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LETTER

Carbon dioxide emissions effects of grid-scale electricity storage in a decarbonizing power system

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Abstract

While grid-scale electricity storage (hereafter 'storage') could be crucial for deeply decarbonizing the electric power system, it would increase carbon dioxide (CO_2) emissions in current systems across the United States. To better understand how storage transitions from increasing to decreasing system CO_2 emissions, we quantify the effect of storage on operational CO_2 emissions as a power system decarbonizes under a moderate and strong CO_2 emission reduction target through 2045. Under each target, we compare the effect of storage on CO_2 emissions when storage participates in only energy, only reserve, and energy and reserve markets. We conduct our study in the Electricity Reliability Council of Texas (ERCOT) system and use a capacity expansion model to forecast generator fleet changes and a unit commitment and economic dispatch model to quantify system CO_2 emissions with and without storage. We find that storage would increase CO_2 emissions in the current ERCOT system, but would decrease CO_2 emissions in 2025 through 2045 under both decarbonization targets. Storage reduces CO_2 emissions primarily by enabling gas-fired generation to displace coal-fired generation, but also by reducing wind and solar curtailment. We further find that the market in which storage participates drives large differences in the magnitude, but not the direction, of the effect of storage on CO_2 emissions.

Introduction

In order to avert severe impacts of climate change on humans and natural systems, carbon dioxide (CO_2) emissions from the electric power sector must rapidly decrease (Fri *et al* 2010). Grid-scale electricity storage (hereafter 'storage') could be a key technology for decarbonizing the electric power system (Mileva *et al* 2016, Sisternes *et al* 2016, Denholm and Hand 2011, Deep Decarbonization Pathways Project 2015). At high penetrations of wind and solar, storage can reduce wind and solar curtailment by shifting generated electricity across time to meet demand (Mileva *et al* 2016). Furthermore, due to its flexibility, storage can help maintain grid reliability by providing ancillary services, such as regulation reserves (Das *et al* 2015, Denholm and Hand 2011). In both cases, storage operations enable greater electricity generation by low-carbon technologies and, in turn, lower system CO_2 emissions. Storage investment can also stimulate greater investment in low-carbon technologies (Linn and Shih 2016, Sisternes *et al* 2016).

Conversely, several recent studies suggest that grid-scale and behind-the-meter storage would increase CO_2 emissions in historic power systems (Hittinger and Azevedo 2015, Carson and Novan 2013, Fisher and Apt 2017). Using 2009 to 2011 data, Hittinger and Azevedo (2015) find that 90% efficient storage engaging in energy arbitrage would have increased CO_2 emissions in wholesale power markets across the US. To determine how storage affects system emissions, these studies use marginal emissions factors (MEFs), which predict the emissions associated with a marginal increase in electricity demand (Siler-Evans *et al* 2012). Because MEFs are calculated using historic data, the findings of these studies pertain to a specific set of generation mixes and fuel prices. As such, these studies yield little insight into how storage will affect CO_2 emissions as decarbonization efforts transform power systems. In light of this shortcoming, other papers have used dispatch models to quantify how storage affects emissions. For instance, Tuohy and O'Malley (2009) find that storage would increase CO_2 emissions while engaging in energy arbitrage in the Irish power system at high wind penetrations.

When engaging in energy arbitrage, storage's effect on CO_2 emissions depends on which power plants charge storage and which power plants storage displaces when discharging (Arbabzadeh *et al* 2016). In historic and current systems, storage would typically charge at night and discharge during the day, when coal and natural gas are the respective marginal fuels (Hittinger and Azevedo 2015). By enabling a shift from gas-fired to coal-fired generation, storage would increase CO_2 emissions (Arbabzadeh *et al* 2016). However, as power systems decarbonize, the generation mix, marginal fuel types, and intra-day price differentials will change. These changes, in turn, may shift storage operations and their effects on system emissions, but the speed and extent to which such changes may occur remains unclear. Better understanding these dynamics would not only inform the long-term utility of storage in decarbonization efforts, but also have direct near-term relevance to policies promoting storage.

Although most studies examine how storage affects emissions via energy arbitrage, storage often instead provides ancillary services (Denholm *et al* 2013, GTM-Research 2016). Given growing flexibility needs of decarbonizing power systems (Lew *et al* 2013), this trend will likely continue. Prior research on storage's effect on CO_2 emissions when providing ancillary services has limited applicability to current or decarbonized systems, as it has been done on a 30 bus test system (Lin *et al* 2016) or electric vehicles (Sioshansi and Denholm 2009).

In this paper, we quantify the operational effects of storage on system CO_2 emissions through 2045 as a power system decarbonizes. We consider two decarbonization targets of reducing CO_2 emissions from electricity generation by 50% and 70% below 2015 levels by 2050. Under each target, we compare the effect of storage on operational system CO_2 emissions when storage participates in only energy, only reserve, and energy and reserve markets. Using scenario analysis, we test the sensitivity of our results to the type of decarbonization policy, natural gas price, coal-fired generator retirements, and storage capacity and efficiency.

Methods

In order to capture detailed fleet composition and operational changes, we leverage two power system optimization models in sequence. First, we forecast changes in the generator fleet every 5 years from 2020 through 2045 using a capacity expansion (CE) model and accompanying heuristics. Second, using generator fleets output by the CE model, we quantify operational system CO_2 emissions with and without storage with a unit commitment and economic dispatch (UCED) model. Given its high computational requirements, we run the UCED model every 10 years from 2025 through 2045. To ground our analysis, we also run the UCED with our initial generator fleet with and without storage in 2015. We construct the CE and UCED models in the General Algebraic Modeling System Version 24.4 (GAMS Development Corporation 2013) and solve them using CPLEX Version 12 (IBM 2014).

