Intermittency or Uncertainty? Impacts of Renewable Energy in Electricity Markets

Paige Weber, Department of Economics, University of North Carolina at Chapel Hill, paigeweber@unc.edu
Matt Woerman, Department of Resource Economics, University of Massachusetts Amherst, mwoerman@umass.edu

Section 1: Overview

Renewables in the United States electricity sector have experienced rapid growth over the last decade, increasing from less than 2% of the generation mix in 2001 to greater than 12% in 2020 (EIA 2020). This trend is poised to continue with renewables accounting for a majority of capacity expansions in 2021 and planned expansions in 2022 (EIA 2022). Renewables offer the potential for a dramatic reduction in electricity sector pollution, and continued cost reductions in these technologies may provide lower electricity prices. Yet, the growth of renewables is not without concern. Predominant renewable resources—wind and solar energy—possess unique characteristics that may pose both technical and economic challenges to the operation of electricity grids: intermittency in generation stemming from exogenous changes in resource availability and uncertainty in generation due to forecast error.

In this paper, we decompose the overall effects of renewable resources on electricity markets outcomes by separately estimating the impacts of renewables' intermittency and renewables' uncertainty. Previous work has estimated the overall effect of wind and solar resources on prices, and a smaller subset of this work includes effects on price dispersion (Woo et al. (2011), Ketterer (2014), and Bushnell and Novan (2021)). In this paper, we separately identify the role of each of these characteristics on price levels and price dispersion. In doing so, we provide novel estimates of how renewables' forecast error impacts wholesale electricity prices. We also estimate how each of these characteristics affects the operations of non-renewables generators, which further identifies how renewables' forecast error imposes costs on electricity markets.

Section 2: Context

Our theoretical framework highlights that price effects across geographies and time need not be comparable in magnitude, as they are a function of the local supply curve elasticity where it intersects the residual demand, both of which are clearly unique across electricity markets. Yet, our estimate of wind generation's margin effect on price—1 GWh of wind reduces prices by $2.27 per MWh—falls within the range of estimates found in the literature. To demonstrate the mechanism generating differences across time and space, we estimate price effects separately in hours with high and low residual demand and show that price effects are larger in periods with higher residual demand. In describing these two sets of results, we avoid the term "merit-order effects" as this embeds several mechanisms in which renewables impact price outcomes. Rather, we distinguish between price effects coming from renewables reducing residual demand and those coming from the known and unknown quantity of renewables supply, where the second two effects can lead to price outcomes from changes in the effective supply curves of conventional generators. In that regard, perhaps our more important contribution is our decomposition of price effects and price dispersion effects based on the unique characteristics of renewables, including novel estimates of the impact of error in renewable energy forecasts on wholesale electricity prices.

In terms of renewables and price dispersion, Woo et al. (2011) and Mallapragada et al. (2021) also study price dispersion effects of wind in ERCOT. Compared with Woo et al. (2011), our paper studies Texas' market in more recent years, 2012–2019, which allows us to study a period with higher wind penetration, reaching 20% in our sample compared to 10% in their earlier study period. Further, we use a different approach to study the impact of renewables on price variance, and we also decompose the effects by the characteristics of renewables. The Woo et al. (2011) approach predicts how an increase in wind generation would impact price dispersion using the estimated variance from a linear model of price as a function of wind generation, which by construction is always positive. Our approach, on the other hand, directly estimates the impact of renewables on price dispersion using observed data to measure price dispersion. Notably, we find that overall renewable energy reduces price dispersion through its dampening effect on prices. Mallapragada et al. (2021) simulate wholesale electricity price distributions to 2050 under alternative constraints on carbon emissions. Their results indicate that more renewables increase price dispersion, increasing the frequency of periods of both very low and very high prices. Our estimation of current outcomes, however, indicates that renewables in Texas have had a dampening effect on price dispersion as they reduce the amount of energy demanded from conventional resources.

Our work contributes to a growing literature seeking to anticipate and prepare for the transition to an increasingly decarbonized electricity grid. There are a number of papers that have estimated the price effect of renewables stemming from their zero-marginal cost property, often termed the "merit-order effect." A survey of this literature by Würzburg, Labandeira, and Linares (2013) finds the estimated effects of one additional GWh of renewable energy have ranged from around to $0.40. to $13.00 per MWh in empirical settings across Europe and the US from studies written from 2001 to 2009. Sakaguchi and Fujii (2021) study the merit-order effects of wind and solar in Japan in the years 2016–2020 and find that wind has a larger price effect in hours with higher prices using quantile regression binning on price. Quint and Dahlke (2019) study the price effects on wind in the U.S. Midwest and document evidence of a lower marginal effect over time, attributed to an increase in wind generation. Cludius et al. (2014) and Zipp (2017) estimate price impacts from merit-order effects in Germany and Clò, Cataldi, and Zoppoli (2015) estimates these effects in Italy.

