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Extreme prices in electricity balancing markets from an approach of statistical physics

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HIGHLIGHTS

- We combine aspects of physical stability and economic efficiency of the power grid.
- Uncertainties in production or consumption are absorbed in ensembles of power grids.
- More renewables result in more skewed distributions of prices and costs.
- Our procedure provides an alternative to optimized power flow under uncertainty.

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ABSTRACT

An increase in energy production from renewable energy sources is viewed as a crucial achievement in most industrialized countries. The higher variability of power production via renewables leads to a rise in ancillary service costs over the power system, in particular costs within the electricity balancing markets, mainly due to an increased number of extreme price spikes. This study analyzes the impact of an increased share of renewable energy sources on the behavior of price and volumes of the Italian balancing market. Starting from configurations of load and power production, which guarantee a stable performance, we implement fluctuations in the load and in renewables; in particular we artificially increase the contribution of renewables as compared to conventional power sources to cover the total load. We then determine the amount of requested energy in the balancing market and its fluctuations, which are induced by production and consumption. Within an approach of agent-based modeling we estimate the resulting energy prices and costs. While their average values turn out to be only slightly affected by an increased contribution from renewables, the probability for extreme price events is shown to increase along with undesired peaks in the costs. Our methodology provides a tool for estimating outliers in prices obtained in the energy balancing market, once data of consumption, production and their typical fluctuations are provided.

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1. Introduction

The increasing environmental awareness, together with the progressive reduction of production and installation costs [1], leads to a considerable growth in the amount of Renewable Energy Sources (RES) that is installed worldwide. Moreover, the increasing propensity to reduce greenhouse gas emissions requires an increment of the energy produced by clean, accessible energy sources such as wind and photovoltaic (PV) generation. Despite the great advantages of these energy sources, their

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intrinsic variability in power production badly fits to the hierarchical structure and the strictly dispatch rules of actual power systems. The limited accuracy of the prediction of their energy production profiles makes the management of these intermittent power sources difficult and limits the amount of RES generation that the power system can tolerate.

After the network liberalization over the last 15 years, the system balancing in real time is performed via the Electricity Balancing Market (EBM), which is a subphase of the Ancillary Services Market (ASM). This market phase shall ensure the correct balanced state over the system at the transmission level, providing the security of the supply at the lowest possible costs. However, the short time-scale and the volatility of this market phase produce higher energy costs when compared with the day-ahead market phase. Therefore an increase in the EBM volume can lead to very high maintenance costs of the system. The growing amount of the installed RES generation introduces a high number of partially correlated fluctuations in the power production. Along with that, it becomes more difficult to predict the amount of energy that is needed for balancing the system.

In general, an increase in production fluctuations could lead to both an increase in market average volumes and a more frequent occurrence of extremely high values of the volume. Whereas an increase in average volumes could be cured by strengthening the reserve capacity, the occurrence of extreme volumes is more difficult to control. Moreover, given the fact that the relation between price and demand, also known as power stack function ([2], and [3]) is highly nonlinear, large volume events can lead to very high energy prices. Such extreme and unwanted price events have been observed already by Nicolosi [4] for the German system: if they happen too often, the total costs of the market session increase and undermine the principles on which the electricity market was designed. Therefore, the forecast of the fluctuations' impact on the balancing market can be vital for an optimal planning of the network growth, and for uncovering possible critical situations of the network. So it is not surprising that the evaluation of volumes and prices of EBMs, and in general, of electricity markets, has attracted much interest in the last years.

Uncertainties are inherent both in the power production and consumption, and as well in the outcome of the trade in the energy balancing market. Approaches considerably differ in how they deal with these uncertainties. More recently, the framework of optimized power flow under uncertainty implements fluctuations for example in the production and consumption in the constraints under which costs are optimized for stable power flow solutions. The uncertainties can be implemented via fixed reserve margins in the simplest way, or via implementing chance constraints along with different scenarios [5] or robust optimization [6]. For a more recent approach see [7].

On the other hand, uncertainties in the trade of the energy market can be described by aggregative games. These are games of selfish retailers, coupled, however, via common objectives or constraints (see, for example, [8,9]) and communicating directly or indirectly with each other. In this treatment the objective usually is to prove the convergence of the optimization algorithm towards a Nash equilibrium. Alternative approaches are based on time series models ([10] and [11]), where the authors use auto-regressive methods to estimate the energy market prices from the past time series, or agent-based modeling [12–14], using a set of historical data for the requested energy that should be provided by the balancing market.

In this paper we follow different approaches in both respects. Our approach, introduced by one of us (M.M) in [15], implements fluctuations in production and consumption in an "ensemble of networks", where each network corresponds to a "microstate" and is characterized by a configuration of production and consumption values, assigned to the network's sites. For the EBM we use a version of the agent-based modeling, in which the agents learn to optimize their bids in view of maximal profit and communicate not directly with each other, but via the feedback from a so-called market authority. This combination of approaches from statistical mechanics and agent-based modeling has been validated already for the Italian EBM in [15]. In this paper we use the same approach in particular to pursue the impact of strong fluctuations in the production and consumption on prices and costs within the EBM, if an artificially increased percentage of the renewables enters the production. To make the paper self-contained, we summarize our methodology in Section 2. In Section 3 we describe the used dataset and present the results in Section 4. Section 5 gives the conclusions and an outlook.

2. Methods

Before going into detail, let us summarize the procedure, which consists of three steps:
(i) Based on real data for production and consumption at a certain representative day in the winter period of 2011–2012 in the Italian grid, we generate a certain set of starting configurations, each one describing a combination of production and load at nodes of the Italian transmission grid, which lead to a stable performance by construction. The real data were taken every 15 min over a whole day for all 6 price zones of the power grid in Italy. We then extrapolate these data towards a higher contribution of RES, ranging from the real value of 24% to 60% in the extrapolates sets. In all extrapolated cases we guarantee a stable performance by running optimal DC-power flow equations to adjust the production by conventional generators so as to guarantee an overall balanced power in the grid.
(ii) Each of the configurations of the resulting set (6 zones $\times$ 96 time instants per day for 24, 30, 40, 50, and 60% of RES) serves as starting point for generating an ensemble of configurations in the spirit of statistical physics. In statistical physics one usually describes a macrostate say of a gas of molecules by an ensemble of microstates; microstates differ by small deviations of the generalized coordinates and momenta, so that an average over many microstates leads to representative macroscopic observables. In analogy here, members of each ensemble differ from the starting configuration and therefore also mutually by small deviations in the load and the renewable energy production, chosen from a Gaussian or Weibull distribution, as explained below. Mean and width of the Gaussian distribution as well as the parameters of the Weibull

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