We conduct our analysis in the Electricity Reliability Council of Texas (ERCOT) power system due to its plentiful wind and solar resources (US National Renewable Energy Laboratory 2016), diverse fuel mix (ERCOT 2016c), and negligible power flows with neighboring systems (ERCOT 2016c). To construct our initial generator fleet, we modify the 2015 ERCOT generator fleet in the National Electric Energy Data System (US Environmental Protection Agency 2015) (see supplementary information (SI) available at stacks.iop.org/ERL/13/014004/mmedia for full details). We obtain future fuel prices from the US Energy Information Administration (US Energy Information Administration 2015, 2016) and Environmental Protection Agency (US Environmental Protection Agency 2013) (SI).

The CE and UCED models share several features. First, given recent transmission buildouts in ERCOT to accommodate wind generation (ERCOT 2015b), we assume transmission will keep pace with generator additions, so ignore transmission in our analysis (Craig *et al* 2017). Second, since ERCOT has limited interconnections with neighboring systems (ERCOT 2016c), we ignore power imports and exports. Third, to capture spatial and temporal variability in wind and solar generation, we match wind and solar plants to hourly simulated wind and solar generation profiles (US National Renewable Energy Laboratory 2010, 2012) and include them as dispatchable resources (SI).

CE model

The CE model optimizes generator additions and electricity generation and reserve provision by added and existing generators in order to minimize costs under system- and generator-level unit commitment constraints (SI). System constraints ensure hourly electricity generation and reserve provision meet electricity demand and reserve requirements, total installed capacity meets the current ERCOT planning margin target (13.75% above peak net demand) (Peterson *et al* 2014), and total annual CO_2 emissions comply with a CO_2 emission cap. Costs minimized by the CE model equal fixed operation and maintenance (O&M)

Table 1. Reserve types, response timeframes, and hourly requirements in the CE and UCED models (Lew *et al* 2013). *SR* and *WR* indicate reserve requirement components based on wind and solar generation, respectively, and *r* and *f* indicate regulation and flexibility reserves. Reserve requirements vary hourly with load and wind and solar generation.

Type	Response timeframe (min)	Hourly requirement
Regulation	5	$\sqrt{(1\%\text{ hourly load})^2 + SR_r^2 + WR_r^2}$
Flexibility	10	$\sqrt{SR_f^2 + WR_f^2}$
Contingency	30	3% hourly load

and capital costs of added generators, plus variable electricity generation and start-up costs of added and existing generators. In order to isolate the effect of adding storage to our system and given significant uncertainty in future demand, we use 2015 hourly demand from ERCOT (ERCOT 2016a) (SI) and assume no load growth over our study period, deferring analysis on how storage affects emissions under future demand scenarios to future work.

In each time step, the CE model can add any number of coal steam with carbon capture and sequestration (CCS), natural gas combined cycle (NGCC), NGCC with CCS, nuclear, wind, and solar generators (see SI for technology parameters). Given our focus on storage operations, we do not include storage in the CE model, but rather perform a parametric analysis of storage additions to the generator fleet optimized in the CE model. To account for generator retirements, we retire generators based on age before each CE run and based on economic performance before and after each CE run (Short *et al* 2011) (SI).

To account for variable wind and solar generation and for generator and transmission outages, the CE model includes three reserve types (Lew *et al* 2013) (table 1) (SI). Given grid flexibility challenges of insufficient generation and the ability to curtail excessive (i.e. under-forecasted) renewable generation, we model all three reserve types as positive reserves, i.e. procure capacity for increasing generation (Lew *et al* 2013). Additionally, given current standard operations, only coal steam, oil and gas steam, and NGCC units can provide reserves (Denholm *et al* 2013). For computational tractability, we run the CE model in hourly intervals for two representative contiguous days per season, the day with peak annual net demand, and the day with the peak annual change in hourly net demand, where net demand equals demand minus solar and wind generation (SI).

UCED model

The UCED model optimizes electricity generation and reserve provision in order to minimize operational costs while meeting electricity demand, reserve requirement, and generator-level unit commitment constraints (SI). The UCED model includes the same reserve types, timeframes, and requirements as the CE model (table 1). Minimized operational costs equal variable electricity generation, regulation reserve provision, and start-up costs. Regulation provision costs, which account for increased variable operation and maintenance costs and heat rate degradation, equal \$10, \$6, and \$4 ($\$_{2012}$) per megawatt-hour (MWh) for coal, NGCC, and oil and gas steam units, respectively (Denholm *et al* 2013, PJM 2016, Lin *et al* 2016). These regulation provision costs generally agree with the median day-ahead regulation up clearing price in ERCOT from 2013 through 2015 of \$5.9 MWh^{-1} (75% CI of [2.6, 16.9] $\$\,\text{MWh}^{-1}$) (ERCOT 2015a). Since the UCED model determines the commitment but not dispatch of reserves, we provide a first-order estimate of the effect of emissions due to dispatching reserves provided by storage on our results (SI).

In order to account for inter-day generator operations, the UCED model runs hourly for a 24 hour optimization window plus a 24 hour look-ahead period. The solution of the first 24 hour period determines the initial conditions for the following UCED run. Since we run the UCED model in overlapping 48 hour periods for an entire year, we cannot include a constraint on annual CO_2 emissions. Consequently, from 2020 through 2045 when we enforce a CO_2 emission limit, we convert the relevant annual CO_2 emission limit to a shadow CO_2 price using a simple economic dispatch model (SI), then include that shadow CO_2 price in generators' operational costs in the UCED model. Note that these shadow CO_2 prices do not represent real costs, but rather function as a compliance mechanism with the annual CO_2 emission limit in the UCED model (Craig *et al* 2017).

