# Emissions Impacts of Wind and Energy Storage in a Market Environment

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**Abstract**

This study examines the emissions impacts of adding wind and energy storage to a market-based electric power system. Using Texas as a case study, we demonstrate that market power can greatly effect the emissions benefits of wind, due to most of the coal-fired generation being owned by the two dominant firms. Wind tends to have less emissions benefits when generators exercise market power, since coal-fired generation is withheld from the market and wind displaces natural gas-fired generators. We also show that storage can have greater negative emissions impacts in the presence of wind than if only storage is added to the system. This is due to wind increasing on- and off-peak electricity price differences, which increases the amount that storage and coal-fired generation are used. We demonstrate that this effect is exacerbated by market power.

## Introduction

Recent years have seen increased interest in renewable electricity in the U.S. and elsewhere. This interest has been driven by several factors, one of which is the emissions and environmental impact of conventional fossil-fueled generation. Wind has pr expansion, due to its currently being the lowest-cost technology and the abundance of wind remodel to represent the interactions between conventional generators, wind, and storage, which is used to derive the dispatch of the system over a one-year period (*24*). The optimized dispatch is combined with emissions rates estimates to model generator emissions of $CO_2$, $SO_2$, and $NO_x$ with and without wind and storage.

# Methods

Our analysis is based on the Electricity Reliability Council of Texas (ERCOT) system in 2005. ERCOT had about 2 GW of wind installed in 2005, which are included in the base system. We compare the base system to systems with up to 10 GW of added wind and up to 10 GW of storage with up to 20 hours of charging capacity. For purposes of comparison, ERCOT had about 83 GW of generation capacity installed and a peak load of 60 GW in 2005.

## Ownership and Market Structure

ERCOT had about 81 GW of conventional (*e.g.* thermal and hydroelectric) generation installed in 2005, of which about 16 GW were coal-fired, 60 GW natural gas-fired, and the remaining used other fuels (*27*). These assets were divided between 53 firms. Of these, two firms—Luminant and Texas Genco—owned a large share of about 18% and 14% (on a capacity basis), respectively. Between them, these two firms owned about 65% of the coal-fired capacity in the system.

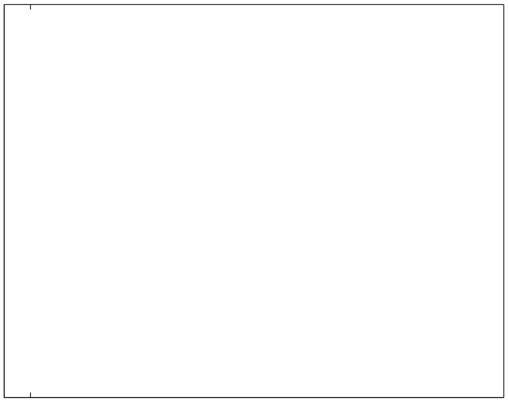
Analyses of the ERCOT market suggest that Luminant and Texas Genco have historically had a greater tendency to exercise market power than the other firms (*28, 29*). Thus we model wind and storage impacts under two market competitiveness cases: the first, which we refer to as the competitive case, assumes that all 53 generating firms behave perfectly competitively; the other, referred to as the oligopoly case, assumes that Luminant and Texas Genco behave as profit-maximizers while the remaining 51 firms behave competitively. Further details regarding the breakdown of generation ownership and the market competitiveness cases considered are given in the Supporting Information.

## Market Operation

In both the competitive and oligopoly cases, we assume that the generating firms submit supply functions, $q_{i,t}(p)$, to a market operator. The function $q_{i,t}(p)$ specifies the maximum amount of energy that firm $i$ is willing to supply in hour $t$ as a function of price. In the competitive case, the supply functions are the inverse of the firms' marginal cost functions. In the oligopoly case, Luminant and Texas Genco's supply functions are found by solving a profit-maximization problem, while the remaining firms submit supply functions equal to the inverse of their marginal cost functions. The derivation of these supply functions do not take into account dynamics of conventional straints on the storage plant and the availability of wind energy. Thus even in the competitive generation case, we assume the wind and storage choose their net sales to maximize profits. This allows us to capture the emissions impacts of competitiveness of the generation sector, without differences in the assumed behavior of wind and storage confounding the results. Storage constraints include roundtrip efficiency losses of the storage estimated using continuous emissions monitoring system (CEMS) data for the year 2005 obtained from the U.S. Environmental Protection Agency. The CEMS data record GJ of fuel burned and kg of $CO_2$, $SO_2$, and $NO_x$ released by each generator on an hourly basis.

