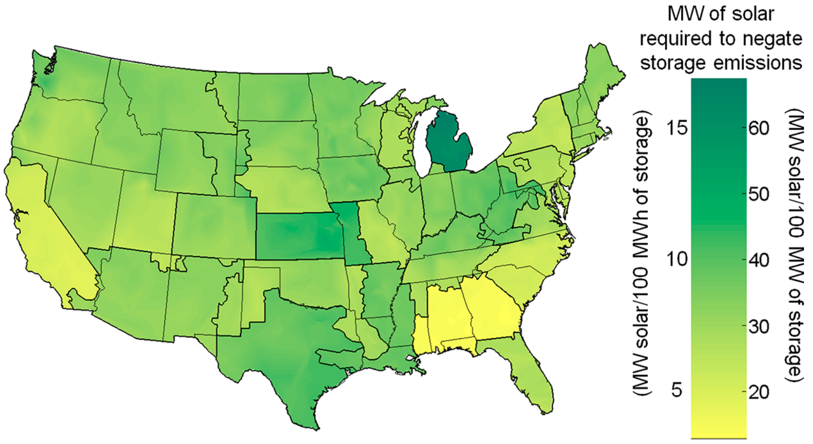

Figure 5. Quantity of solar (in MW) required to negate the CO_2 emissions from 100 MWh (left side of bar) or 100 MW (right side of bar) of storage, assuming storage can charge from the grid. Depending on location, 12−67 MW of solar displaces enough CO_2 to negate the emissions increase associated with 100 MW of storage. Because energy storage is scaled to a 4 h rate, the left and right scales of the color bar are fixed at a 4:1 ratio.

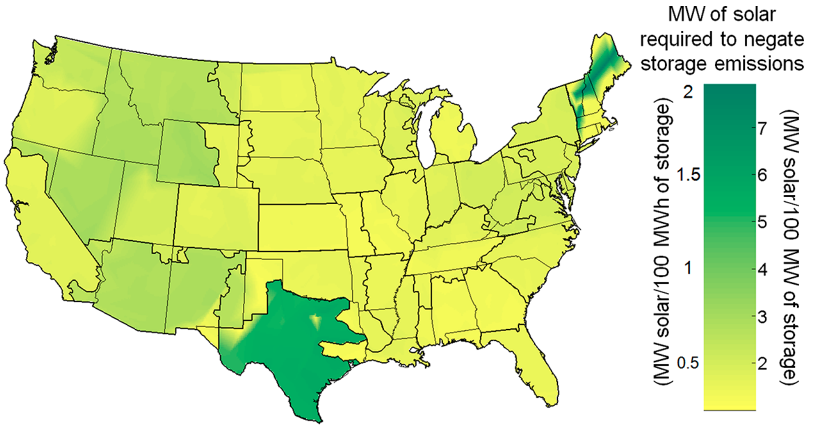

Figure 6. Quantity of solar (in MW) required to negate the CO_2 emissions from 100 MWh (left side of bar) or 100 MW (right side of bar) of storage, assuming storage can charge only from colocated solar generation. Depending on location, 1−8 MW of solar displaces enough CO_2 to negate the emissions increase associated with 100 MW of storage. Because energy storage is scaled to a 4 h rate, the left and right scales of the color bar are fixed at a 4:1 ratio.

emissions due to storage operation would be displaced by the first 9−18 MW of wind, with the remaining 82−91 MW of wind offering a net emissions benefit.

Figure 4 shows similar results for the case where storage is constrained to charge from local wind power. The ratios are notably lower in this case: any installation that has more than 2.5 MW of wind for every 100 MW of storage would have a net CO_2 emissions benefit. The primary reason that this ratio is so low is because of the implausible system design, which results in very low utilization of storage. It is unlikely that any developer would consider a system with 2.5 MW of wind and 100 MW/400 MWh of storage that was constrained to charge from the 2.5 MW wind farm. At that ratio, storage operates to frequently charge small amounts of wind energy in off-peak periods, which is generally discharged all together during a brief period of high prices. While the specific design is unrealistic, these results (Figure 4) are useful for showing the "break-even" ratio for locations where storage charges from colocated wind, while results from Figure 3 are appropriate for considering the joint effects of system-level wind and storage.

