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Wind can reduce storage-induced emissions at grid scales

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HIGHLIGHTS

- Grid-scale energy storage are modeled to arbitrage in electricity market.
- Storage-induced emissions are estimated in two power grids with high and low wind penetration.
- High wind penetration can favorably pair with storage and reduce air pollutant burden.
- Carbon dioxide, sulfur dioxide, nitrogen oxides, and mercury emissions are estimated.
- Storage-induced emissions are 42-64% lower in the high- than in the low-wind grid.

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ABSTRACT

Energy storage provides many benefits that can improve electric grid performance but has been shown to increase overall system emissions. Yet, how energy storage might interreact with renewables in existing grids and how these interactions affect overall emissions remain unclear. Here, we estimate emissions induced by battery energy storage in two regions of the United States with very different levels of wind penetration using high-resolution, both spatially and temporally, locational marginal prices and hourly marginal emission factors. We find that the emission intensity of carbon dioxide, sulfur dioxide, nitrogen oxides, and mercury is 4264% lower in the high wind penetration grid (28%) than in the low wind penetration grid (< 5%). This is due in part to a significant share of wind dispatched as marginal fuel in baseload hours when battery storage charges from the grid, reducing storage-induced emissions. Our study suggests that more wind generation can favorably pair with storage and reduce the air pollution burdens otherwise caused by storage.

1. Introduction

Energy storage technologies are widely acknowledged as effective tools to improve grid reliability [1,2], shave peak load [3,4], and integrate renewables [5,6], particularly wind [7–9] and solar [10]. Recently, deploying energy storage in the United States (US) power system has been encouraged and/or mandated by federal and state policies and regulations. For example, in February 2018, the Federal Energy Regulation Committee (FERC) issued Order 841 to "remove barriers to the participation of electric storage resources in the capacity, energy and ancillary services markets operated by Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs)" [11]. At the state level, utilities are required to install or procure certain amount of energy storage capacity by 2020 or 2030 in California [12–14], Massachusetts [15], New Jersey [16], New York [17], and Oregon [18]. These policy targets facilitate storage technology deployment and market access, and provide opportunities for multiple revenue streams to utilities [2,19].

With the prospect of greater storage deployment in the near future and the increased global attention placed on reducing the health and climate impacts of electricity systems [20,21], the emissions impacts of increased grid system storage remain largely unclear [22,23]. While

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energy storage, per se, does not generate emissions, it stores electricity and discharges it at 70–95% efficiency [24–26]. Incremental emissions of storage sourced power come from this efficiency loss plus the difference between the marginal emissions of the electricity grid system fuel mix when the storage technology charges and the marginal emissions displaced when it discharges [27]. The net impact of storage therefore hinges on when it charges and discharges and what fuel sources are on the margin at those times, accounting for energy loss [28].

Previous studies of the U.S. grid have found that storage can often increase system emissions [29–31]. This is because storage is assumed to likely charge from baseload power plants (often coal powered) when prices are low, and discharge when the grid is largely powered by peaking power plants (often natural gas powered) when prices are high [29,30]. In determining the marginal generation storage uses and displaces when charging and discharging, earlier papers have generally omitted renewables, assuming that wind and solar, in particular, cannot be dispatched on the margin due to their intermittency [32–35]. However, due in large part to advances in dispatch control systems, real-time forecasting, and changes in electricity market rules, renewables are now commonly dispatched on the margin [36,37]. For example, the Midcontinent Independent System Operator (MISO) launched the Dispatchable Intermittent Resources (DIRs) program in 2011 [38] and dispatched wind as marginal power resource for nearly half of the time in the past few years [39]. The PJM Interconnection (PJM) has also undertaken several initiatives that have led to nearly 4% of marginal resources being wind units in the past few years, even with a fairly low rate of wind penetration of about 2% [40,41].

The enhanced dispatchability of renewables in exiting grids in the U.S. increases the likelihood of their interactions with storage, which are critical to understanding its emission impacts. Yet, few studies have examined this question, and it is unclear if such interactions would aggravate, alleviate, or have little effect on storage-induced emissions. Here, we explore the relationship between renewable power penetrations (specifically, wind power) and battery storage through hypothetically deploying grid-scale battery energy storage systems in two subregions of the MISO system. These locations operate in similar electricity energy mixes, with the exception of very different levels of renewable wind power penetration (Fig. 1; Methods). We assume that battery storage technologies introduced maximize annual net operational revenue by taking advantage of highly volatile locational marginal prices – buying low (to charge) and selling high to (to discharge). We estimate storage-induced emissions in each region by modeling net revenue maximizing battery storage charging and discharging patterns linked to hourly marginal fuel types and grid emissions including renewables. To simulate how the storage technologies might operate, we use unique real-time hourly locational marginal pricing (LMP) data that we have compiled for ~150 locations in the studied regions [42]. With this unique high-resolution dataset, we could accurately capture the economically optimal charge and discharge patterns of storage, which are a key element in determining its value and induced emissions. We focus on four key air pollutants, i.e., carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and mercury (Hg) for which data are available.