## Wind Data

We use modeled wind generation data developed by 3TIER for the National Renewable Energy Laboratory's Western Wind and Solar Integration Study (WWSIS) to model wind generation. This dataset provide-1.8(n)3.9817569(v)-1.87468(i)-3.049O fueled generation in the competitive case as opposed to 45.8% in an oligopoly. The withholding of coal-fired generation occurs during low-load periods, in which the dominant firms' natural gas-fired generators are shutdown. By submitting above-cost bid compared to the competitive case, in which coal-fired generation is marginal and displaced by wind. Thus, the first 5.5 GW of wind added to the system have a relatively modest effect with an average of 111 MWh of coal-fired generation being displaced annually per MW of added wind capacity. The same 5.5 GW of wind have a much greater impact in the competitive case, with 896 MWh of coal-fired generation being displaced on average per MW of wind. Additional wind beyond the first 5.5 GW have a greater impact, however, since at sufficiently high penetrations coal-fired generation will increasingly be marginal and displaced. Each additional MW of wind beyond the first 5.5 GW results in annual coal-fired generation reductions of between 145 MWh and 389 MWh in the oligopoly case. This incremental wind has an even greater impact in the competitive case, however, with annual coal-fired generation reductions of between 1,097 MWh

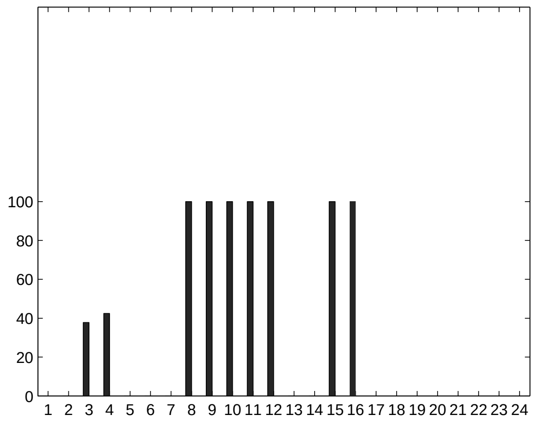


the shifting of generating loads results in marginal generators having lower emissions rates. These lower rates yield a $NO_x$ reduction, which outweighs the emissions increase caused by greater generation and the arbitraging effect.

## Joint Emissions Impacts of Wind and Storage

Adding wind and storage to a system together increases storage use compared to the storage-only case. This is because wind suppresses energy prices by displacing high-cost generation from the market. Since this price effect is associated with wind availability and hourly wind availability can be highly variable, wind increases hourly price differences and arbitrage opportunities. Our analysis assumes joint ownership of wind and storage, however the same effects persist in a disjoint-ownership case and storage use and emissions impacts will largely be the same in the two cases. This is because wind will have the same price-suppressing impact regardless of storage ownership.

Figure 3 shows, as an example, the operation of 5 GW of storageppog-389.104(673(t)-3.05095(h)-1.87468(e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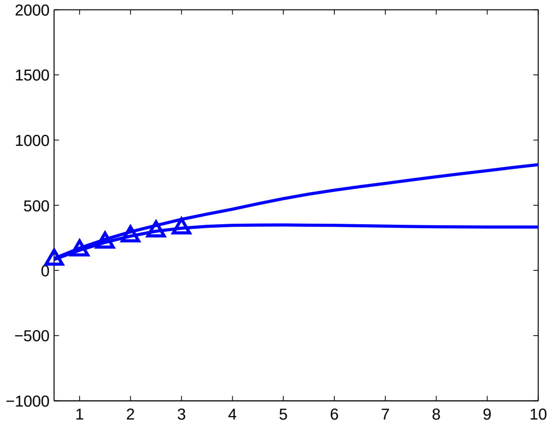
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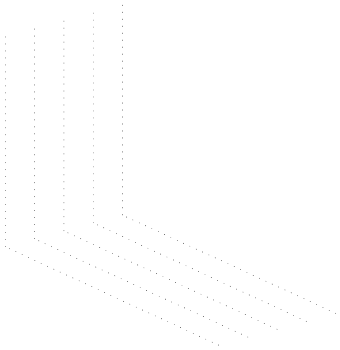
which is the emissions increase between the wind-and-storage and wind-only cases, less the emissions increase between storage-only and base cases. Thus $\xi_u$ measures the extent to which storage impacts generator emissions due to the increased arbitrage opportunities created by wind. Figure 6