Storage model

We quantify system CO_2 emissions with the UCED model without storage and with storage participating in only energy, only reserve, and energy and reserve markets. To reflect variable O&M costs (He *et al* 2016), we assume electricity generation and regulation reserve provision costs of storage equal \$2 MWh^{-1} (Lazard 2016). To model initial large-scale storage deployment in ERCOT, we add 500 MW of storage to the fleet optimized in the CE model regardless of the market in which storage participates. This storage capacity equals less than 1% of our 2015 generator fleet and 40% of the 2020 California storage mandate (California Public Utilities Commission 2014), although we also parametrically model 1.5 GW of storage as detailed below. Table 2 details how we parameterize storage given the market it participates in.

Table 2. Storage parameters given the market in which it participates, and which storage technology each set of parameters is based on given real-world applications of each technology (Randall 2017, Hittinger and Azevedo 2015, San Martin *et al* 2013).

Market(s) storage participates in	Power capacity (MW)	Energy capacity (MWh)	Efficiency (%)	Max ramp rate (MW min^{-1})	Represented storage technology
Only energy	500	4000	81	8.3	Pumped hydropower
Only reserves	500	2000	81	500	Lithium ion battery
Energy and reserves	500	2000	81	500	Lithium ion battery

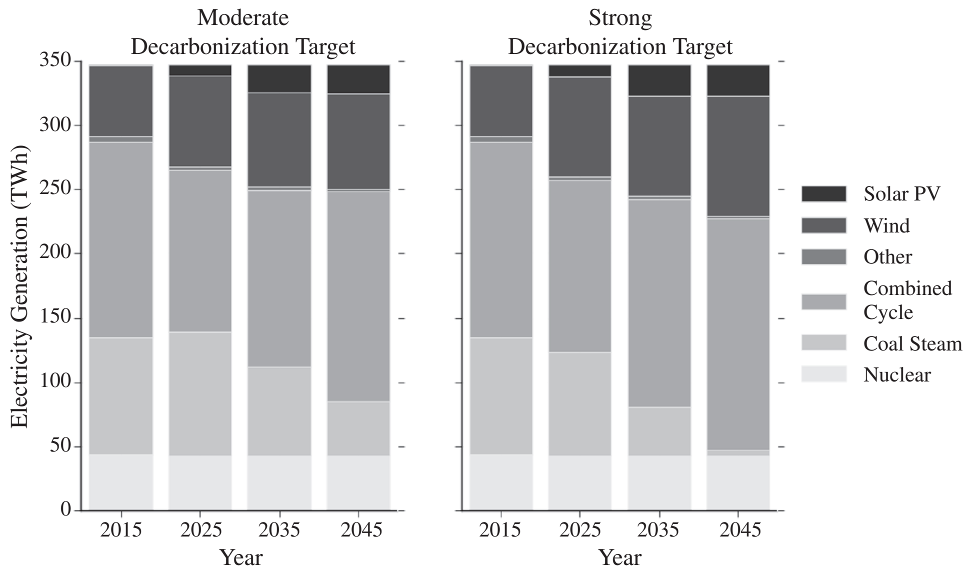

Figure 1. Electricity generation by fuel type in each analyzed year under the moderate (left) and strong (right) decarbonization target.

Scenarios

We assess moderate and strong power system decarbonization targets of 50% and 70% below 2015 levels by 2050, respectively. To ensure annual CO_2 emission caps bind emissions each year, we estimate 2015 CO_2 emissions from electricity generation in ERCOT as 175 million tons by running our UCED model with our 2015 fleet and no shadow CO_2 price. To test the sensitivity of our results to the type of decarbonization policy, we also consider two scenarios in which we enforce each decarbonization target in the CE but not UCED model. These scenarios approximate decarbonizing only through changes to fleet composition, e.g. with a clean energy standard. To test the sensitivity of our results to key storage and fleet parameters under each decarbonization target, we also consider scenarios with early coal-fired generator retirements (at 45 rather than 65 years old), low natural gas prices (3.1–3.8 $\$_{2012}$ MMBtu^{-1} from 2020–2045), and high storage capacity (1.5 GW) and storage efficiency (90%) (SI).

Results

Annual generation and reserve provision by fuel type without storage

Figure 1 provides annual generation by fuel type output by our UCED model without storage across years and decarbonization targets. Our 2015 generation mix largely agrees with the observed 2015 generation mix in ERCOT of 48% NGCC, 28% coal, 11% nuclear, and 11% wind (ERCOT 2016b). Coal-fired generation increases in 2025 under the moderate decarbonization target due to rising natural gas prices and a weak CO_2 emission limit. Otherwise, as CO_2 emission limits tighten, wind, solar, and NGCC generation gradually displace coal-fired generation. Without storage in the fleet, NGCC generators provide more than 80% of each reserve type across years and decarbonization targets, while coal-fired generators provide most of the remainder (SI). Through 2045, reserve provision by NGCC generators partially or fully displaces that by coal-fired generators, depending on the reserve type and decarbonization target.