2. Methods

2.1. Study regions

The regions we choose to demonstrate these effects in this study are the North and Central subregions in the Midcontinent Independent System Operator (MISO) system. As one of the world's large energy markets, MISO manages the high voltage transmission grid and electric power markets for its utility members, delivering electricity to 42 million people across 15 U.S. states and one coordinating member, Manitoba, in Canada (see S1). The MISO North subregional grid (hereafter as "North") has members in Iowa, Minnesota, Montana, North Dakota, South Dakota, and Manitoba, Canada; the MISO Central subregional grid (hereafter as "Central") serves members in Indiana, Illinois, Kentucky, Michigan, Missouri, and Wisconsin [43]. North has a relatively high renewables penetration of ~30% (primarily wind), whereas Central has low renewables penetration of ~5% with more coal and natural gas (Fig. 1). MISO also has a South subregion, which covers Arkansas, Louisiana, Mississippi, and Texas [43]. However, as of 2018, the South subregion had virtually no renewables on the system with an energy mix comprised of natural gas (56%), nuclear (22%), and coal (17%), and is not included in our comparative analysis.

2.2. Compilation and processing of MISO locational marginal pricing data

We have collected and developed a unique dataset of high-resolution electricity prices used in this study are the locational marginal prices (LMP) throughout MISO North and Central subregions for the years 2015–2018. The real-time LMP data was obtained at five-minute increments between 04/08/2015 and 12/31/2018 from the MISO real-time LMP contour map, an open-access portal of MISO system operation [42]. There are in total 33 LMP locations in North and 119 LMP locations in Central. The dataset is unique in that it not only provides the finest known and publicly available temporal resolution of real-time LMP in MISO but also reveal the spatial location for each price increment. Such detailed geographic information of MISO LMP has not been published by previous studies or made available in MISO's historical LMP market data archive. The improved spatial resolution can facilitate more precise, location-specific analyses than those dependent on

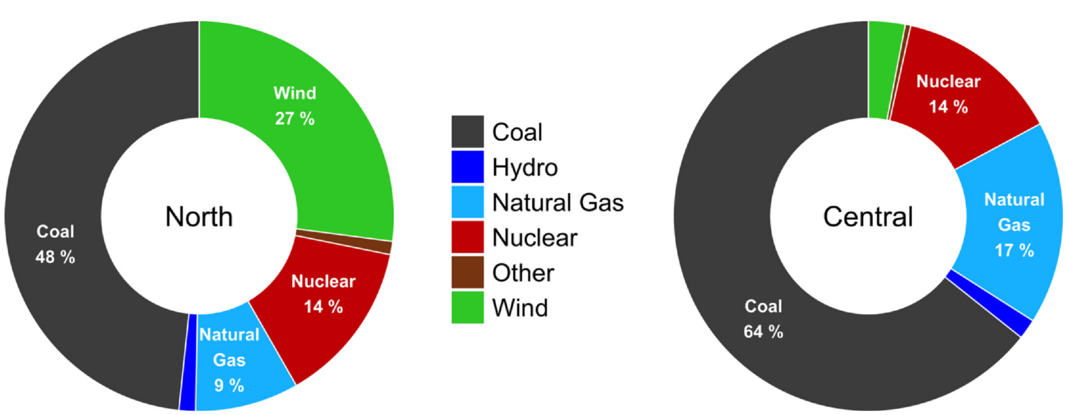

Fig. 1. Fuel mix in North and Central subregional grids of the Midcontinent Independent System Operator (MISO) system. These two grids have similar fuel mixes with regard to shares of fossil fuels (coal and natural gas together dominate both mixes) and nuclear (14% in both mixes) but quite different in terms of renewable wind power penetration: 27% in North compared to less than 4% in Central.

region- or state-level LMP [27,44,45]. To ensure computational compatibility, we aggregate the multi-year, five-minute LMP to single-year, hourly level then use the hourly LMP (8760 data points) in revenue optimization model for energy storage. Because the aggregation is applied at each location, spatial granularity of the data is reserved. Summary statistics of the hourly LMP data are presented in the S2 section in Supplementary Information (SI).

