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Capacity expansion of stochastic power generation under two-stage electricity markets

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ABSTRACT

Energy imbalances due to power forecast errors have a significant impact on both the cost of operating the power system and the profitability of stochastic power generating units. In this paper, we propose a modeling framework to analyze the effect of the costs of these imbalances on the expansion of stochastic power generating units. This framework includes the explicit representation of a day-ahead and a balancing market-clearing mechanisms to properly capture the impact of forecast errors of power production on the short-term operation of a power system. The proposed generation expansion problems are first formulated from the standpoint of a social planner to characterize a perfectly competitive market. We investigate the effect of two paradigmatic market designs on generation expansion planning: a day-ahead market that is cleared following a conventional cost merit-order principle, and an ideal market-clearing procedure that determines day-ahead dispatch decisions accounting for their impact on balancing operation costs. Furthermore, we reformulate the proposed models to determine the optimal expansion decisions that maximize the profit of a collusion of stochastic power producers in order to explore the effects of competition at the investment level. The proposed models are first formulated as multi-level programming problems and then recast, under certain assumptions, as single-level mixed-integer linear or non-linear optimization problems using duality theory. The variability of the forecast of the stochastic power production and the demand level throughout the planning horizon is modeled using yearly duration curves. Likewise, the uncertainty pertaining to power forecast errors is characterized through scenario sets. The main features and results of the proposed models are discussed using an illustrative example and a more realistic case study based on the Danish power system.

1. Introduction

The share of low-carbon power production technologies, such as wind and solar, is continuously increasing in current power systems to comply with the ambitious targets to reduce greenhouse gas emissions. Unlike conventional generating units, the production of these energy sources relies on weather conditions and therefore, they suffer from their uncontrollable and intermittent nature. Furthermore, the production of renewable energy sources can only be partially predicted in advance, which increases the uncertainty involved in the operation of a power system.

This shift of the generation mix creates unique challenges for operating power systems in an efficient and reliable manner and influences the performance of current electricity markets. One key issue on the successful integration of renewable generation into power systems is the appropriate use of system flexibility to efficiently deal with the variable and uncertain character of these energy sources. In fact, the utilization of system flexibility highly conditions the impact of power forecast errors on the total operation cost of a power system and the profitability of stochastic generating units [1–5]. Consequently, modeling the short-term operation of a power system accurately is crucial when evaluating the long-term capacity expansion of stochastic generating units [6]. Furthermore, the design of the electricity market may also have, by extension, an important effect on stochastic capacity investments, inasmuch as the market organization may determine the availability of flexible resources for the balancing operation of the power system [7–9].

The impact of renewable power generation on long-term capacity expansion models was first addressed three decades ago in [10,11]. Since then, more recent works propose various models to investigate the impact of specific influential factors on the

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optimal capacity expansion of stochastic generating units. Neuhoff et al. [12] provide a methodology to capture the spatial variation and correlation of wind availability in investment models. The introduction of security constraints to optimally allocate wind power capacity is discussed in [13]. The impact of a high level of wind power penetration on the optimal future power generation mix is analyzed in [14]. Likewise, the models proposed in [15,16] investigate the effects of unit commitment constraints on the generation expansion planning of power systems with renewable energy sources.

Although existing generation expansion models have focused on capturing the variability of renewable power production, they systematically disregard the uncertainty pertaining to short-term forecast errors of stochastic power generation. In this paper, we propose a modeling framework that allows us to investigate the effects of short-term forecast errors of renewable power production on generation expansion planning. While existing models approximate the functioning of the market by a single-stage clearing procedure, our contribution lies in enriching the current modeling of the short-term system operation by considering a two-stage electricity market that includes a forward market, which is cleared one day in advance based on forecast values, and a balancing market, which copes with real-time power imbalances. We propose a family of models formulated from a central planner perspective to determine the optimal generation expansion plan that minimizes the sum of operating and investment costs. The operating costs include both the day-ahead dispatch cost based on forecasts and the expected balancing costs according to the probability distribution of the forecast errors.

