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Rethinking restructured electricity market design: Lessons learned and future needs

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ABSTRACT

Many principles underlying the design of restructured electricity markets that are in-use today were developed over three decades ago when power systems were considerably different than today's and tomorrow's systems are. Systems of the past typically relied on large dispatchable thermal generators to supply energy. This can be contrasted with power systems today, which are experiencing rising penetrations of weather-dependent renewable energy sources that have limited dispatchability. Moreover, many power systems are experiencing growing adoption of distributed energy resources and novel uses of electric energy by end customers, which adds to demand uncertainty and variability. However, these technologies also provide opportunities for more active participation of the demand-side in maintaining system reliability and service quality.

Given these marked changes in the architecture of electric power systems, we are at a unique point at which the tenets of restructured electricity market design can be re-evaluated. While this re-examination is largely driven by changes in power system designs, we can also rely on lessons learned from the past three decades of market-restructuring experience. In this paper, we highlight some of the challenges in designing electricity markets brought about by changes in system designs. We also discuss a number of lessons learned from market designs that have been implemented. We then suggest some important principles that should underlie future reforms of electricity market designs and raise design questions that require further research and examination.

1. Introduction

Electricity-market restructuring has a history dating back to the 1980s [1]. In many cases, reforms of electricity markets were undertaken to improve the operational and planning efficiencies of power systems. Market restructuring can also serve to transfer technology and cost risks away from customers to investors. Many of the principles underlying the market designs that were employed then (and which survive today) are rooted in the historic architecture of electric power systems. However, the electric power systems of today and tomorrow 'look' considerably different than most power systems did thirty years ago.

Electric power systems of the past typically relied on a small number of large dispatchable thermal generators to supply energy needs. This historical system design is unsustainable, however. In a recent assessment, the United States Energy Information Administration projects that world energy consumption will grow by 52% between the years 2010 and 2040 [2]. Much of this consumption increase is driven by long-term economic growth. Three Intergovernmental Panel on Climate Change scenarios suggest that this increasing energy (and associated fossil-fuel) use may result in atmospheric CO_2 concentrations that are between 22% and 111% greater than the 450-ppm stabilization scenario [3]. Adding to climate concerns are the risks of unanticipated shocks in the supply of fossil fuels.

These realities, combined with renewable generation technologies becoming cost-competitive with conventional alternatives [4,5], have contributed to a radical transformation of many electric power systems. Power systems have seen increasing penetrations of renewable energy sources, with these trends expected to continue into the future. The use of renewable energy is not a panacean solution, however, and renewables can have negative impacts on system operations and planning. Increasing penetrations of renewables, such as wind and solar, mean that a decreasing portion of the energy supply is dispatchable [6–9]. This is because real-time wind and solar availabilities are weather-dependent, uncertain, and variable. Another burgeoning problem associated with the use of renewable resources is that they can increase the ramp in the net load profile (*i.e.*, demand less renewable output). This effect of renewable generation results in what has been colloquially

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termed the 'duck curve,' which can increase the need for flexible dispatchable resources that can ramp their output up and down quickly [10]. The duck-curve effect can also result in 'overgeneration' situations, in which the system must curtail the output of renewable generators to maintain load balance.

Many power systems are also undergoing important demand-side changes. One is the growing adoption of distributed energy resources by end customers [11,12]. These resources are largely 'uncontrollable' by system operators. Distributed renewable resources carry the same issues of being weather-dependent, uncertain, and variable that utility-owned and -operated renewable resources do. However, distributed renewable generators raise an additional 'visibility' issue insomuch as many electric utilities do not have separate meters to monitor and be able to forecast their real-time output. Even dispatchable distributed energy resources can be challenging for system operators to manage, because they may be controlled by the end customer or another entity (*e.g.*, an aggregator) that does not coordinate their operating behavior with that of the overall system. As such, forecasting available energy from distributed energy resources can be challenging and may require costly and widely distributed monitoring and sensing equipment. Thus, distributed energy resources are often modeled as increased demand uncertainty. Other factors, such as novel uses of electricity (*e.g.*, for electromobility [13]), can also increase demand uncertainty. On the other hand, distributed energy resources and novel uses of electricity may engender greater demand-side flexibility, which can mitigate some of the challenges associated with renewable integration [14].

Despite these fundamental changes in the supply and demand sides of electric power systems, the market models and structures that are used to coordinate the two sides of the system largely have not kept pace. Instead, today's market designs are legacies of historical system designs that assume a system that mostly relies on dispatchable thermal generation and little supply- or demand-side uncertainty.

