Measuring the Benefits of Delayed Price-Responsive Demand in Reducing Wind-Uncertainty Costs

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***Abstract*—Demand response has benefits in mitigating unit commitment and dispatch costs imposed on power systems by wind uncertainty and variability. We examine the effect of delays in consumers responding to price signals on the benefits of demand response in mitigating wind-uncertainty costs. Using a case study based on the ERCOT power system, we compare the cost of operating the system with forecasts of future wind availability to a best-case scenario with perfect foresight of wind. We demonstrate that wind uncertainty can impose substantive costs on the system and that demand response can eliminate more than 75% of these costs if loads respond to system conditions immediately. Otherwise, we find that with a 30-minute lag in the response, nearly 72% of the value of demand response is lost.**

***Index Terms*—Power system economics, wind power generation, wind forecast errors, real-time pricing, unit commitment**

Nomenclature

A. Model Sets and Parameters

$\mathbf{T}$ time index set,
$\mathbf{I}$ conventional generator index set,
$\mathbf{W}$ wind generator index set,
$c_i^V(\cdot)$ generator i's variable cost function,
c_i^{NL} generator i's no-load cost,
c_i^{SU} generator i's startup cost,
K_i^- generator i's minimum operating point,
K_i^+ generator i's maximum operating point,
R_i^- generator i's rampdown limit,
R_i^+ generator i's rampup limit,
$\bar{\rho}_i^{SP}$ generator i's spinning reserve capacity,
$\bar{\rho}_i^{NS}$ generator i's non-spinning reserve capacity,
τ_i^- generator i's minimum-down time,
τ_i^+ generator i's minimum-up time,
$\bar{\omega}_{w,t}$ maximum generation available from wind generator w in time period t,
$p_t(\cdot)$ inverse demand function in time period t,
$\bar{\eta}_t$ total reserve requirement in time period t, and
η_t^{SP} spins51(f)-4C ene

Wind variability and uncertainty can also be accommodated using demand response. Having electricity demand follow wind output reduces the need for fast-responding generation. Papavasiliou and Oren [4] study the use of load control, wherein deferrable loads are directly controlled and scheduled to follow wind availability. They develop two methodologies for load scheduling and estimate the value of such a scheme. Klobasa [5] examines the effects of demand response in a future German power system with 48 GW of wind, showing that it reduces wind-uncertainty costs to less than €2/MWh. Sioshansi [6] studies the Texas (ERCOT) system with 14 GW of wind and real-time pricing (RTP). He shows that RTP can eliminate up to 93% of wind-uncertainty costs, depending on the price-responsiveness of the demand. Dietrich *et al.* [7] examine the effect of demand shifting and peak shaving on wind integration, showing that these programs can reduce wind-uncertainty costs by up to 30%.

These analyses implicitly assume that demand responds to real-time signals immediately, without any latency. While this assumption may be reasonable for some forms of direct load control, it can be more tenuous for indirect price-based mechanisms, such as RTP. This is because there may be a lag between price signals being sent, consumers observing them, and adjusting their behavior in response. Automated controls may alleviate such latency, however, since they reduce the need for consumers to exert real-time control. Such latency can reduce the value of RTP in mitigating wind-uncertainty costs, since its benefit arises from load quickly responding to wind availability and reducing the need for generators to provide balancing energy. Thus, a shortcoming of this literature is that it does not account for such latency in estimating the benefits of demand response in mitigating wind-uncertainty costs.