viewed as providing bounds on the impacts of wind and storage. Some of the emissions fluctuations (*e.g.* non-smooth and non-monotone emissions impacts of wind and storage) are possibly specific to the 2005 data that we base our analysis on, and may not be general results. Nevertheless, the findings regarding shifting of generation between generating fuels and technologies would likely occur in other systems. This is because marginal generating technologies and emissions rates can differ by time of day and also be sensitive to market competitiveness. For instance, California has virtually no coal-fired generation. Nevertheless, hourly marginal emissions rates can vary depending on whether combined- or simple-cycle natural gas-fired generation is marginal (*35*).

Our analysis assumes joint ownership of wind and storage, because storage is considerably more valuable to a wind generator than to a standalone storage operator or conventional generator (*24*, *36*). As noted before, storage use and emissions impacts would largely be the same with disjoint ownership of wind and storage. Our joint-ownership assumption should not, however, be taken to suggest that wind and storage must or should be jointly owned. Our analysis further assumes that wind and storage are owned by a single profit-maximizing firm. Although wind ownership was rather concentrated in 2005 (Taneot bcippptlocnaser4]TJ -294.48 -23.885095(o)-1.8706(n)-353.

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# Supporting Information

## Emissions Impacts of Wind and Energy Storage in a Market Environment

# ERCOT Market Structure

For these reasons, we consider two market competitiveness cases. The first assumes that all firms behave competitively and submit cost-based bids. The second assumes that only the two largest firms exercise market power by submitting profit-maximizing bids into the market, while the remaining firms submit competitive cost-based bids. Given the empirical findings regarding market behavior, these are likely bounding cases, with the true impacts of wind and storage being closer to the oligopoly case. Table S2 summarizes the breakdown of generation technologies in the ERCOT market in 2005 between the dominant firms and the competitive fringe, on a capacity basis.

Table S2: Breakdown of thermal generation technologies between dominant firms and competitive fringe, on a capacity basis, in 2005.

| Generating Fuel | Dominant Firms | Competitive Fringe |
|---|---|---|
| Nuclear | 71 | 29 |
| Coal | 65 | 35 |
| Natural Gas Combined Cycle | 4 | 96 |
| Natural Gas Steam Turbine | 37 | 63 |
| Natural Gas Combustion Turbine | 55 | 45 |

## Conventional Generator Behavior

In both the competitive and oligopoly cases we assume that the conventional generators submit supply functions of the form $q_{i,t}(p)$ to the market. This function specifies how much energy firm $i$ is willing to generate in hour $t$ as a function of the price, $p$. In the competitive case, firms submit supply functions equal to the inverse of their marginal cost functions. We compute costs based on the portfolio of generators that each firm owns, generator heat rates reported by Global Energy problem:

$$\max_{p} \Pi_{i,t}(p) = p \cdot \left[ D_t(p) - X_t + \varepsilon_t - \sum_{j \in \omega(i)} s_{j,t}(p) \right] - c_i \left( D_t(p) - X_t + \varepsilon_t - \sum_{j \in \omega(i)} s_{j,t}(p) \right), \quad \text{(S1)}$$

where $\omega(i)$ denotes the set of profit-maximizing generating firms in the market other than firm $i$. The first-order necessary condition for each firm's optimal choice of $p$ can be manipulated to yield the following set of coupled differential equations (there will be one equation for each profit-maximizing firm):

$$q_{i,t}(p) = (p - c'_{i,t}(q_{i,t}(p))) \left( -D'_t(p) + \sum_{j \in \omega(i)} q'_j(p) \right). \quad \text{(S2)}$$

Eq. (S2) will typically have multiple solutions, however if the profit-maximizing generators are symmetric, then a unique symmetric equilibrium can be found by solving the following single differential equation:

$$q_t(p) = (p - c'_t(q_t(p))) \left( -D'_t(p) + (\hat{n} - 1) q'_t(p) \right), \quad \text{(S3)}$$

where $\hat{n}$ is the market Herfindahl-Hirschman index and the subscript $i$ has been eliminated due to symmetry (*44*).