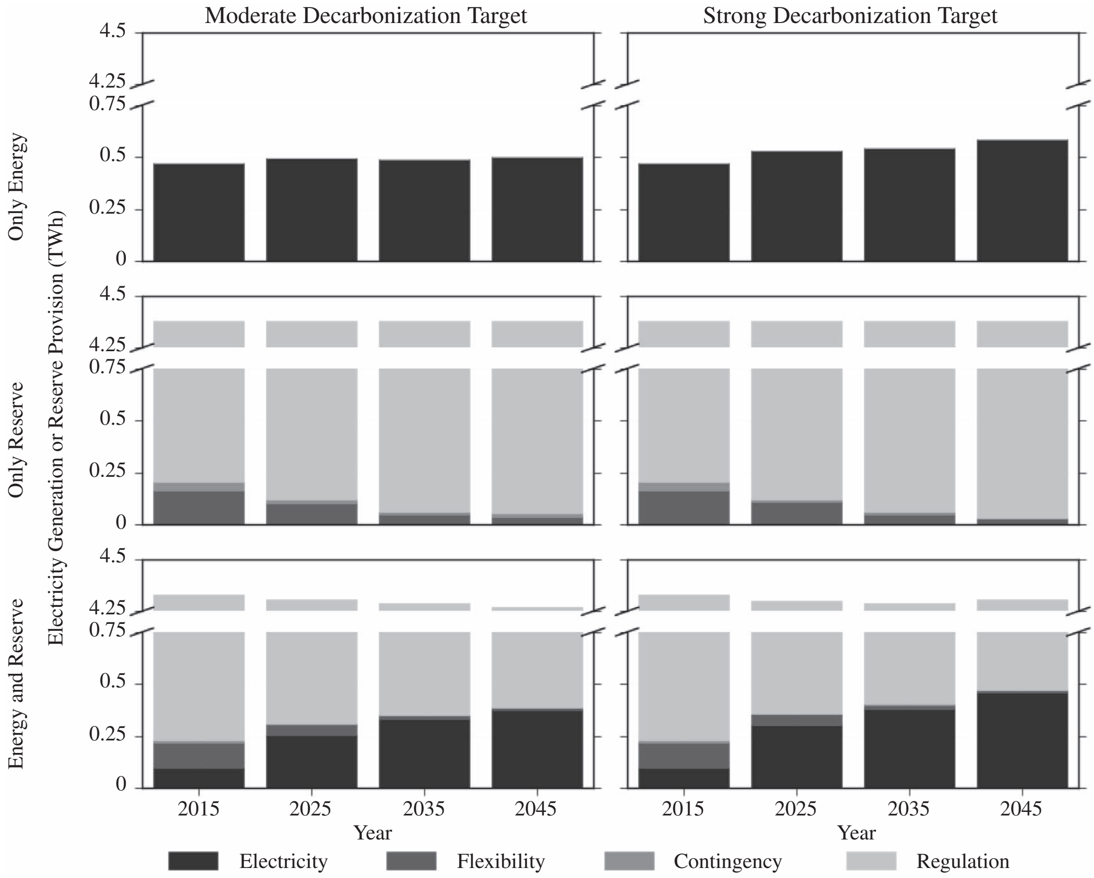

Figure 2. Storage electricity generation or flexibility, contingency, or regulation reserve provision under the moderate (left) and strong (right) decarbonization targets when storage participates in only energy (top row), only reserve (middle row), or energy and reserve (bottom row) markets.

In the scenarios without storage, tightening annual CO_2 emission limits drive changes in electricity generation and reserve provision through changes in fleet composition and operations. Fleet capacity increases from 93 GW in 2015 to 100 and 104 GW in 2045 under the moderate and strong decarbonization targets, respectively, as combined wind and solar capacity grows from 14 GW to 32 and 37 GW, respectively, and coal-fired capacity shrinks from 19 GW to 8 and 3 GW, respectively (SI). Shadow CO_2 prices, which capture operational changes in the UCED model, range from \$0–13 ton^{-1} and \$0–43 ton^{-1} under the moderate and strong decarbonization targets, respectively, from 2015 to 2045 (SI).

Storage operations

Across years and decarbonization targets, utilization of storage is significantly less when it participates only in the energy market than when it participates only in reserve markets or in both energy and reserve markets (figure 2). Furthermore, when participating in energy and reserve markets, storage provides 10–40 times more reserves than energy. When providing reserves, storage primarily provides regulation reserves due to its operational flexibility and low offer cost. In fact, storage provides 50%–80% of regulation reserve requirements when participating in only reserve or both energy and reserve markets across years and decarbonization targets.

Over time, two shifts in storage operations occur that indicate increasing value of storage for load balancing. First, when participating in energy and reserve markets, storage provides progressively more energy and less reserves through 2045, such that provided energy increases from 2015–2045 by four and five times under the moderate and strong decarbonization targets, respectively (figure 2). Second, when only participating in energy markets, daily peak discharge by storage shifts with daily peak net demand as increasing wind and solar generation shift the latter from late afternoon in 2015 to early evening in 2045 (figure 3). When participating in both energy and reserve markets, peak daily discharge by storage occurs later in the evening than when only participating in energy markets in order to maintain a sufficient charge for reserve provision throughout the day (figure 3). Notably, charging operations also change across years, as storage begins to charge midday in 2035 when participating in only energy and in both energy and reserve markets, paralleling growth in solar generation.