We address this shortcoming by studying the effect of consumer delays in responding to price signals on the benefits of RTP in reducing wind-uncertainty costs. This paper has

$$\text{s.t.} \quad \mathbf{l_t} = \sum_{\mathbf{i}\in\mathbf{I}} \mathbf{q_{i,t}} + \sum_{\mathbf{w}\in\mathbf{W}} \boldsymbol{\omega}_{\mathbf{w,t}}, \qquad \forall\ \mathbf{t} \in \mathbf{T}; \tag{2}$$

$$\sum_{\mathbf{i}\in\mathbf{I}} (\boldsymbol{\rho}^{\mathbf{SP}}_{\mathbf{i,t}} + \boldsymbol{\rho}^{\mathbf{NS}}_{\mathbf{i,t}}) \geq \bar{\boldsymbol{\eta}}_{\mathbf{t}}, \qquad \forall\ \mathbf{t} \in \mathbf{T}; \tag{3}$$

$$\sum_{\mathbf{i}\in\mathbf{I}} \boldsymbol{\rho}^{\mathbf{SP}}_{\mathbf{i,t}} \geq \boldsymbol{\eta}^{\mathbf{SP}}_{\mathbf{t}} \cdot \bar{\boldsymbol{\eta}}_{\mathbf{t}}, \qquad \forall\ \mathbf{t} \in \mathbf{T}; \tag{4}$$

$$\bar{\boldsymbol{\eta}}_{\mathbf{t}} = 0.03 \cdot \mathbf{l_t} + 0.05 \cdot \sum_{\mathbf{w}\in\mathbf{W}} \boldsymbol{\omega}_{\mathbf{w,t}}, \qquad \forall\ \mathbf{t} \in \mathbf{T}; \tag{5}$$

$$\mathbf{K}^{-}_{\mathbf{i}} \mathbf{u_{i,t}} \leq \mathbf{q_{i,t}}, \qquad \forall\ \mathbf{i} \in \mathbf{I}, \mathbf{t} \in \mathbf{T}; \tag{6}$$

$$\mathbf{q_{i,t}} + \boldsymbol{\rho}^{\mathbf{SP}}_{\mathbf{i,t}} \leq \mathbf{K}^{+}_{\mathbf{i}} \mathbf{u_{i,t}}, \qquad \forall\ \mathbf{i} \in \mathbf{I}, \mathbf{t} \in \mathbf{T}; \tag{7}$$

$$\mathbf{q_{i,t}} + \boldsymbol{\rho}^{\mathbf{SP}}_{\mathbf{i,t}} + \boldsymbol{\rho}^{\mathbf{NS}}_{\mathbf{i,t}} \leq \mathbf{K}^{+}_{\mathbf{i}}, \qquad \forall\ \mathbf{i} \in \mathbf{I}, \mathbf{t} \in \mathbf{T}; \tag{8}$$

$$0 \leq \boldsymbol{\rho}^{\mathbf{SP}}_{\mathbf{i,t}} \leq$$

standard deviations, thus RTP should have similar effects if spatial correlation is explicitly modeled. On the other hand, better capturing spatial correlation should lead to a lag in the demand response having less of an effect on RTP's benefit in reducing wind-uncertainty costs. This is because discrepancies between time-t and -(t

TABLE III

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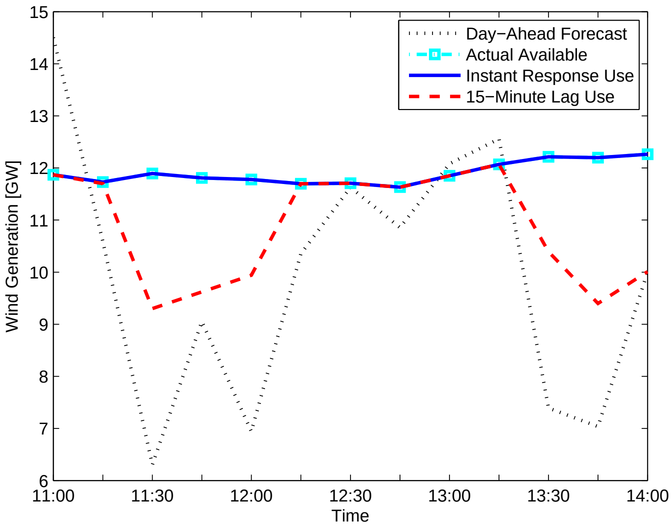

Fig. 5. Wind available and used from 11:00 to 14:00 on 1 January with immediate and lagged demand response.

interactions between these technologies.

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