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Renewable resources portfolio optimization in the presence of demand response

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HIGHLIGHTS

- Optimal renewable planning model in conjunction with demand response is presented.
- Adding renewable resources can reduce uncertainty costs more than production costs.
- Inter-hourly demand response is not as useful as intra-hourly demand response.
- Optimal renewable resource level is as sensitive to carbon tax as to first cost.

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ABSTRACT

Demand response is viewed as a practical and relatively low-cost solution to increasing penetration of intermittent renewable generation in bulk electric power systems. This paper examines the question of what is the optimal installed capacity allocation of renewable resources in conjunction with demand response. We introduce an integrated model for total annual system cost that can be used to determine a cost-minimizing allocation of renewable asset investments. The model includes production, uncertainty, emission, capacity expansion and mothballing costs, as well as wind variability and demand elasticity to determine the hourly cost of electricity delivery. The model is applied to a 2024 planning case for British Columbia, Canada. Results show that cost is minimized at about 30% wind generation. We find that the optimal amount of renewable resource is as sensitive to installation cost as it is to a carbon tax. But we find the inter-hourly demand response magnitude is much less helpful in promoting additional renewables than intra-hourly demand elasticity.

1. Introduction

According to the Energy Information Agency (EIA) International Energy Outlook developing economies have seen a steady growth in renewable energy resources in recent years. Wind and solar resources in particular show the strongest growth with EIA projecting that more than three quarters of all new additions in 2015 will be renewable [1]. The advantages of renewable energy are manifest and in the absence of viable alternatives to reducing greenhouse gas emissions, they are expected to remain the electricity generation resource of choice for new additions for many years to come. Unfortunately, all is not well where renewable electricity generating resources are concerned. Significant economic and operational considerations impose practical limits on the total amount of renewables that can be deployed in bulk electric power systems. Land use considerations, power system reliability, and electricity market design are among the many issues that contribute to constraints on the total deployment of renewables, particular those that rely on intermittent prime-movers, like wind and solar energy. Hydro-electric generation has long been employed as a significant renewable source of electricity. But climate change may jeopardize the magnitude and certainty with which the existing asset base can meet demand [2,3], while lack of productive new dam siting options, population displacement, habitat destruction and fish stock degradation limit the growth of new assets. Wind power has seen rapid growth in recent years, but the need for reliable resources limits the penetration of wind generation unless additional intermittency mitigation measures are considered [4]. Solar resources are also becoming

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Nomenclature

C	annual cost, in $/y
c	hourly cost, in $/h
G	annual generation, in MW h/y
g	hourly generation, in MW h/h
p	price, in $/MW h
Q	quantity, in MW
q	hourly demand, in MW h/h
t	time, in h
v	normalized hourly wind generation, per unit of installed wind capacity

Greek symbols

α	magnitude of the variable cost component of supply curve, in $/MW h
β	curvature of the supply curve, in a non-dimensional unit
γ	base price of the first dispatchable generation, $/MW h
ϵ	emission factor of a resource, in tCO_2/MW h
κ	curvature of the demand curve, in a non-dimensional unit
τ	time-substitution delay of inter-hourly demand response, in h
ω	fractional resource allocation, per unit of installed capacity

Subscripts

BG	base load generation
D	demand response
E	emission
IG	intermediate load generation
M	market
P	production
PG	peak load generation
R	reserve
SV	scarcity value
CT	carbon tax
U	uncertainty
W	wind

increasingly available but have intermittency challenges similar to those of wind. In addition residential rooftop solar resources are challenging the classical utility revenue model [5] and are known to cause voltage control issues in distribution systems in response to cloud transients and the diurnal cycle [6,7]. There are also early signs that the wholesale market designs are not well suited to high penetration of renewables and the specter of revenue adequacy problems has been raised [8,9]. Finally, the reliable, robust control and optimal operation of an increasingly complex bulk electricity system has become a very real concern [10].

The traditional utility approach to renewable intermittency is to allocate additional firm resources to replace all potentially non-firm renewables resources. These firm resources are generally provided by fast-responding fossil-fuelled thermal plants and hydro (where available) power generation as well. The need for fast-ramping resources discourages the dispatch of high-efficiency fossil and nuclear generation assets while promoting low-efficiency fossil for regulation and reserve services. The early state of development of many wholesale regulation markets precludes consideration of market-based remedies at this time, although arguably one should consider renewables before committing to any particular market design.

Demand response is generally regarded as a lower-cost alternative to fast-response generation reserves that reduces the dispatch of expensive generation resources [11–14], although the response speed, magnitude and duration are important considerations [15]. The effect of demand response on the daily generation schedule is known [16] and sometimes demand response is even presented as a virtual power plant [17]. But load control strategies for demand response can be challenging to deploy [18] in part due to competing local and global objectives [19,20] and in part due of the complexity of the load control modeling and design problem itself [21]. Numerical modeling of resource adequacy for large-scale planning problems is difficult to implement [22] and demand response models typically do not capture the salient features of load necessary to make optimal resource allocation decisions. This is particularly true when considering the interaction of renewable intermittency and demand response capabilities [23].

Effective and widely used strategies for optimizing the scheduling and operation of bulk-system resources have used markets to solve the cost-minimizing resource-allocation problem since they were proposed in the early 1980s [24]. Market-based control strategies were later adapted to building control systems [25], generalized to feeder-scale operations [26], then utility-scale operations [27], and most recently proposed for ancillary services [28]. Integrated demand dispatch mechanisms allow consideration of the combined economic impact of both intermittent generation under traditional wholesale markets and so-called “transactive” retail-side demand response dispatch system. It seems therefore possible to define global cost functions that incorporate the essential characteristics of both intermittent generation and demand response.

In recent years many have contributed relevant and very detailed models [29–32] addressing the individual aspects discussed above. Wang et al. [33] reviewed prototyped real-time electricity markets, focusing on their market architectures and incentive policies for integrating distributed energy resources and demand response. Kwag and Kim [34] introduced a new concept of virtual generation resources, according to which marginal costs are calculated in the same manner as conventional generation marginal costs using demand response information: magnitude, duration, frequency and marginal cost. Sreedharan et al. [35] determined the avoided cost of demand response in a restructured market with renewables in California. Dallinger et al. [36] showed that a demand response program based on smart charging of electric vehicles can facilitate the integration of intermittent resources in California and Germany. Mahmoudi et al. [37] proposed a new wind offering strategy in which a wind power producer employs demand response to cope with power production uncertainty and market violations. To this end, the wind power producer sets contracts with a demand response aggregator. Rajeev and Ashok [38] proposed a dynamic load shifting program using real-time data in a cloud computing framework to enable the effective capacity utilization of renewable resources. Heydarian-Forushani et al. [39] investigated the impacts of different electricity markets on the optimal behavior of a demand response aggregator in a renewable-based power system. Fripp [40] introduces Switch, a new open-source optimization model for long-term planning of power systems with large shares of renewable energy. Santoro et al. [41] used a stochastic approach based on Monte Carlo simulation technique to simulate the impacts of demand response in power systems with integrated renewable resources over one year period. They showed the optimization of demand response and renewable production reduces locational marginal prices.