Effect of storage on generation by fuel type

Generator-level electricity generation output by our UCED model indicates that storage affects system CO_2

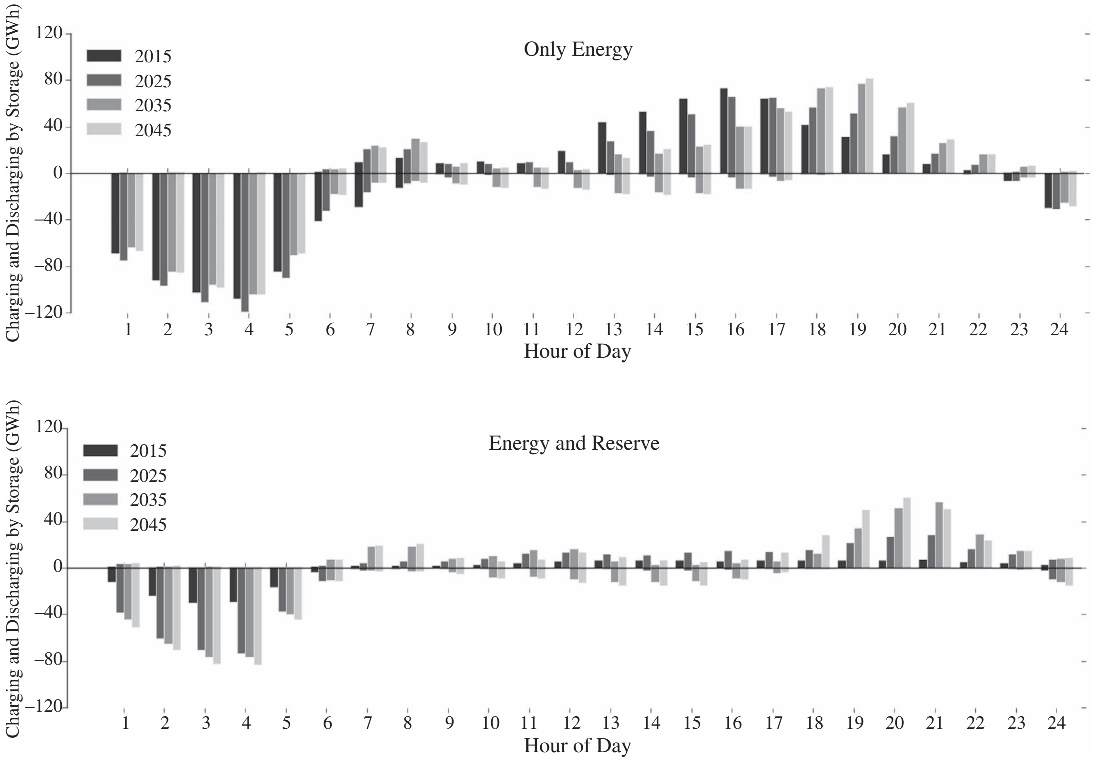

Figure 3. Discharging (positive values) and charging (negative values) by storage for each hour of the day summed across all days in each year from 2015 through 2045 under the moderate decarbonization target when only participating in the energy market (top) and when participating in both energy and reserve markets (bottom). Similar results occur under the strong decarbonization target. Note that hours with charging and discharging do not indicate concurrent charging and discharging, but rather that over all days in the year, storage charges in that hour on some days and discharges in that hour on other days.

emissions by changing other generators' operations in several ways. When providing energy, charging and discharge storage enables a shift in power output between generators across time. Additionally, when providing reserves, storage offsets reserves from other generators. Consequently, economic generators may increase their generation, whereas uneconomic generators primarily online to provide reserves may turn off.

When participating in only the energy market, storage enables a shift from gas-fired to coal-fired generation in 2015 and 2025 under both decarbonization targets (figure 4), when CO_2 emission limits are weak. In 2035, storage switches to enabling a shift from coal-fired to gas-fired generation under the moderate target and from coal-fired to gas-fired, wind, and solar generation under the strong target. In 2045 under the moderate target, storage enables a shift from coal-fired to gas-fired generation to a greater extent than in 2035. In 2045 under the strong target, though, a tight CO_2 emission limit and the near elimination of coal-fired generation leads storage to enable a switch from inefficient gas-fired to lower-CO_2-emitting gas-fired, wind, and solar generation (SI). Across years, storage reduces wind curtailment under both decarbonization targets and reduces solar curtailment under the strong target. Across years and decarbonization targets, storage reduces wind curtailment by 10%–30% and solar curtailment by 0%−20% so that wind and solar curtailments are each less than 2% of total wind and solar generation. Reduced curtailments as a result of storage are higher for wind than solar due to wind's higher generation share (figure 1) and the lower correlation of demand with wind (−0.1) than solar (0.4) generation. As wind and solar penetration increase through 2045, storage tends to reduce wind and solar curtailment more.

When participating only in reserve markets, storage enables a shift from gas-fired to coal-fired generation in 2015 under both decarbonization targets (figure 4). Specifically, reserves provided by storage allow economic coal-fired generators to shift from reserve provision to electricity generation. Furthermore, due to higher storage utilization in reserve than energy markets, storage increases coal-fired generation by an order of magnitude more in 2015 when providing reserves instead of energy. In 2025, storage switches to enabling a shift from coal-fired to gas-fired generation under both targets. Due to higher storage utilization in reserve than energy markets, storage increases gas-fired generation significantly more in 2025–2035 when providing reserves instead of energy. However, under the moderate target, storage shifting coal-fired to gas-fired generation decreases each year through 2045, such that by 2045, storage has a smaller effect on generation by fuel type when participating in only reserve markets than in only the energy market. This downward trend

