Market Design, Welfare, and Environmental Implications of Recognizing Wind Production Uncertainty in PJM

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Overview

Systems with high shares of wind power generation face increased challenges to operate reliably and efficiently due to the low cost, variability, and uncertainty of this energy resource. To ensure reliable supply of demand, system operators schedule generation and transmission resources at least a day ahead of real-time (RT) operation to allow sufficient time for the startup of slow power generators. However, day-ahead (DA) wind production cannot be predicted accurately, so wind resources enter the DA market with their expected production. Additionally, the DA scheduling and generally market clearing process, conducted based on deterministic models, do not account for the uncertainty around production of wind energy resources. As a result, two DA wind production distributions with identical expected values of generation but different uncertainty, result in the same DA allocation and prices. The incomplete characterization of wind production uncertainty at the DA scheduling stage causes an information gap that leads to inefficient scheduling and dispatch of electricity generators degrading the electricity market design outcomes: efficiency, reliability, affordabaility, and cleanness.

To deal with this problem, several adjustments to the traditional design of electricity markets, hereafter called deterministic market clearing (DMC), have been proposed or implemented including the introduction of a) multi-interval look-ahead real-time unit commitment (RTUC), to adjust the commitment of fast start generators and adjust production schedules as the updated forecasts become available, b) new efficient ancillary service (ramp capability) products to DMC, referred to as augmeneted deterministic market clearing (ADMC), and c) stochastic market clearing (SMC) which uses stochastic optimization models to directly consider uncertainties and their associated costs in core market processes, i.e., commitment, scheduling, and pricing.

Previous literature has investigated the adjustments mentioned above, but the analyses have been limited in scope, methods, or questions, and as a result, a comprehensive comparative analysis of the deterministic and stochastic market clearing designs has not been conducted yet. The objective of this paper is to fill this gap and offer a comparison of the performance and efficiency of the market with SMC and ADMC. Our objective is to clarify a set of interrelated questions: to what extent SMC and ADMC lower the annual system's operation costs and air emissions (CO_2, SO_2, and NO_x)? How do they affect efficiency, cost-recovery of producers, and affordability of electricity for consumers? How do they remunerate provision of flexibility by conventional energy producers?

Methods

To conduct the comparative analysis, this study replicates the operation of PJM DA and RT markets and intraday commitment processes with ADMC and SMC designs for one year with hourly granularity, and compares their outcomes with DMC as the base case. Simulating system's operations includes setting the optimal DA commitment trajectory of generators (on/off status, startup, and shutdown) and DA production schedules, adjusting the intraday commitments, and optimizing the RT dispatch of online electricity generators, along with finding DA and RT prices and settling the energy and ancillary service markets transactions between consumers and producers.

Because there is a tradeoff between economic and reliability outcomes, we set up our experiment so that both models achieve the same reliability levels and hence compare them only on the basis of economic and environmental outcomes; that is, the value of lost load (VOLL) and maximum ramp capability reserve requirements are set to assure both DMC and SMC comply with the system reliability requirements (i.e., having no loss-of load events) at the least possible cost.

The comparative analysis is conducted on a 12% scaled version of the PJM Interconnection power generation fleet, based on data reported in the National Electric Energy Data System (NEEDS v.4.10) compiled by EPA. Coincident wind and load hourly data come from historical records of the Boneville Power Authoirty (BPA) for the years 2011-2015.

Results

Table 1 presents the economic and environmental outcomes of different market designs relative to DMC. The last eight rows of Table 1 show costs, supply-side revenues, producers' and social surplus, and uplift (revenue sufficiency guarantee) payments reported in million \$. The last three rows report air emissions in million short tons. As shown, the augmented deterministic and stochastic designs lower the producers' costs relative to the DMC base case. However, the cost reduction obtained by SMC is three times in the reduction achieved by ADMC. The plants operation costs include the fuel costs for