2.3. Energy storage model and revenue optimization

We develop an optimization model to determine the revenue-maximizing hourly operation of battery storage system when participating, as a price taker, in the MISO real-time wholesale market at each of the 33 LMP locations in North and 119 LMP locations in Central. To reflect the realistic operational patterns of energy storage, we set the battery system to only charge from and discharge to the grid, even if it is collocated with other generation facilities; therefore, its annual net operating revenue is maximized from energy arbitrage. Location-specific electricity prices and region-specific emission factors are used in our analysis to reveal the profitability and climate impacts of battery storage operating in the MISO North and Central subregional grids.

We simulate the battery storage system based upon the general specifications of the Tesla Powerpack battery, as it represents the state-of-the-art technology for grid-scale battery storage [46]. Each system contains 10 units of the Tesla Powerpack battery and has energy capacity of 2.1 MWh, alternating current (AC) power of 0.5 MW, round-trip efficiency of 88%, and depth of discharge (DoD) rate of 100%. The system operates on an hourly basis to maximize annual net operating revenue, which means the battery either charges or discharges at any given hour - charging and discharging up to 24 times each day. We specify a linear programming model such that the maximized annual net operating revenue and corresponding hourly operation patterns of the battery (Eq. (6), where S_t is net energy stored, P_t is the price, Q_t^{inflow} and $Q_t^{outflow}$ are the energy flows in and out of the battery at time t) subject to constraints identified in Eqs. (1)–(7).

Maximize:

$$\sum_{t=1}^{T} P_t \times Q_t^{outflow} - \sum_{t=1}^{T} P_t \times Q_t^{inflow} \tag{1}$$

Subject to:

$$S_t^{battery} = \sum_{t=1}^{t} Q_t^{inflow} \times \sqrt{\eta} - \sum_{t=1}^{t} Q_t^{outflow} \times \frac{1}{\sqrt{\eta}} \tag{2}$$

$$S_0^{battery} = 0 \tag{3}$$

$$\forall\ t,\ S_t^{battery} \geq 0 \tag{4}$$

$$\forall\ t,\ S_t^{battery} \leq Q^{battery} \tag{5}$$

$$\forall\ t,\ Q_t^{inflow} \in [0,\ 0.5] \tag{6}$$

$$\forall\ t,\ Q_t^{outflow} \in [0,\ 0.5] \tag{7}$$

In the model, the round-trip efficiency η is split geometrically between the processes of charge and discharge (Eq. (2)). Net energy stored in the battery system $S_t^{battery}$ is initialized at zero (Eq. (3)) and is constrained to be between zero and the system's designed energy capacity $Q^{battery}$ (Eqs. (4) and (5)) at time t. Eqs. (6) and (7) set the lower and upper bounds of charge and discharge rate at time t.

2.4. Estimation of emission factors and absolute emissions

Marginal emission factors (MEFs) have been widely acknowledged as a more appropriate metric, than average emission factors (AEFs), to assess emissions caused by increase or decrease of grid generation in response to a change in demand [27,34,47,48]. We use the method of calculating MEFs from Li et al., because we consider renewable sources in the MEF estimates and reflect the current marginal fuel mix in the MISO grid [47]. Specifically, we use electricity system data obtained from MISO and Air Market Program Data (AMPD) archive of the U.S. Environmental Protection Agency (EPA) [49–51], then apply 288 separate linear regression (Eq. (8)) approaches of change in emissions $\Delta E_{m,h}$ against change in grid generation $\Delta G_{m,h}$ for the MISO North and Central subregions, where the slope $\beta_{m,h}$ is the MEF estimate (in metric tons of pollutant per megawatt-hour) for month m and hour h:

$$\Delta E_{m,h} = \beta_{m,h} \Delta G_{m,h} \tag{8}$$

Lastly, we calculate the annual total emissions by multiplying the hourly battery energy inflow (charge) and outflow (discharge) by corresponding subregional MEFs for the hour of day and month (Eq. (9)).

$$Emission_{annual} = \sum_{t=1}^{T} MEF_{h,m} \times Q_t^{outflow} - \sum_{t=1}^{T} MEF_{h,m} \times Q_t^{inflow} \tag{9}$$

3. Results

3.1. Storage charging and discharging patterns

In the two studied regions, storage shares similar charging and discharging patterns (Fig. 2): they charge during low price hours and discharge during higher price hours, which are usually well aligned with low and high demand hours, respectively. As shown in the upper charts of Fig. 2, storage tends to charge the most during the nigh hours, when demand and price are generally low. In the summer, the high-power charging (power rate larger than 0.4 MWh/h) window is slightly postponed, likely due to continued air conditioning load through the late evening. The charging power rate of storage during the daytime is relatively low (power rate of less than 0.1 MWh/h), except for 2–4 pm in the winter months, when it increases to about 0.3 MWh/h. On the discharging side (lower charts of Fig. 2), the clear "X" shape indicates that demand is higher in summer afternoons and winter mornings and evenings, which incentivizes the storage to inject discharged electricity to the high-priced grid as much as it can, within the physical constraints of the storage system (see Methods). The high-power discharge window in summer afternoons is likely reflective of increased air conditioning load, while the high discharge window during winter mornings and evenings likely reflects typical residential load patterns in the region.