As shown in Table S1, Luminant and Texas Genco are roughly symmetric in that they own similar shares of generating capacity in the market. Moreover, the composition of their generator fleets (*i.e.* generating technologies and fuels used) is fairly similar. Thus we model these two firms assuming that they are symmetric and follow the equilibrium supply functions given by Eq. (S3).

## Wind and Storage Optimization Model

Once we determine the supply functions submitted by the generators, we can define the price of energy in each hour in terms of net energy sales from wind and storage. If we let $D_t$ denote the actual system demand in hour $t$, the hour-$t$ energy price is given by:

$$p_t^{\square}(X_t) = \min_p \left\{ p \,\middle|\, \sum_i q_{i,t}(p) = D_t - X_t \right\}. \tag{S4}$$

Note that this function is defined in the same manner (although with different supply functions) in both the competitive and oligopoly cases. We assume that wind and storage are used to maximize profits, while accounting for the effect of $X_t$ on the price of energyaont920540 , 384044(u).3505( t (l) ]

The model is given by:

$$\max_{v,s,d,w,X} \sum_t p_t^{\square}(X_t) \cdot X_t + \rho \cdot w_t \tag{S5}$$

$$\text{s.t.} \quad v_t = v_{t-1} + s_t - d_t \qquad \forall\, t \tag{S6}$$

$$X_t + s_t - d_t/\eta = w_t \qquad \forall\, t \tag{S7}$$

$$0 \leq w_t \leq \bar{w}_t \qquad \forall\, t \tag{S8}$$

$$0 \leq s_t \leq \kappa \qquad \forall\, t \tag{S9}$$

$$0 \leq d_t \leq \eta\kappa \qquad \forall\, t \tag{S10}$$

$$0 \leq v_t \leq h\kappa \qquad \forall\, t \tag{S11}$$

Eq. (S5) is the objective function, which maximizes profit from energy sales and the wind PTC, which we assume to be \$30/MWh. Eq. (S6) defines the storage level in each hour in terms of charging and discharging decisions and the previous hour's storage level. Eq. (S7) relates net energy sales in each hour to wind energy used and energy stored and discharged. Eq. (S8) through Eq. (S11) impose limits on the wind use, charging, discharging, and storage level variables in each hour, based on the output of the wind generator and technical characteristics of the storage plant. The model places no restriction that storage only be charged using wind energy—thus wind and storage could be a net buyer of energy if it charges more energy than wind produces in an hour.

This model assumes that the added wind and storage are operated by a single profit-maximizing firm. While Table S3 shows that wind assets were relatively concentrated in 2005, this assumption can overstate the extent to which wind and storage can exercise market power by adjusting sales to maximize profits. Relaxing this assumption would not affect wind generation, since wind is never curtailed under our single-firm assumption. This is because the wind PTC makes wind sufficiently valuable that it is never beneficial to curtail generation. Storage use could increase, however, since it is profit-maximizing to reduce storage use from a competitive level to maintain higher price difference between on- and off-peak periods (*20, 36*). Based on our findings, especially contrasting the emissions effects of storage in the competitive and oligopoly generation cases, it is likely that this greater use of storage would yield higher generator emissions.

Table S3: Breakdown of wind generation assets, on a capacity basis, in 2005. The remaining seven firms each own less than 5% of the wind capacity in the market.

| Generating Firm | Generating Capacity (%) |
|---|---|
| FPL Group | 33 |
| Babcock and Brown | 14 |
| Shell Wind Energy | 13 |
| Desert Sky | 9 |
| Pecos Wind | 9 |
| Trent Wind | 8 |

This optimization framework can also be used to model the wind-only case by setting $h = 0$. Similarly, by fixing $\bar{w}_t =$

On the other hand, an SFE model yields a richer strategy space, which is also more reminiscent of actual electricity markets. Since it better represents the operation of actual electricity markets, we opt for the SFE-based model. Nevertheless, since the timing of market interactions can impact market outcomes, contrasting our results with a Cournot-type game would be a useful exer87468(e)-248.588(S