As one example of this disconnect between today's market and system designs, many restructured electricity markets rely on day-ahead and real-time markets to coordinate electricity supply. The historical role of the day-ahead market is, in part, to provide commitment, dispatch, and price information to thermal generators that may have lengthy startup and slow response times (*e.g.*, steam turbines can take more than six hours to startup whereas nuclear plants can require multiple days' planning notice to cycle on or off). Thus, the day-ahead market ensures that such generators are online and available to provide energy when needed by the system. The real-time market is largely intended to provide imbalance energy and capacity to manage relatively small errors in forecasting load day-ahead.

A day-ahead market may be of limited value, however, to a power system that relies on renewable energy for a non-trivial portion of its energy. This is because weather-dependent renewable energy sources may not be able to accurately predict their real-time availability day-ahead. Moreover, inflexible generators with slow response times may see a diminished role in such power systems of the future. Instead, there may be a growing role for flexible dispatchable generators (*e.g.*, natural gas-fired combined-cycle and combustion-turbine generators), which can provide balancing energy and ramping capabilities to the system. With such a system design, a market structure that relies on day-ahead and real-time markets *only* may be an inefficient paradigm.

Some market redesigns have taken place over the past few years in reaction to changes in system designs. Examples include revisions to capacity markets to accommodate the weather dependence of renewable energy resources [15] and the introduction of a flexible ramping product in the California ISO market to mitigate the duck curve effect [16,17]. However, these revisions to market rules have been largely piecemeal attempts to address the unique market-design, operational, and pricing challenges that are raised by renewable energy resources. It is not clear that applying 'patches' of these types to an underlying market design that is not tailored to the design of today's and tomorrow's power systems will provide the most efficient coordination mechanism in the long term.

The academic literature related to market redesign is also largely piecemeal in nature. Nanduri and Das [18] provide a comprehensive review of market-design issues and areas of research. Given that this survey is conducted in 2009, it mainly discusses issues related to price forecasting, bilateral contracting, auction design and the resulting offering strategies undertaken by market participants, and market power (*i.e.*, issues of importance at the time). Thus, this survey does not consider the impacts of future system architectures on market design. Biskas et al. [19,20] propose a market-splitting algorithm that could be implemented in the emerging integrated day-ahead European market. Sleisz and Raisz [21] propose a computationally efficient market-clearing model that can account for supply orders and ramping limitations. Müsgens et al. [22] analyze the incentive and efficiency properties of balancing markets, with a focus on the design that is implemented in Germany. Casolino et al. [23] examine the problem of market design from the perspective of a natural gas-fired combined-cycle generator. Specifically, they analyze how different design choices can affect the optimal participation and profitability of such generating units.

This paper contributes to this literature by providing a more comprehensive framing of the important issues that should be considered as market designs continue to evolve to address the various changes in the underlying system. We do this in three parts. First, in Section 2 we provide a high-level survey of restructured-electricity-market designs that are in-use today. This includes a discussion of the evolution of designs over the past thirty years and some of the major lessons learned. This does not include a detailed accounting of any particular market design, as that would entail an exhaustive and lengthy survey. Next, Section 3 provides a more detailed accounting of the major challenges that market designers and operators must contend with, given the ongoing changes to the designs of electric power systems. We see a number of important challenges. First, markets must evolve to better represent uncertainties in the supply and demand sides of the system. Second, the physical constraints of the system and production facilities should be properly represented in market models. Third, pricing and market rules should balance system efficiency with respect for private property rights. Finally, the retail side of the market should be redesigned to allow for demand-side resources to participate actively in system operations. Section 3 also surveys some of the work that is presented in the technical literature that provides partial solutions to some of these challenges. Section 4 describes a number of important design principles that should be considered in redesigning future restructured electricity markets. This section also highlights some important research questions that require further study to most efficiently refine restructured-electricity-market designs. Section 5 concludes. The appendix provides a summary of a number of terms that are used throughout the paper.

2. Current restructured-electricity-market designs

Each restructured electricity market (even those within the same country) have numerous differences in their designs. Moreover, these market designs are undergoing constant refinement to deal with new challenges that market operators, regulators, market monitors, and other stakeholders encounter. Indeed, one of the challenges of designing restructured electricity markets is that they always entail tradeoffs. Designers recognize that market models cannot fully capture all of the nuances of power system planning and operations. Many of the refinements in market designs have arisen because the market-design choices originally made resulted in important market inefficiencies that subsequent reforms mitigate.

This section gives a high-level overview of the major design elements that are in-use in many restructured electricity markets today. This discussion is focused around four common themes: unit commitment and dispatch, future markets and capacity planning, transmission