3.2. Marginal fuel types and emission factors

Because of the difference in renewable penetration, contribution of marginal fuel types differs between the two regions (Fig. 3). In the North grid, where wind accounts for ~27% of total electricity generation, wind contributes to marginal generation at notable levels (14% to 36%) from low to high system generation. Coal contributes 45% to 73% and natural gas contributes another ~19% in marginal generation. In contrast, in the Central grid, where wind accounts for ~4% of total electricity generation, wind rarely contributes to marginal generation. Instead, coal and natural gas account for most marginal generation in this region. At low system generation times, coal accounts for up to 80% of marginal generation and natural gas takes over the remainder, whereas the numbers reverse, by and large, at high system generation times, with a minor contribution from hydropower (Fig. 3).

As a result, marginal emission factors (MEFs; emissions per megawatt hour (MWh)) across charge–discharge patterns can be quite different between the North and Central subregions (Fig. 4). In North, MEFs are relative stable across its load profile. In other words, during low system generation times of the day/month (often when storage is charging), MEFs are not substantially different from when there is high load on the system (often when storage is discharging). However, in the Central subregion, MEFs vary substantially as system load changes. In this case, when battery storage charges, often at low system generation times when prices are low, it draws on marginal fuel mixes with high

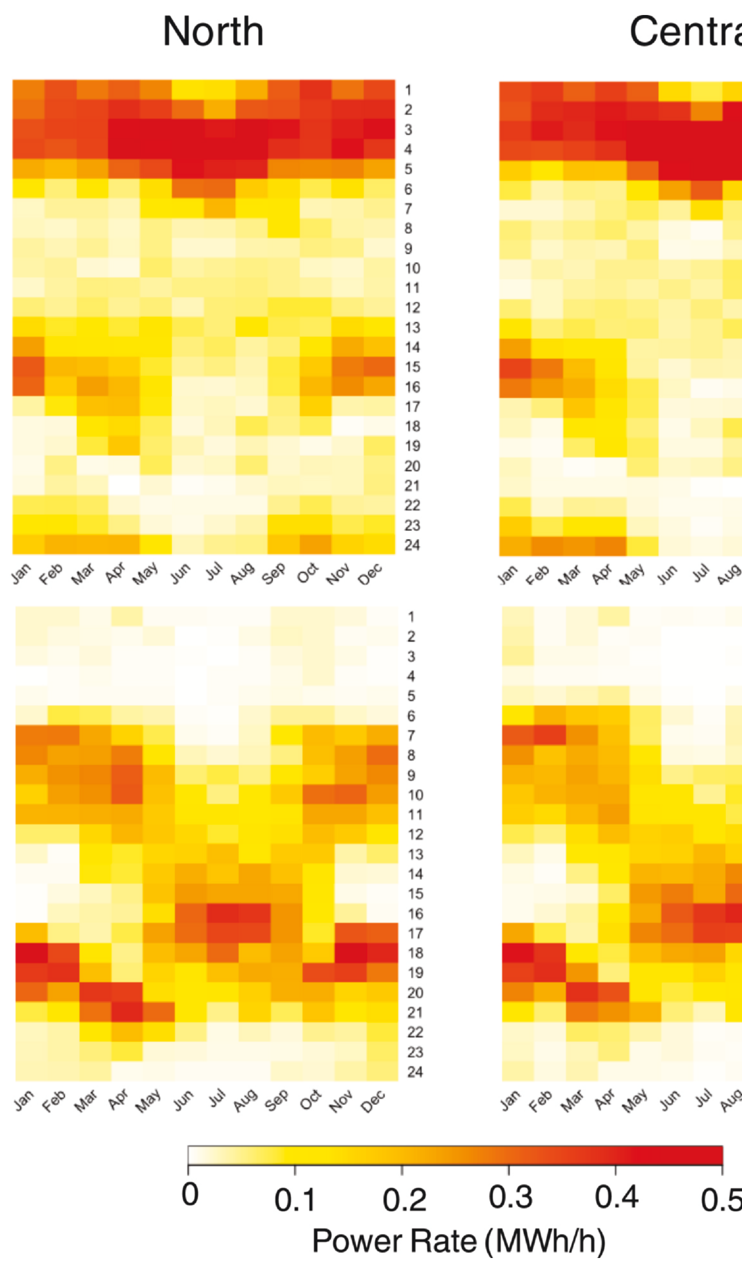

Fig. 2. Charge (top) and discharge (bottom) patterns of grid-scale energy storage in North and Central.