Figures 5 and 6 show similar results as Figures 3 and 4 but for solar/storage installations. Figure 5 shows that between 12 and 67 MW of new solar is required to offset the CO_2 emissions from 100 MW of storage, assuming that storage is permitted to charge from the grid. These ratios are higher than for wind, though that is expected: in most locations, 1 MW of solar offsets less CO_2 emissions than 1 MW of wind because of the lower capacity factor of solar. Figure 6 shows that a solar/storage system where storage is required to charge from local solar generation requires between 1 and 8 MW of solar for every 100 MW of storage to break even on grid CO_2 emissions. As with wind, these ratios are very low and represent an unlikely design but show that any realistic solar/storage system (with storage of similar or smaller scale relative to solar) would safely result in net system emissions reductions.

The locational variations in Figures 3−6 are a combined result of several different factors. First, average emissions due to storage operation vary by location (Figure 2). Second, renewable productivity varies by location: wind capacity factors vary between 28% and 56% in our data set, while solar capacity factors vary between 14% and 26%. Third, the emissions benefits of wind/solar vary by location, resulting from the relationship between periods of renewable energy production and time-varying marginal emissions. Finally, in the cases where storage is constrained to charge from renewables, the relationship between periods of production and high-price periods affects emissions. For example, when storage is unconstrained, it will usually charge in the middle of the night. But if it is constrained to charge from

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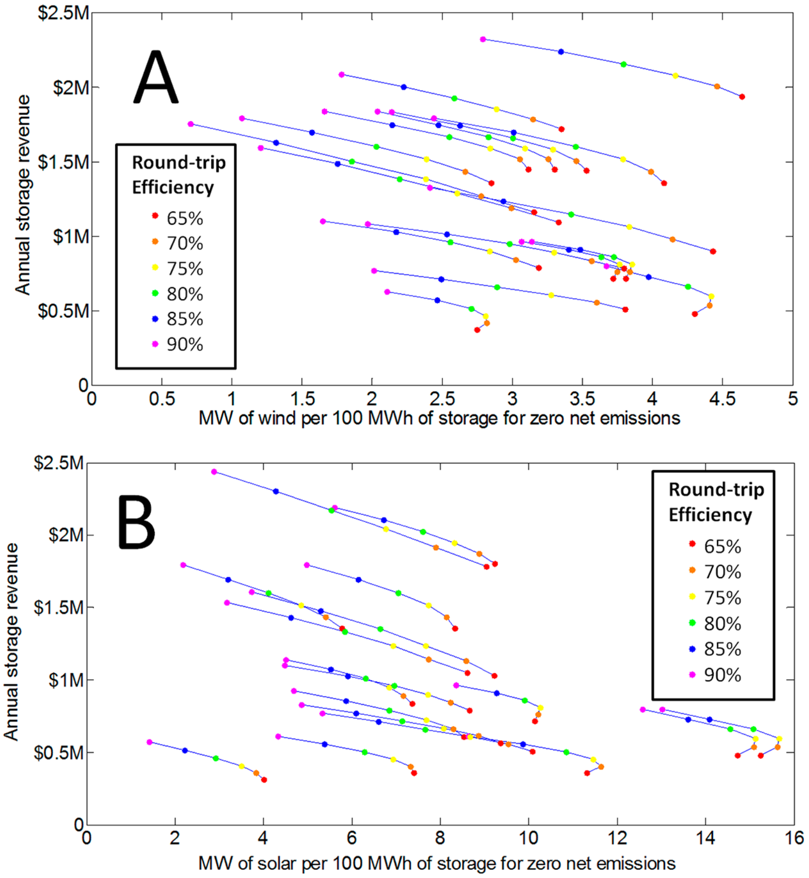

Figure 7. Analysis of the sensitivity of storage revenue to the round-trip efficiency and the (A) wind:storage and (B) solar:storage ratio required for renewable energy to displace the estimated storage emissions for 17 representative sites. These results use the base-case 25 MW/100 MWh design and assume that storage is permitted to charge from the grid when needed (and are thus comparable to Figures 3 and 5).

local solar, it will often charge in the morning or mid-day, when solar is producing but prices are lower than the late afternoon/evening peak.