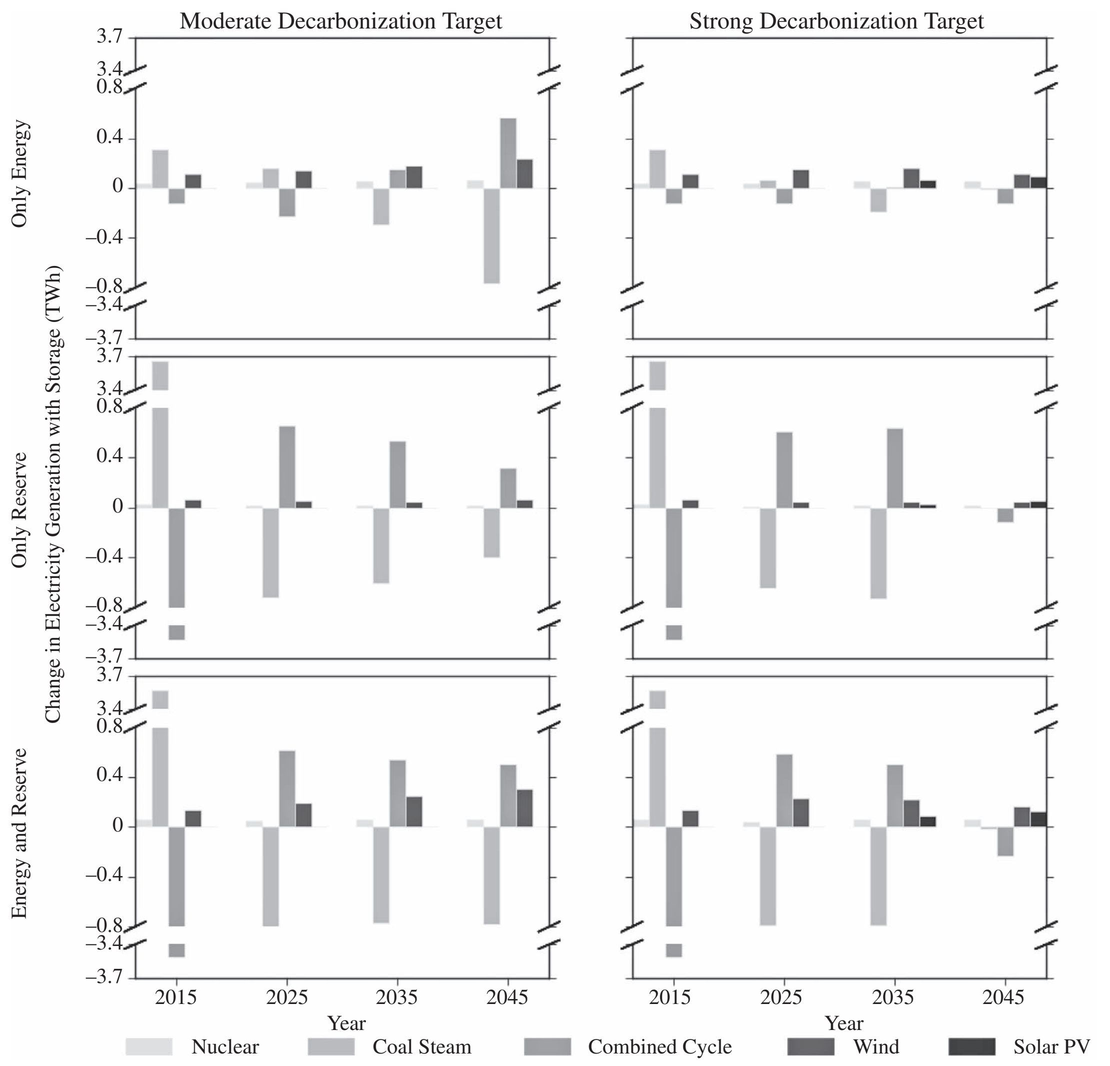

Figure 4. Change in generation by fuel type with storage versus without storage under the moderate (left) and strong (right) decarbonization targets when storage participates in only energy (top row), only reserve (middle row), or energy and reserve (bottom row) markets. Positive values indicate storage increases generation.

reflects decreasing reserve provision by coal-fired generators (SI). In 2045 under the strong decarbonization target, storage switches to causing a shift from inefficient gas-fired to lower-CO$_2$-emitting gas-fired, wind, and solar generation (SI).

When participating in reserve and energy markets, storage has similar but larger effects on generation by fuel type compared to when it participates in only energy or in only reserve markets across most years and decarbonization targets (figure 4). In 2015, storage enables a shift from gas-fired to coal-fired generation, then switches in 2025 to enabling a shift from coal-fired to gas-fired generation. In 2045 under the strong decarbonization target, storage further switches to enabling a shift from inefficient gas-fired to efficient gas-fired, wind, and solar generation (SI). Notably, across years and decarbonization targets, storage also reduces wind curtailments by 25%–50% more and solar curtailments by 0%–100% more when participating in energy and reserve markets than in only energy or in only reserve markets.

Change in system CO$_2$ emissions

Storage's effect on generation by fuel type as determined by our UCED model largely drives its effect on operational system CO$_2$ emissions (see the SI for equation used to calculate change in CO$_2$ emissions) (figure 5). Across our analysis, storage only increases CO$_2$ emissions in 2015, when storage enables a shift from gas-fired to coal-fired generation (figure 4). Furthermore, in 2015, storage increases CO$_2$ emissions by over an order of magnitude more when participating in only reserve or in both energy and reserve markets than in only the energy market. This result reflects large differences in how much storage increases coal-fired generation in 2015 when participating in different markets (figure 4).