Table 1: Economic and environmental outcomes of alternative DMC and SMC designs

	DMC	ADMC	SMC
Total plants Cost	Base (1,125)	-0.36%	-0.90%
DA plants cost	Base (1,124)	-0.29%	-3.38%
RT plants costs	Base (0.5)	-152.31%	5536.93%
Producers' revenue	Base (1,809)	3.40%	1.73%
Producers' surplus	Base (684)	9.59%	6.36%
Social surplus	Base (258,888)	0.002%	0.005%
Uplift payment 1	Base (3)	-55.17%	-55.20%
Uplift Payment 2	Base (21)	-47.27%	-58.25%
CO_2 emissions	Base (37326.95)	-1.60%	-3.52%
NOx emissions	Base (21.41)	-2.09%	-7.51%
SO2 emissions	Base (354.35)	-2.13%	-4.74%

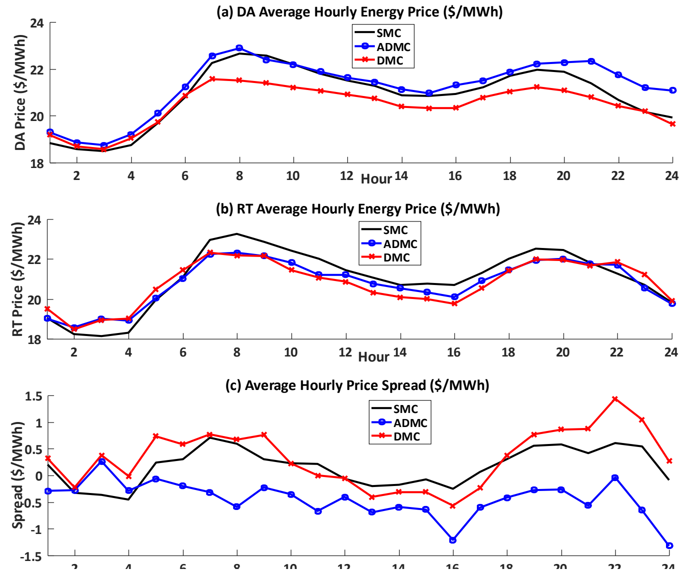

Figure 1: Annual average hourly DA and RT energy prices and price spread

startup and operation costs. Also, the distribution of costs between the DA and RT market operations imply that SMC shifts a sizable portion of the trade from DA to RT market which lowers the DA costs and increases the RT costs. Accounting for the wind production uncertainty and its associated costs in the DA processes makes SMC to raise the portion traded in the RT market where more accurate information about wind production is available.

Both ADMC and SMC increase the producers' revenues and surplus, and by increasing DA prices. The increased producers' surplus under ADMC and SMC suggests that both designs would offer sufficient incentives for producers to offer their ramp capability to the grid. In terms of the social welfare, SMC outperforms ADMC. Although both ADMC and SMC improve the social welfare, the increase caused by SMC ($12 million) is three times greater than that of ADMC ($4 million). Comparing producers' surplus and social surplus implies ADMC and SMC reduce the consumer's surplus, while the consumer welfare reductions caused by SMC ($31 million) are half those observed under ADMC ($62 million).

SMC is more effective than ADMC in reducing total uplift payments to producers. These uplift payments have been decomposed into two components presented in the last two rows of Table 1. *Uplift payment* 1(*UP1),* is equal to the uplift payments made to cover the startup costs of power plants. *Uplift payment* 2, (*UP2)* is equal to the payment made to cover other pricing non-convexities not covered by the DA and RT energy prices. ADMC and SMC respectively cut the total uplift payments by respectively 46% and 58%. Although, the absolute reduction in UP2 caused by ADMC and SMC is very similar, it is a much higher component of the revenue under SMC and hence proves SMCs effectiveness minimizing the prominence of uplift payments. Uplift payments are deemed undesirable because they reduce the transparency of the market and hence fail to send the right signals for enticing participation or investment in the right resources.

The reported CO_2, NOx, and SO_2 emissions demonstrate the environmental benefits of augmented designs and the superiorty of SMC. The DA and RT prices and the spread between them under alternative designs are illustrated in Figure 1 and suggest DA prices under SMC better account for the wind production uncertainty and minimize the spread between DA and RT prices.

Conclusions

An economically feasible augmented deterministic design marginally improves the economic and environmental outcomes. However, SMC results in superior outcomes, increases producers' surplus and social welfare and reduces air emissions to greater extents through more efficient scheduling and dispatch of conventional and wind energy producers.