Sensitivity Analysis. The above results all assume the same storage configuration: a 25 MW/100 MWh plant with a round-trip efficiency of 75%. Thus, here we test the effect of different round-trip efficiencies on our results (Figure 7) as well as the effect of different charge/discharge rates (Figure 8). As the round-trip efficiency improves, revenue always increases, and there is a general shift toward requiring less renewable generation for every unit of new energy storage because less energy is wasted through inefficiency. However, at low efficiencies (below 70%), improving the efficiency results in more frequent use of storage and can actually increase the total emissions, requiring more renewable generation. For the charge/discharge rate, increasing the rate (while keeping the energy capacity fixed) increases both revenue and the amount of renewable generation required. With a higher charge rate, the same storage device can cycle more frequently and deeply, which tends to increase the effects of existing operation: allowing for more revenue but generating larger net system emissions.

■ DISCUSSION

Energy storage is frequently associated with renewable electricity, primarily as a tool to reduce or eliminate the production variability of wind or solar generation. However, adding energy storage to existing electricity systems in the U.S. normally results in emissions increases through shifting of generation sources and an overall increase in electricity use. Despite that, the existence of storage can help support the addition of new wind and solar, and our results help to estimate the net effect of new renewable generation and storage. We used a marginal emissions factor approach to evaluate how the CO_2 emission reductions from adoption of wind and solar compare to the emissions increases from storage and how their ratio varies by location.

Bulk energy storage is most profitably operated independently of wind or solar generation, and colocated renewable/storage facilities may be expected to follow this strategy. However, a scenario where storage charges only from local wind or solar would make sense under a business model where the generation facility wants to offer a "firm" 100% renewable energy product. Alternately, some storage technologies have constraints on their energy source: for example, a solar thermal plant with thermal storage is unlikely to "charge from the grid". Furthermore, there are benefits to colocated storage that charges only from local renewable energy: electrical losses are slightly reduced if the generation and storage are connected by direct current, and tax benefits are gained through the Investment Tax Credit to pay for storage that is integrated with solar and charges predominantly (75% or more) from solar.[12] However, the value and emissions effects of storage are generally independent of any colocated renewable energy unless those renewables would otherwise be curtailed. This suggests a possible improvement to the existing Investment Tax Credit for storage, which could be offered to any storage placed in a location that experiences significant curtailment of renewable generation. This would allow storage

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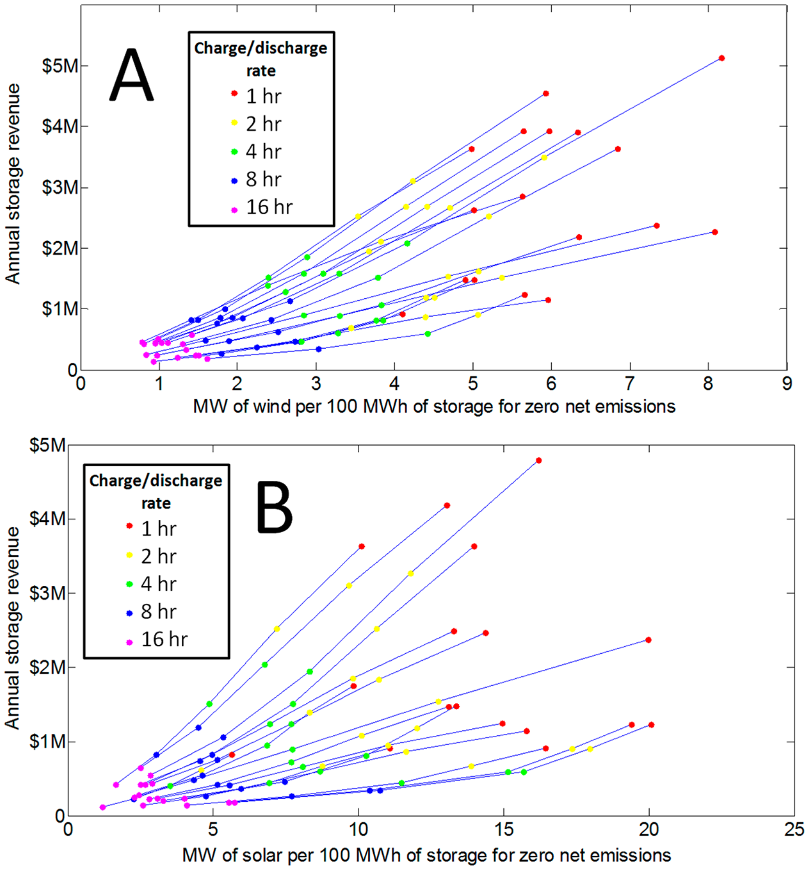

Figure 8. Analysis of the sensitivity of storage revenue to the storage charge/discharge rate and the (A) wind:storage and (B) solar:storage ratio required for renewable energy to displace the estimated storage emissions for 17 representative sites. These results use the base-case 75% round-trip efficiency, fix the storage capacity at 100 MWh, and assume that storage is permitted to charge from the grid when needed (and are thus comparable to Figures 3 and 5).

to earn the higher revenue of an "unconstrained" system while resulting in actual emissions savings by using otherwise-curtailed renewable energy. Such a policy would not need to specify that storage use the nearby curtailed renewable energy because the storage device would already have a large market incentive to do so because that energy would be offered at zero or negative cost.