This paper also contributes to existing literature on investigating the impact of short-term market design on generation expansion planning. To this end, we model two market-design paradigms that differ on their ability to cope with forecast errors, namely:

1. *Inefficient market clearing*: according to which the clearing of the day-ahead market does not anticipate the need for flexible power capacity to balance the system in real time. This clearing mechanism is representative of market designs where there is no provision of operating reserve capacity prior to or in concurrence with the determination of the day-ahead energy dispatch.
2. *Efficient market clearing*: in which the clearing of the day-ahead market does account for the need for balancing power capacity in real time by jointly optimizing the day-ahead dispatch and the subsequent balancing operation of the power system. Therefore, this market-clearing mechanism endogenously determines the optimal amount of reserve capacity to be procured in concurrence with the day-ahead energy dispatch [17–21].

Under a deregulated market, the proposed cost-minimization approach provides the foreseen generation expansion decisions under a perfectly competitive market [22]. Alternatively, some works formulate generation expansion problems to determine the investment decisions that maximize the profit of strategic power producers owning stochastic power generating units [23–27].

In order to investigate the effects of competition at the investment level, we also propose in this paper a set of generation expansion models assuming that stochastic power producers cooperate to make investment decisions under a collusion agreement. The proposed models are first formulated as bi-level optimization problems (to capture the subordination of operation outcomes to generation expansion decisions) and then recast as mathematical programs with equilibrium constraints (MPECs) as in [28–34]. The upper-level problem determines the investment decisions to maximize the profit of the collusion of producers, while the lower-level problem represents the clearing of the electricity market. Unlike existing ones, the proposed models account for the projected revenues obtained by the stochastic power producers in both the day-ahead and the balancing markets under the two different market designs described above.

The resulting optimization problems consider the variability of the expected stochastic power production and demand level throughout the planning horizon by approximating their associated historic duration curves using time segments of different durations, as it is customary in expansion planning problems [25,29,32,33,35–38]. Likewise, the uncertainty pertaining to forecast errors of power production and demand is characterized through scenario sets generated by randomly sampling their probability distribution functions.

The contributions of this paper are thus threefold. First, we develop a modeling framework to explicitly account for the impact of power forecast errors on the optimal generation expansion plan of stochastic power production. To do so, the short-term operation of the system is modeled through a two-stage electricity market that includes a day-ahead and a balancing market. To the best of our knowledge, this feature makes the resulting generation expansion models the first of its kind. Secondly, we analyze the effect of market design on generation expansion by considering two paradigmatic market-clearing mechanisms that differ in whether or not future balancing energy needs are taken into account when clearing the day-ahead electricity market. Thirdly, we investigate the impact of competition at the investment level by comparing the generation expansion plan that maximizes the social welfare with that obtained by a strategic collusion of power producers.

The remainder of this paper is organized as follows. Section 2 introduces generic generation expansion models from the standpoints of a social planner and a collusion of stochastic power producers. Section 3 presents the simplifying assumptions and procedures to recast the bilevel and three-level models proposed in Section 2 as single-level mixed-integer linear or non-linear optimization problems. Section 4 describes the procedure to characterize the variability and uncertainty of the stochastic power production. Section 5 presents the numerical results for a small power system to illustrate the differences among the proposed generation expansion models. Besides, the results of a more realistic case study based on the Danish power system are discussed in Section 6. Finally, Section 7 concludes the paper.

2. Investment models

This section introduces the family of optimization models used to investigate the impact of forecast errors of renewable power production on the generation expansion of stochastic power generating units. Our modeling framework covers two different market designs, which essentially differ in how proficient the electricity market is in coping with these forecast errors, and two different degrees of competition at the investment level, namely, perfect competition and collusion. The generation expansion models presented in this section are formulated in a generic manner in order to illustrate how the aforementioned aspects can be mathematically formulated using bilevel and three-level optimization problems. The simplifying assumptions and the procedures to recast them as equivalent single-level optimization problems are discussed in detail in Section 3.

All generation expansion models presented in this section are formulated assuming a static approach, whereby the optimal capacity of stochastic power generation and its location are computed for a single representative year, as in [25,32,39,40]. In this