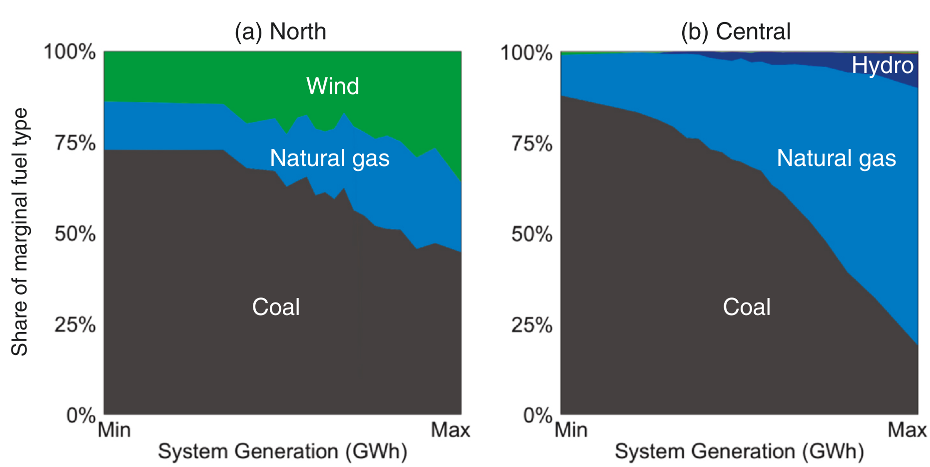

Fig. 3. Share of marginal fuel type as a function of system generation in North (a) and Central (b).