Overall, our results suggest that any plausible design for a wind/storage or solar/storage plant would reliably reduce CO_2 emissions anywhere in the U.S, relative to the status quo. In places where storage has been deployed with wind or solar, it tends to be on a scale that is equal to or smaller than the wind or solar (in MW terms). Some existing examples of colocated wind and storage include the Notrees Storage Project in Texas, with 153 MW of wind and a 36 MW/9MWh battery,[22] and the Laurel Mountain wind installation in West Virginia, which has 98 MW of wind and a 32 MW/8 MWh battery.[23] In both of these installations, the relative scale of the battery and its high charge/discharge rate means that the battery tends to smooth out variability rather than time-shift large amounts of wind energy. That is not the case, though, for the Solana Generating Station in Arizona, which has 250 MW of net solar thermal with 250 MW/1680 MWh of thermal storage, used to both smooth output and time-shift some of the solar electricity to peak demand in the late afternoon.[24] The proposed Pathfinder Wind Project in Wyoming would have 2.1 GW of wind generation and 1.2 GW of compressed-air storage, which would firm and time-shift the wind output.[25] In all cases, the scale of storage (in MW) is equal to or smaller than the colocated renewable energy.

While we conclude that plausible wind/storage or solar/storage projects would reliably result in emissions reductions, our results show that emissions increases due to storage operation can cut into the expected emissions benefits of renewable energy. As an example, if the Pathfinder Wind Project were to be built in Wyoming as designed, it would take 150 MW of wind generation (out of the total of 2100 MW) to offset the emissions from the 1.2 GW of storage. As a result, the wind/storage project would reduce emissions 93% as much as a wind-only project. While safely above zero, it is important to consider the effect of the storage operation on the net emissions benefit of a renewable/storage facility.

In a similar sense, these results can inform the discussion around emissions effects of energy storage mandates, such as in California. California's energy storage mandate requires utilities to install 1.3 GW of storage by 2020.[5] With the assumption that this storage is not constrained to charge from local solar and the marginal emissions will be similar to the ones observed in the system today, our results suggest that 25 MW of new solar would be required to offset the emissions induced by every 100 MW of new storage in California. Thus, the 1.3 GW of new storage could be considered a net emissions benefit if it induces more than 325 MW of new solar. California has almost 20 000 MW of solar generation, of which more than 5000 MW was deployed in 2016.[26] While most of this would have been deployed without the California storage mandate, it is certainly reasonable to suggest that the 1.3 GW of storage enables at least 325 MW of additional solar deployment on top of the tens of thousands that