Section 3: Results

We find that an additional one GWh of wind generation reduces wholesale electricity prices in Texas by around $2.27 per MWh, and these effects are highly heterogeneous with the largest effects occurring in hours with high residual demand for conventional generators, defined as consumer demand less renewable energy. We also find that wind generation decreases dispersion of hourly prices because of its impact on decreasing prices by reducing residual demand. However, when controlling for this residual demand price dampening effect, renewables increase price dispersion. As with the price effect, the price dispersion effects are highly heterogeneous across the hours of the day and are larger when the residual demand is greater.

In our decomposition analysis, we find heterogeneous effects by each of wind generation's unique characteristics. We estimate that one GWh of unforecast wind generation has a bigger effect on prices and price dispersion than one GWh of forecast generation, a result that we attribute to differences in the conventional supply curve that is available when market conditions are predicted well versus hours with substantial forecast error. In addition, we find that the effect of wind forecast error on wholesale electricity prices is larger than the effect of demand forecast error, indicating a difference in the way grid operators manage uncertainty in residual demand coming from renewables versus demand.

We also examine the mechanisms generating these results and find that wind forecast error leads to a greater extensive margin response from non-wind generators—particularly natural gas turbines—as compared to forecast wind. That is, when wind generation is poorly forecast, more units must start up or shut down to balance the market as compared to when wind is perfectly forecast. These findings are particularly important given two key descriptive findings about error. One, although demand in Texas is around seven times the size of wind generation, the magnitude of average hourly forecast error for wind is roughly 50% larger than the forecast error for demand. Two, while both raw error and error rate in demand forecasting has been improving over time, the same trend is not observed for wind forecasting.

Section 4: Concluding remarks

Overall, we find that a key dimension of wind generation's impact on grid outcomes stems from uncertainty in generation—indicated by error in generation forecasts. Wind's price effect from the residual demand effect mirrors the impact of electricity demand, and the impact of hourly changes in wind is similar to the impact of constant wind. Additionally, the effects of demand error are similar to the effects of forecast demand. The effects of wind error, however, are unique among all electricity market outcomes we study. These findings are particularly salient given the trends observed in demand versus wind forecast error, with demand error steadily decreasing over time while similar improvements are not as marked for wind forecast error. Thus, in preparing for an increasingly decarbonized electricity system, grid operators would do well to focus on improving wind forecasts, which would dampen price variation and alleviate the need for costly extensive margin responses to wind generation.

References

Bushnell, James, and Kevin Novan. 2021. "Setting with the Sun: The Impacts of Renewable En- ergy on Conventional Generation." Journal of the Association of Environmental and Resource Economists 8, no. 4 (July 1, 2021): 759–796.

Clò, Stefano, Alessandra Cataldi, and Pietro Zoppoli. 2015. “The merit-order effect in the Italian power market: The impact of solar and wind generation on national wholesale electricity prices.” Energy Policy 77:79–88.

Cludius, Johanna, Hauke Hermann, Felix Chr Matthes, and Verena Graichen. 2014. “The merit order effect of wind and photovoltaic electricity generation in Germany 2008–2016: Estimation and distributional implications.” Energy economics 44:302–313.

Ketterer, Janina C. 2014. “The Impact of Wind Power Generation on the Electricity Price in Ger- many.” Energy Economics 44 (July 1, 2014): 270–280.

Mallapragada, Dharik S, Cristian Junge, Cathy Xun Wang, Johannes Pfeifenberger, Paul L Joskow, and Richard Schmalensee. 2021. Electricity Price Distributions in Future Renewables-Dominant Power Grids and Policy Implications. Technical report. National Bureau of Economic Research.

Quint, Dov, and Steve Dahlke. 2019. “The impact of wind generation on wholesale electricity market prices in the midcontinent independent system operator energy market: An empirical investigation.” Energy 169:456–466.

Sakaguchi, Makishi, and Hidemichi Fujii. 2021. “The impact of variable renewable energy penetration on wholesale electricity prices in Japan.” Munich Personal RePEc Archive, no. 110554.

U.S. Electricity Information Administration. 2020. Electric Power Monthly. URL: https://www.eia.gov/electricity/monthly.

U.S. Electricity Information Administration. 2022. Preliminary Monthly Electricity Generator Inventory (Form EIA-860M). URL: https://www.eia.gov/electricity/data/eia860m/.

Woo, C. K., I. Horowitz, J. Moore, and A. Pacheco. 2011. “The Impact of Wind Generation on the Electricity Spot-Market Price Level and Variance: The Texas Experience.” Energy Policy 39 (7): 3939–3944.

Würzburg, Klaas, Xavier Labandeira, and Pedro Linares. 2013. “Renewable Generation and Elec- tricity Prices: Taking Stock and New Evidence for Germany and Austria.” Energy Economics, Supplement Issue: Fifth Atlantic Workshop in Energy and Environmental Economics, 40 (December 1, 2013): S159–S171.

Zipp, Alexander. 2017. “The marketability of variable renewable energy in liberalized electricity markets—an empirical analysis.” Renewable Energy 113:1111–1121.