Under the moderate decarbonization target, storage decreases system CO$_2$ emissions from 2025 through 2045, regardless of the market in which it participates (figure 5). When only participating in the energy market, storage enables progressively greater CO$_2$ emission reductions through 2045. Conversely, when

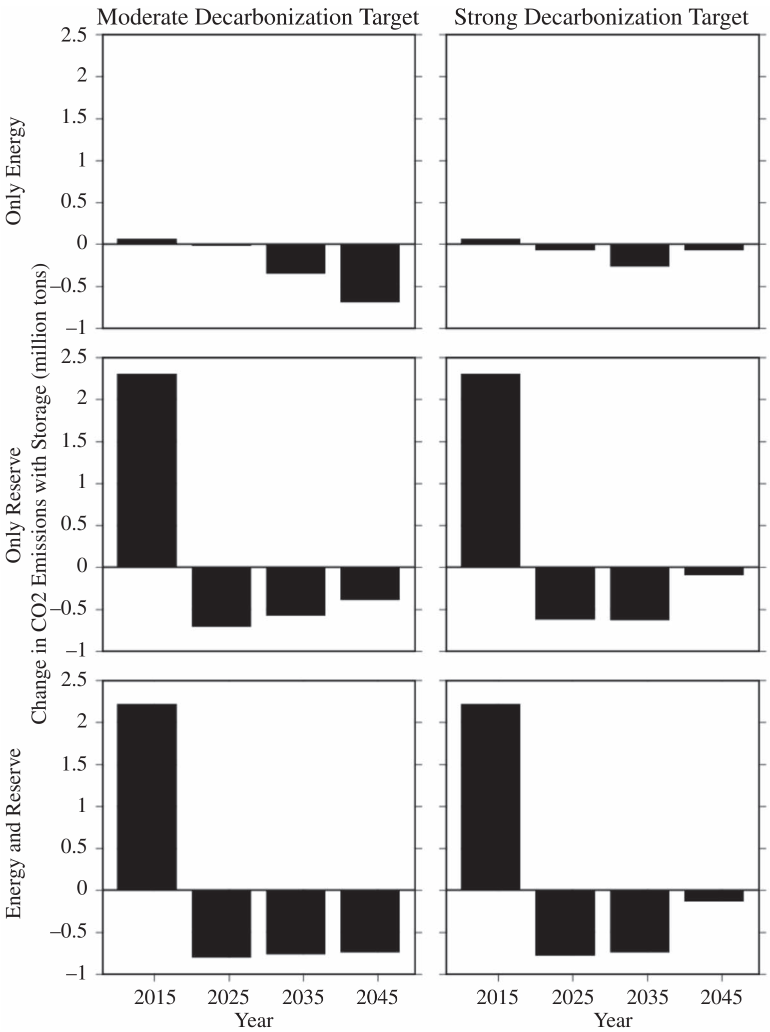

Figure 5. Change in system CO_2 emissions with storage versus without storage under the moderate (left) and strong (right) decarbonization targets when storage participates in only energy (top row), only reserve (middle row), or energy and reserve (bottom row) markets. Positive values indicate storage increases CO_2 emissions.

only participating in reserve markets, storage enables diminishing reductions in CO_2 emissions through 2045. These results parallel trends in how storage reduces coal-fired generation (figure 4). However, from 2025 to 2045 storage achieves the greatest system CO_2 emission reductions when participating in both energy and reserve markets.

Under the strong decarbonization target, storage reduces CO_2 emissions from 2025 through 2045 regardless of the market in which it participates, like under the moderate decarbonization target (figure 5). Furthermore, the effect of storage on CO_2 emissions in 2025 and 2035 is similar in relative and absolute magnitude across markets under both decarbonization targets. Unlike under the moderate target, though, CO_2 emission reductions from storage are lower in 2045 than in 2035, by 75%–85%. These diminishing reductions associated with storage in the strong decarbonization target do not correspond to lower storage utilization (figure 2), but rather to storage switching from enabling a shift from coal-fired to gas-fired, wind, and solar generation to enabling a shift from inefficient gas-fired to lower-CO_2-emitting gas-fired, wind, and solar generation (figure 4, SI).

Changes in CO_2 emissions due to storage when participating in only reserve or in both energy and reserve markets shown in figure 5 only account for commitment of reserves, but dispatching of reserves provided by storage could incur additional CO_2 emissions. As detailed in the SI, we conduct a first-order analysis of emissions associated with the dispatch of regulation reserves provided by storage. From 2025 to 2045 under both decarbonization targets, these emissions would negate 6%–51% of CO_2 emission reductions due to storage when participating in only reserve or in both energy and reserve markets.

Sensitivity analysis

To test the robustness of our results, we conduct several sensitivity analyses under the moderate and strong decarbonization targets (SI). When we include CO_2 emission limits in our CE model but do not include shadow CO_2 prices in our UCED model, storage increases CO_2 emissions through 2035 under both decarbonization targets and in 2045 under the moderate decarbonization target regardless of the market in which it participates. In these instances, although NGCC and renewable capacity supplant some coal-fired capacity over time, storage primarily enables a shift from gas-fired to cheaper coal-fired generation. While storage also reduces wind and solar curtailment, consequent emission reductions are less than emissions from greater coal-fired generation. Conversely, in 2045 under the strong decarbonization target, storage reduces CO_2 emissions with no shadow CO_2 price across markets in which it participates, as storage primarily enables a shift from gas-fired to wind and solar generation. Notably, in that year coal-fired generation is nearly eliminated and wind and solar generation account for a third of total electricity (figure 1), roughly indicating the fleet mix at which storage would begin to reduce emissions when decarbonizing only via fleet composition changes.

Under both decarbonization targets, tripling storage capacity from 0.5–1.5 GW amplifies the effect of storage on CO_2 emissions. For example, under the moderate decarbonization target, 1.5 GW of storage increases CO_2 emissions one to four times more in 2015 and decreases CO_2 emissions two to four times more in 2025 through 2045 than 0.5 GW of storage. At a higher capacity, storage provides more energy and reserves, which enables larger changes in generation by fuel type in each year. Increasing storage efficiency from 81% to 90% does not significantly change how storage affects system CO_2 emissions.

