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Modeling wind power curtailment with increased capacity in a regional electricity grid supplying a dense urban demand

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HIGHLIGHTS

- A regional wind power expansion model is developed with new wind power time series.
- 6–10 GW wind power can be deployed in the New York grid with minimal curtailment.
- Baseload generators have very large impact on curtailment at high wind capacities.
- Seasonal mismatches in wind supply and demand can be significant at high capacities.
- Targeted, modest transmission upgrades can significantly reduce wind curtailment.

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ABSTRACT

Many US states have targets for vastly expanding electricity generation from renewable resources. As installed wind capacity increases, several factors can lead to the curtailment of potential wind-generated electricity. Reliably estimating wind power outputs remains a challenge given the dearth of available hub height-altitude wind speed data and measured outputs from newer turbines. A methodology to make such estimates with large increases in wind capacity is described. A regional wind power model, including subroutines for evaluating Statewide grid constraints, and a linear program to solve the model were developed to assess capacity factors and curtailments with deep penetration of wind power into an existing grid under several constrained scenarios implied by demand, baseload generation and transmission. Actual zonal demand and interzonal transmission limits were used for the New York State electricity grid, which has significant potential for wind power mostly distant from the concentrated electricity demand in and around New York City.

The analysis indicates that current wind power outputs in the State underperform when compared to what the potential output should be at the same locations and could be if better wind regime sites were selected. Even with improved selection of sites and turbines, no constraints considered caused curtailment until systemwide capacity exceeds 6 GW; beyond this capacity, curtailment occurs only due to the presence of inflexible baseload generators until systemwide capacity exceeds 15 GW. At deeper penetrations of wind, mismatches in potential wind power supply and electricity demand coupled with continuously operating baseload generators have the most significant impact on the curtailment of wind-generated electricity, with much of the curtailment occurring during October-March. Interzonal transmission constraints further increase wind curtailment and would require very large transmission capacity increases to capture fully; however, more modest increases in transmission capacity can significantly reduce curtailment.

1. Introduction

The role of renewable energy sources of electricity to achieve deep reductions in greenhouse gas (GHG) emissions to mitigate the effects of climate change has been well-documented [1,2]. Vast deployment of these technologies – including wind, solar and hydroelectric power, among others not yet representing a significant portion of global energy supply – have been proposed in broad scope GHG emissions reduction studies at global [3], regional [4] and local [5] scales. With some combination of wind and solar power likely to represent a significant majority of new low-carbon electricity generation in most areas, their intermittent

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Nomenclature

B	baseload electricity generation (MW)
C_{wind}	total wind turbine capacity at a site (MW)
CF	capacity factor
$CF^{(act)}$	actual existing site wind power capacity factor (MW h)
$CF^{(NREL)}$	wind power capacity factor, as predicted by NREL wind model data (MW h)
$CF^{(pred)}$	wind power capacity factor, as predicted for existing site turbines at a hub height-adjusted wind speed (MW)
c	total installed wind power capacity (MW)
D	electricity demand (MW)
$E^{(act)}$	actual existing site wind-generated electric energy (MW h)
E_{hydro}	actual hydroelectric energy (MW h)
h	wind turbine hub height (m)
h_0	wind turbine reference hub height (m)
L^+	positive flow transmission limit (MW)
L^-	reverse flow transmission limit (MW)
l	transmission line loss factor
NL	net load (MW)
n_{hrs}	number of hours
$P^{(curve\text{-}NREL)}$	wind-generated electric power, as predicted by NREL model manufacturer power curves at a given wind speed (MW)
$P^{(forecast)}$	forecast wind power output (MW)
$P^{(NREL)}$	wind-generated electric power, as predicted by NREL wind model data (MW)
$P^{(pred)}$	wind-generated electric power, as predicted for existing site turbines at a hub height-adjusted wind speed and actual manufacturer's power curve (MW)
r	wind power scaling factor
S_{cap}	set of sites included in analysis for a given systemwide wind capacity
S_z	set of sites in a zone
T	transmission (MW)
t_s	time scale for net load ramping calculations (min)
U	wind-generated electricity utilized (MW)
v	wind velocity (m/s)
v_0	wind velocity at reference hub height (m/s)
W	wind power output (MW)
W^*	logit transformation of normalized wind power
Z	total number of zones
α	friction coefficient
μ	mean
ρ	Spearman's rank correlation
σ	standard deviation
τ	time step duration (min)

Subscripts

dem	demand constraint indicator
dem.base	indicator of combined demand and baseload generator constraints
dem.trans	indicator of combined demand and transmission constraints
e	existing site index
h	wind turbine hub height (m)
hydro-const	indicator of the constant hydroelectric baseload generation
m	month
NYC	New York City
NYS	New York State
nuc	nuclear
s	NREL site index
t	time step
z	NYISO zone index

availability and output variability will require adaptation throughout the energy delivery system [6], including in transmission networks [7], selection and operation of other generators [8], market design and demand management [9].

Much prior research has evaluated and projected the electricity generation from renewable sources within urban areas, in terms of technology development [10], building integration [11] and resource potential [12]. While identifying opportunities for in-city renewable energy deployment are admirable and perhaps a necessary part of the overall shifting energy landscape, the potential supply is small relative to the electricity demand in a dense urban area. For example, New York City (NYC) is projected to continue to require approximately 33% of the total annual electricity demand for New York State ("the State") whereas NYC-based renewable energy resources represent 16% of the Statewide technical potential [13]. The cost of installing such technologies in a dense urban area further reduces the likelihood of relying on this approach for a significant portion of the total renewable electricity supply; NYC-based renewable energy is expected to contribute only 2.2% of what is deemed economically viable Statewide [13].

Since various United States federal statutes in the late 20th Century (commonly referred to as "deregulation"), the wholesale electricity market is generally managed by an Independent System Operator (ISO) or Regional Transmission Organization (RTO) [14]; New York State became one of the early adopters of the new approach. A detailed review of the design and operation of these markets can be found elsewhere [15]; however, the increase in these organizations and similar market structures outside the US led to more rapid development of computational models of electricity markets [16].

We are interested in a particular situation that demonstrates the challenges as progressively less desirable sites are selected for renewable resource deployment [17]: Expansion of large-scale wind power in a regional electricity grid. The region corresponds to a "balancing authority" identified in the National Renewable Energy Laboratory (NREL) Eastern Wind Integration and Transmission Study (EWITS) [18], a particularly broad-scope study of potential wind power in the U.S. from the Great Plains to the Atlantic Coast. That study identified long-distance, high-capacity transmission from the Plains to the Midwest and East as the primary means of improving the economics of large-scale wind power, but did include 8–24 GW of on-shore wind power in the New York ISO (NYISO). However, the NYISO region was treated as a single zone in [18], despite unique intraregional challenges caused by zonal demand, existing baseload generators and inter-zonal transmission limits with potential wind power sites mostly distant from the concentrated electricity demand in and around New York City.

This paper examines the effect of adding up to 37.5 GW of wind capacity to the New York State electricity grid (with particular emphasis on 10, 20 and 30 GW scenarios). Specifically, the expected curtailment was analyzed assuming existing transmission and baseload generators remained as expected in the time-frame that large-scale wind power might be deployed, as well as by eliminating or reducing those constraints. Seasonal curtailment effects, relative impact of constraints included in combination with others and increases in transmission capacity were also evaluated. Several new methods, relying on extensive data sets, are developed to improve the accuracy of the model used in the analyses described herein. The paper is organized to first describe the