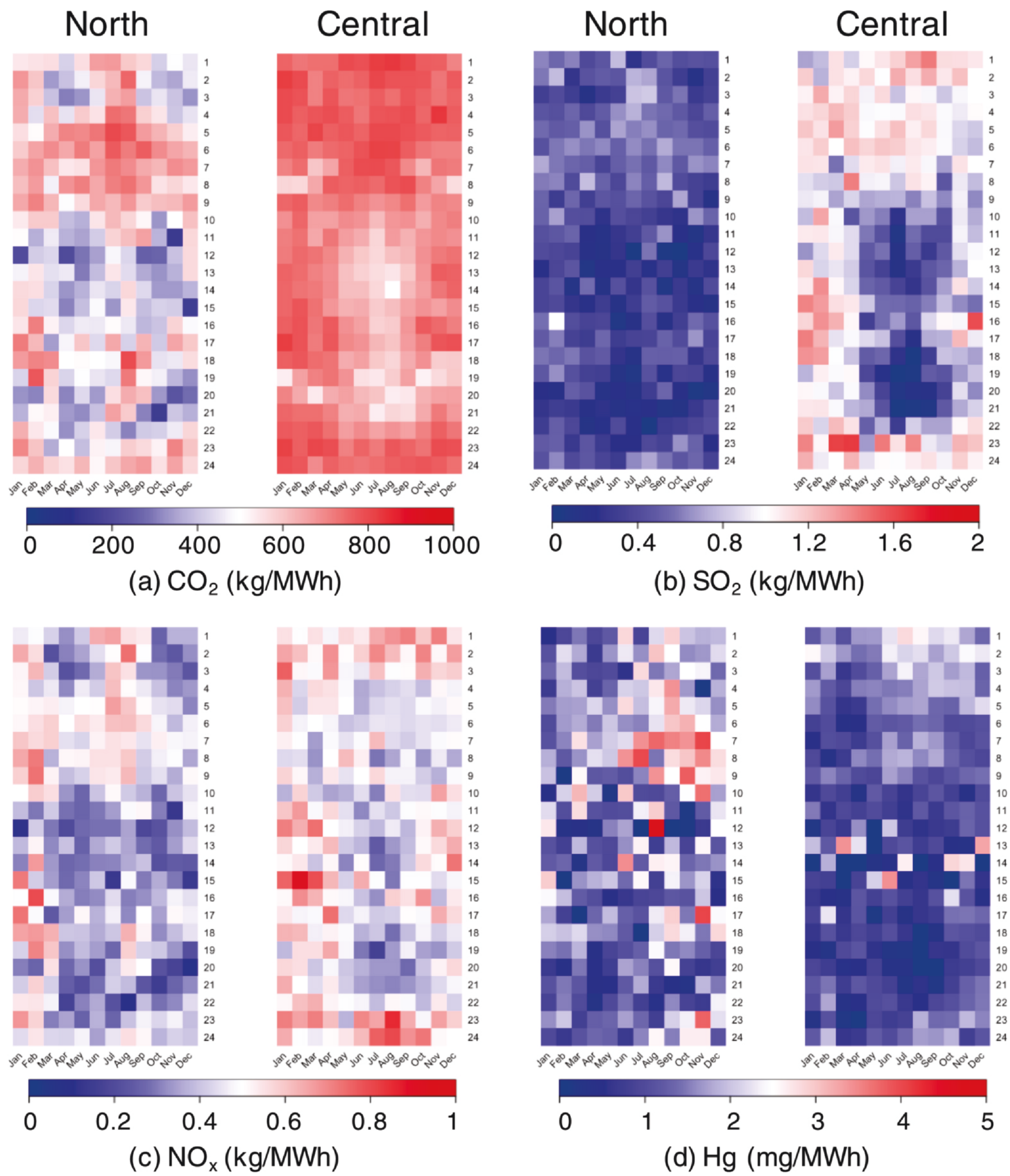

Fig. 4. Marginal emission factors (MEFs) for CO_2 (a), SO_2 (b), NO_x (c), and Hg (d) in North and Central.

emission intensities because of the dominant contribution of coal (up to 80%) in marginal generation. When it discharges, often at high system generation times, it displaces marginal fuel mixes with much lower emission intensities given the dominant contribution of natural gas (up to 70%) together with hydro (up to 10%). These considerable differences enlarge the gap between MEFs at storage charge and discharge times in the Central subregion.

3.3. Storage-induced emissions and explanations

Combining storage charging and discharging patterns with the regional MEFs and accounting for efficiency loss, we find that deploying energy storage in current North and Central grids under economically optimized simulated conditions will likely increase CO_2, SO_2, NO_x, and Hg emissions by 102 kg, 0.14 kg, 0.08 kg, and 0.29 mg in North and 182 kg, 0.39 kg, 0.14 kg, and 0.66 mg in Central per MWh supplied to the grid (Fig. 5). But importantly, the increases are much smaller in North where significantly more wind power operates on the margin than in Central. Storage-induced marginal emissions in the North subregion of MISO, where wind power penetration has reached 27% of generation on average, are found to be between 42% and 64% lower than emissions in the MISO Central subregion (where all renewables represent less than 5% of all sources). By pollutant, emissions in North are estimated to be lower:44% for CO_2, 64% for SO_2, 42% for NO_x, and 57% lower for mercury than in Central. The lower emission intensities in North can be partly attributed to its higher wind penetration, explained below.

The net emissions of storage are affected simultaneously by two factors: 1) the charging and discharging rate of storage (MWh/h) and 2) grid MEFs (kg/MWh or mg/MWh) at charging and discharging hours. We visualize these two factors in the top row of Fig. 6(a-d), where each point represents a cell in the heatmaps of Figs. 3 and 4, and observe that grid MEFs are always lower in North than in Central except for Hg. We also fit linear regression lines for the scattered points. Note that the discharge rate is interpreted as negative charge rate when determining the fitted lines. We find slopes of the fitted lines are steeper in Central (green) than in North (blue), which means, in general, the difference between grid MEFs at charging and discharging hours are larger in Central than in North. For example, if storage is scheduled to discharge at 0.3MWh/h in Central, it often is pre-charged by grid generation with MEFs CO_2 of 760 kg/MWh then displaces grid generation with MEFs CO_2 of 660 kg/MWh, which creates a CO_2 emission difference of

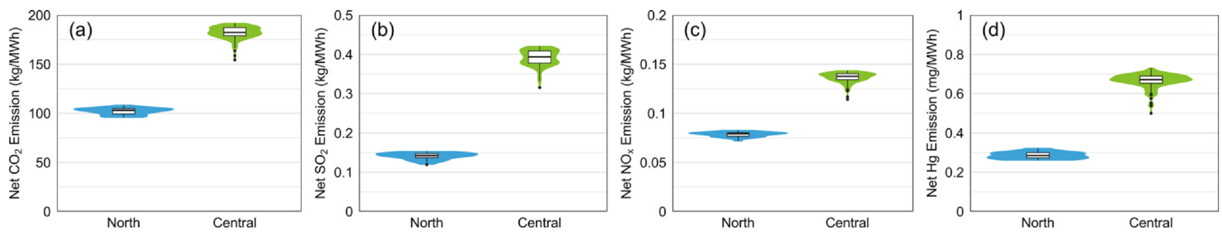

Fig. 5. Net CO_2, SO_2, NO_x, and Hg emissions induced by the storage. Marginal CO2, SO2, NOx, and Hg emissions per megawatt hour (MWh) supplied by the storage in the Central grid are estimated at 182 (± 7) kg, 0.39 (± 0.021) kg, 0.14 (± 0.005) kg, and 0.66 (± 0.038) mg, while in the North grid, they are 102 (± 4) kg, 0.14 (± 0.009) kg, 0.08 (± 0.003) kg, and 0.29 (± 0.018) mg.