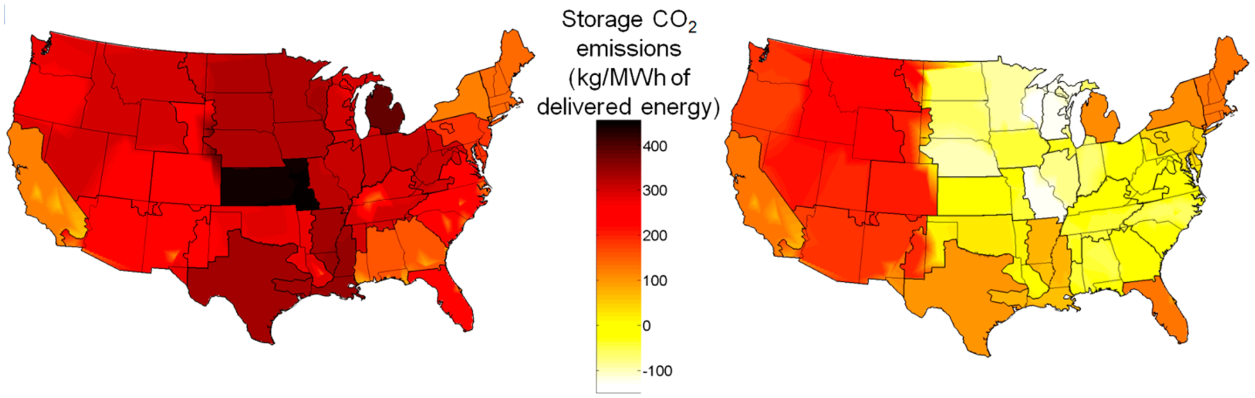

Figure 9. Average net CO_2 emissions resulting from the operation of the base-case storage device at 48 locations in the U.S. under perfect information on future electricity prices under 2014 MEFs (left) and under modified MEFs representing combined-cycle natural gas as the off-peak marginal generator (right). The storage parameters, prices, and operation are the same in both panels, but the MEFs for the right panel are modified so that the maximum emissions factor between 10 p.m. and 7 a.m. is 410 kg of CO_2/MWh. Regions that already have low marginal off-peak emissions (California, New York, and New England) have a very small shift. In the Midwest, however, storage goes from having the highest net emissions to having negative net emissions because it charges from efficient combined-cycle plants and displaces peaker coal and natural gas units.

will be deployed this decade. Policymakers should be aware that the direct emissions effect of adding storage to the grid is neutral at best and that its environmental benefits are dependent on its ability to encourage new renewable electricity generation.

There are important limitations to our results that we also want to highlight. First, the conclusions above apply only to bulk energy storage. Several researchers have investigated the value that fast-ramping energy storage can provide for wind smoothing,[27−29] which is a distinct application from bulk storage. Second, these results only apply to energy storage that acts as a price-taker. If a significant amount of storage were operating in an area, the results would be different, though not necessarily better. Third, bulk energy storage colocated with wind or solar generation can be of great value, both economically and environmentally, when transmission or ramping constraints prevent all of the renewable energy from being used, which is currently rare in the U.S. However, this will shift over time. Solar and wind are already being curtailed in small quantities in some systems, and those sources are expected to grow rapidly in coming years. For example, on March 26, 2017, California curtailed 6500 MW of solar generation (about one-third of the output that day).[30] This event was notable because it is currently uncommon. But if electricity systems are unable to accommodate increasing amounts of variable renewable generation—through transmission, demand response, flexible generation, or other approaches—zero-carbon renewables may become the marginal generator for many hours of the year. This outcome would shift our results, making storage more economically and environmentally attractive than what we observe using 2014 emissions and price patterns.

Our results would also change with other shifts in generation mix, such as a replacement of base-load coal generation by combined-cycle natural gas (CCNG). As an illustrative example, we have considered a case where coal generation is no longer on the margin during off-peak periods (Figure 9). For this illustration, we have changed the MEFs such that any emissions factor above 410 kg of CO_2/MWh occurring between 10 p.m. and 7 a.m. is set to 410 kg of CO_2/MWh, the emissions rate of the average U.S. combined-cycle plant.[31] This change essentially imagines that the off-peak generator is now at least as clean as a CCNG power plant. While this does not change prices or operational patterns, it illustrates the large effect that a shift in off-peak marginal generation could have on storage-induced emissions. As shown in Figure 9, this change has little effect on storage-related emissions in California, New York, or New England, where both peak and off-peak marginal generation is relatively clean. In the Midwest, though, changing only the off-peak generation to CCNG results in net negative emissions from storage because storage charges from combined-cycle power and displaces peaker coal and natural gas plants.

Energy storage is complementary to renewable generation, but it also complements any low-marginal-cost technology. Bulk energy storage can enable the deployment of large amounts of renewable energy, but only through the inverse effects that these two technologies have on market variability: variable renewables tend to cause increased price fluctuations, while energy storage tends to decrease price fluctuations. Energy storage should properly be seen as a technology for controlling price variability and managing demand/generation with the open understanding that the direct effect of storage is to increase the net emissions from an electricity system. However, the addition of storage can support or induce the addition of new wind or solar generation, and we estimate the amount of new wind/solar required to offset the emissions effect of new storage. While the indirect effect of storage on wind and solar adoption is complex and difficult to estimate, it seems likely that any plausible wind/solar plus storage plant would reliably reduce electricity system emissions anywhere in the U.S.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.7b03286.

Locational maps, annualized net emissions, and emissions savings from renewable-only deployments (PDF)
Marginal emissions factors used in this work (XLSX)

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The authors declare no competing financial interest.

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