Selling Wind

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Renewable energy sources are increasingly important in electricity markets, and they have the potential to impact strategy and conduct in these markets. In 2018, wind energy was responsible for 6.5% of U.S. electricity generation, nearly doubling its market share and total production from five years prior. Renewable electricity is a critical component of global efforts to reduce carbon dioxide emissions, and its growth is expected to continue. Existing literature focuses on strategic behavior in electricity markets without substantial amounts of renewable energy, but few studies focus on how stochastic resource availability impacts strategic behavior and market power. Existing strategies for market power monitoring in electricity markets will be increasingly challenged by an influx of renewable generation, since regulators have imperfect information regarding energy availability from stochastic resources.

We offer a simple model to investigate how strategic firms sell electricity from renewable energy assets. Wind farms have stochastic production constraints: the total amount of energy they can produce at any time is uncertain *ex-ante*. We focus on wind energy, but the model is applicable to any asset with stochastic production constraints.

We focus particularly on the extent of resource heterogeneity—that is, the extent to which the production constraints of different firms or resources are correlated. As we show, an increase in dispersion (a decrease in correlation) improves welfare because it improves asset diversification, but *also* because it changes the conduct of firms and weakens their market power. We show that this insight is robust for any concave and downward-sloping inverse demand function. We first present the analysis for a simplified single-period electricity market with wind energy, and we extend the results to markets with multiple wind generators and traditional fossil-fuel generation.

We study strategic firms with private information regarding their realized energy availability, or "state." This energy availability is equivalent to a production constraint because it limits the extent of production by the firm in any given period. Since the resource availability of wind energy is uncertain, from an individual firm's perspective its competitors' production constraints are stochastic. However, the resource availability of wind farms is often correlated; firms can gain important information about their competitors' production constraints from the realization of their own resource availability. As such, the extent of heterogeneity (correlation) becomes an important factor that impacts strategic behavior, market power, and welfare.

We model producer competition as an incomplete information Cournot game with correlated types, where the type refers to the stochastic resource availability (production constraint) that is private information for each individual producer. We utilize a parameter d to represent the level of heterogeneity amongst wind producers; high d represents low correlation between resources. We link the extent of stochastic dependence to strategic behavior and welfare (in equilibrium), extending the existing literature on Cournot games with incomplete information.

As our model makes apparent, they key issue affecting market conduct is not just stochastic production constraints—it is that stochastic production constraints are *dependent* across firms. In

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reality, this dependence is true of both total energy output and also real-time errors versus day-ahead forecasts. As we show, the level of stochastic dependence or heterogeneity has monotonic effects on withholding and welfare.

The results provide clear insight to explain how stochastic dependence can impact welfare in imperfect electricity markets. Decreasing correlation in wind resource availability is beneficial for two reasons: First, it increases the diversification of resources, increasing the expected value of price times output. Second, it reduces strategic withholding, as it changes the information that a producer has regarding its competitors. The results of our model imply that imperfect competition in energy markets can affect investment in renewable energy, resulting in a system with sub-optimal levels of resource heterogeneity.

We also utilize the model to examine the effects of heterogeneity on collusion and on policies to prevent collusion. We investigate the effects of public sharing of high-quality weather forecasts, using the limiting case whereby the true realized energy availability of firms is monitored and shared. The results suggest an important dichotomy: information sharing through improved forecasting is socially beneficial, but it does not always improve producer profits. As such, it will not necessarily be undertaken by producers acting in their own best interest. We conclude that public forecasting—while beneficial—is unlikely to be enacted by market participants acting in their own best interests.

These results provide a framework for evaluating policies that impact investment and information-provision in imperfectly competitive markets, like electricity markets. The results can help us understand how policies that impact the dispersion of renewable energy resources, and thus the characteristics of stochastic energy availability, ultimately impact welfare in imperfectly competitive electricity markets.