100 kg/MWh; while in North, the difference would only be 38 kg/MWh (539 kg/MWh at charging hour and 501 kg/MWh at discharging hour). Consequently, as storage operates overtime, it induces more net emissions in Central than in North.

In the bottom row of Fig. 6(e-h), we group the points from Fig. 6a-d by discharge and charge and show distributions of MEFs for all emission types. When comparing the distributional characteristics of MEFs in the discharge group against those in the charge group, we find that the differences between MEFs in the two groups are more significant in Central (green) than in North (blue). This finding supports our observation in Fig. 6a-d and helps to further explain why storage induces more net emissions in the Central subregion than in the North.

4. Discussions

Grid-scale energy storage and renewable energy have been found in many studies as necessary elements to reduce emissions form the electricity sector. Indeed, our findings indicate that higher wind penetration in power grids can significantly lower emissions induced by energy storage. Deploying renewables in power grids can be complementary to energy storage with regard to reducing emissions if dispatched as marginal units when storage is charging. But adding renewables can amplify the emissions induced by energy storage, if renewables are dispatched as marginal units at times when storage is discharging. Because the charge–discharge patterns of storage are driven by energy demand curves, similarity between the curves of renewable generation and demand decides whether renewables and storage would complement or cancel each other. For instance, wind generation in the Upper Midwest is more available overnight than during daytime, which is often the opposite to demand and could lead to more wind energy charged into storage. Solar power is the opposite and electricity produced from photovoltaics tends to share a similar daily generation curve with demand. Depending on the system, this could potentially result in solar generation becoming unwanted by storage since storage has to discharge (to sell electricity at higher price than it paid to charge). Other renewables, such as hydro power, that do not have obvious generation curves like wind and solar power may have a more uncertain effect on reducing storage-induced emissions. If they are more often dispatched as marginal units when storage charges, low-emission energy are stored in batteries and will be released to replace high-emission power generation hours later. As a result, these renewables would be complementary for reducing storage-induced emissions. As renewables and storage are expected to increase in U.S. grids, it is important to gain better insights into potential interactions and consequent economic and environmental impacts indifferent grid environments.

Our methods of estimating marginal emission factors and storage charging-discharging patterns can be applied in other regions. Because economic dispatch is the commonly norm to unlock market value of energy storage, it is reasonable to assume that storage will operate similarly in other parts of the world. Our findings that storage induced emissions are moderated by wind power may still be generalizable in other regions, as electric power grids in significant parts of the world, such as the US, China, and European countries, are still dominated by fossil fuels but are experience growing wind penetration. While the general approach may likely hold in other regions, findings about storage induced emissions will be specific to fuel mix of other regional grids and how these grids respond to shifts in load.

Additional visualizations of hourly electricity prices and marginal share of wind can be found in the SI (see Fig. S1a and Fig. S2). The