Under both decarbonization targets, low natural gas prices also do not significantly change our results, as adding storage to the generator fleet reduces CO_2 emissions from 2025 through 2045. Across years, decarbonization targets, and which market storage participates in, these emission reductions are greater than, equal to, or less than those achieved by storage under the base scenarios. Under both decarbonization targets and low natural gas prices, gas-fired capacity, including with CCS under the strong decarbonization target, increases through 2045 and fully displaces coal-fired capacity in 2045. Consequently, through 2035 storage reduces CO_2 emissions primarily by enabling a shift from coal-fired to gas-fired and wind generation, and in 2045 reduces emissions primarily by enabling a shift from higher-CO_2-emitting gas-fired to CCS-equipped gas-fired and wind generation.

In the early coal-fired generator retirements scenarios, storage leads to smaller CO_2 emission reductions than in the base scenarios under both decarbonization targets. Early coal-fired retirements rapidly decrease coal-fired capacity and generation. Under the moderate decarbonization target, adding storage to the generator fleet increases coal-fired generation from remaining coal plants without exceeding the CO_2 emission limit through 2045. Consequently, under the moderate target, storage either increases CO_2 emissions or reduces them significantly less than in the base scenario through 2045. Conversely, under the strong decarbonization target, storage reduces coal-fired generation from remaining coal plants due to the strong CO_2 emission limits through 2045, like in the base scenario. Consequently, under the strong target, storage reduces CO_2 emissions, albeit often by less than in the base scenario, through 2045.

Discussion

To better understand how storage affects operational system CO_2 emissions as a power system decarbonizes, we quantified how storage affects CO_2 emissions from 2015 through 2045 under CO_2 emission reduction targets of 50% and 70% below 2015 levels by 2050. Like prior studies (Hittinger and Azevedo 2015, Carson and Novan 2013), we found that storage would increase CO_2 emissions in the 2015 ERCOT system. However, under both decarbonization targets, we found that storage would reduce CO_2 emissions within 10−20 years, well before deep decarbonization. Storage achieves these emission reductions by enabling a shift from coal-fired to gas-fired generation and, to a lesser extent, by reducing wind curtailment. Furthermore, we found that storage achieved greater emission reductions in systems with significant coal-fired capacity than in systems where gas-fired, wind, and solar capacity had nearly eliminated coal-fired capacity. Thus, storage can further decarbonization efforts not only in deeply decarbonized systems with high renewable penetrations, but also in moderately decarbonized power systems with high coal-fired capacity and relatively low renewable penetrations.

Given that storage units will participate in reserve markets rather than or in addition to the energy market, we also compared how storage affects CO_2 emissions while participating in only energy, only reserve, or energy and reserve markets. We found that the market in which storage participates can significantly change the magnitude, but not the direction, of the effect of storage on system CO_2 emissions. Across years and decarbonization targets, storage reduces CO_2 emissions the most when participating in both energy and reserve markets.

Via sensitivity analysis, we found that decarbonizing only through fleet composition (and not operational) changes flipped storage from a net-negative to net-positive CO_2 emission technology except when coal-fired generation was nearly eliminated and wind and solar generated a third of total electricity. Thus, storage may have significantly different effects on CO_2 emissions in systems with decarbonization policies that affect system composition and operation, e.g. a carbon tax, versus only system composition, e.g. a clean energy standard. We also found that early coal-fired generator retirements, by reducing CO_2 emissions and consequently the implicit cost of CO_2 emissions under an emission limit, could reduce or negate the emission benefits of storage, although storage applications in other contexts, e.g. co-located with wind farms, may still yield emission benefits. Conversely, our results were robust to higher storage capacity and efficiency and lower natural gas prices.

Our analysis has several limitations that could be addressed in future work. First, we do not optimize for storage deployment in our CE model, which would likely increase wind and solar deployment (Sisternes *et al* 2016, Linn and Shih 2016). Higher renewable penetrations would likely cause storage to reduce renewable curtailment and emissions more. However, it would also reduce the implicit CO_2 emission cost under the cap and, consequently, potentially reduce the shift from coal- to gas-fired generation enabled by storage. Thus, the net effect of optimizing storage deployment in our CE model on how storage affects operational system CO_2 emissions is uncertain. Second, we estimate storage energy losses and emissions associated with dispatching of reserves after rather than within the UCED model, which could lead to overestimation of reserves provided by storage. Third, by dispatching generators at an hourly resolution, we may underestimate renewable energy curtailment and renewable integration benefits of storage. Fourth, transmission constraints, which we ignore here, could drive spatial heterogeneity in the effects of storage on system CO_2 emissions.

Finally, considering system operational costs in addition to emissions associated with storage could highlight win-wins or trade-offs between the two and further inform policymaking. For instance, in the near-term, our analysis indicates that using storage to provide energy leads to a smaller increase in emissions compared to using storage only for reserves or for energy and reserves. If storage used only for energy also leads to lower costs, then given a storage deployment mandate, policies encouraging storage to participate in energy rather than reserve markets could yield best possible cost and emission outcomes.

Conclusion

Our results indicate that policies promoting storage can yield operational CO_2 emission reductions in the mid-term if comprehensive decarbonization policies, like a carbon tax, exist. Furthermore, policies can significantly change how storage affects CO_2 emissions by encouraging participation in energy and/or reserve markets. Thus, storage can play a significant role in decarbonization efforts in the mid- and long-term, but storage-specific and decarbonization policies play a key role in determining whether and to what extent this occurs.

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