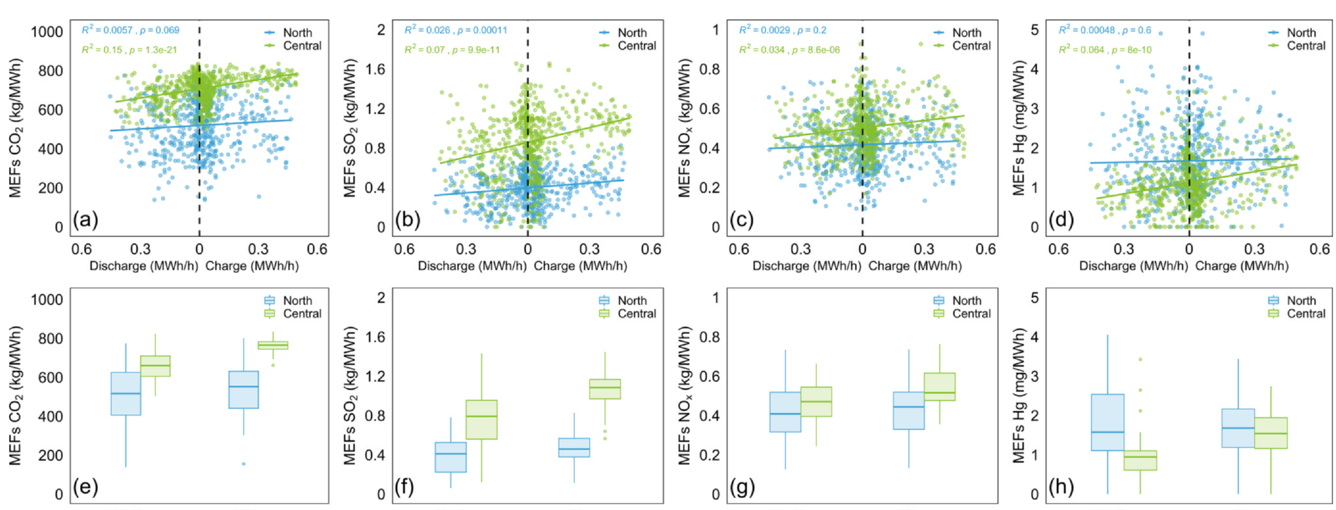

Fig. 6. Correlation between marginal emission factors (MEFs) for CO_2 (a), SO_2 (b), NO_x (c), and Hg (d) and charge/discharge rate of battery storage in North and Central (top row). Distribution of MEFs for CO_2 (e), SO_2 (f), NO_x (g), and Hg (h) during storage discharging and charging times (bottom row). In e-h, horizontal thick lines are the median, boxes represent the 25th-to-75th percentile range (i.e. interquartile range), whisker lengths are 1.5 times the interquartile range, and points represent outliers.

figures are displayed in the same temporal layout with the purpose to clarify that low prices are not necessarily always related to, or resulted from, high renewable generation. Observing Fig. S1a and Fig. S2 together, we see that the marginal share of wind is actually higher during high-price hours (10am to 9 pm) but not as high as one would expect during low-price hours (1am to 9am). It is important to note that renewables like wind are dispatchable to the extent that they are available. Improved forecasting technologies can predict their short-term availability with fairly high accuracy, but they may not be immediately available and completely dispatchable like coal and natural gas. Furthermore, transmission congestion in power grids is another critical factor, in addition to marginal cost of generation, that often rises real-time LMPs. When demand is high in a certain location, consuming cheap renewables generation that was transmitted through congested grid would cause the locational marginal price at this location to become much higher than the marginal cost of renewables generation.

There are a few limitations to our results and many opportunities for future research. First, while the specific results only apply to energy storage that participates in the Midcontinent Independent System Operator wholesale market as a price-taker, the research highlights many important issues relevant to other jurisdictions and markets. For example, if significant new storage capacity were added to the grid, they may not arbitrage in the market as price-taker any more as their operation could affect locational marginal price and further change the emissions they induce. If the grid were decarbonized by deploying PV or wind, the results could also change in interesting ways, shaped by changes in locational marginal price, value of storage, and shifting arbitrage opportunities. Second, our study is focused on the MISO North and South grids, where coal is the dominant fuel and wind power is the main renewable. But in regions where the grid has significantly different fuel mix, for instance natural gas or renewables is the dominant fuel type, the impact of renewables on storage induced emissions may be different. Third, we use locational marginal prices to model operating patterns for storage but do not constrain the storage to only charge from the hypothetically co-located generator. Although co-located energy storage and renewable generation can have great economic and environmental values [27,52], this scenario is out of the scope of this study, but ripe for future analysis. Issues surrounding the impacts and opportunities for storage are multi-faceted and system dependent. Careful analysis of the impacts and policies promoting storage need to take these system issues into account.

5. Conclusion

We assess how grid-scale energy storage can interact with renewables in existing grids in the United States and how these interactions affect storage-induced emissions. By simulating storage in two grids with similar generator mixes (i.e., North and Central subregions in the Midcontinent Independent System Operator footprint) except for different levels of renewable penetration, we find that storage induced emissions would be substantially lower, by 42–64%, in the grid with much higher wind penetration. Because the charge–discharge patterns of storage are quite similar in the two regions (Fig. 2), the differences in emission intensities are a result of their marginal generation fuel mixes at times of charge and discharge (Fig. 3). Compared with the Central subregion, North has a much higher wind penetration (28% vs 4%), where wind steadily contributes significant shares to marginal generation from low to high system demand (or base- to peak-load). Without the additional wind resources, there would likely be more coal burned during base-load hours when storage charges from the grid, as in the case of the Central subregion (Fig. 3b), leading to higher emissions. In other words, high wind penetration and wind on the margin in the North grid importantly moderate storage-induced emissions by suppressing the differences between marginal emissions at charging and discharging times (Fig. 6).

CRediT authorship contribution statement

Yi Yang: Conceptualization, Investigation, Writing - original draft, Writing - review & editing. **Mo Li:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Supervision, Validation, Visualization, Writing - original draft, Writing - review & editing. **Timothy M. Smith:** Conceptualization, Project administration, Resources, Supervision, Writing - review & editing. **Elizabeth J. Wilson:** Conceptualization, Resources, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2020.115420.

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