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Price-based unit commitment electricity storage arbitrage with piecewise linear price-effects

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ABSTRACT

Electricity storage plants can be used for many applications, with one of the most studied applications being arbitrage in the day-ahead market. Although the arbitrage value is related to the presence of price spreads, it also depends on the effect of (dis)charge actions on prices, as arbitrage generally reduces price spreads by increasing off-peak prices when charging and decreasing peak prices when discharging. As such, there are two important assumptions in price-based unit commitment arbitrage models: first, whether the storage operator is assumed to have perfect knowledge of future prices, and second, whether they recognize that their (dis)charge actions may affect those prices, i.e., the price-taking or price-making assumption. This article proposes a comprehensive formulation of the arbitrage problem including detailed operating constraints, and focuses on relaxing the price-taking assumption by considering real-world price-effect data, published in the form of hourly piecewise linear relationships between quantity and price based on submitted bids, which are referred to as "market resilience functions". These can be used to (1) evaluate the price-taking and price-making assumptions based on simplified price-effects, and to (2) provide an upper limit to the arbitrage value under the assumption that prices and price-effects are known at the decision stage. In addition, a stepwise approximation to the piecewise linear functions is developed to reduce computation time, i.e., from mixed-integer nonconvex quadratic programming to mixed-integer linear programming, while providing lower- and upper bound approximations to the arbitrage value. The developed models are applied to the Belgian day-ahead market for 2014, and show that the price-effect has a strong impact on the operation and arbitrage value of large-scale storage.

1. Introduction

1.1. Motivation

The storage of electricity represents a combination of three functions [1]: consuming electricity, accumulating the energy in some form, and generating electricity. Only part of the consumed electric energy is converted to energy stored in the buffer during charging because of a charge efficiency $0 < \eta^c \leq 1$, while only part of the stored energy is converted back into electric energy during discharging because of a discharge efficiency $0 < \eta^d \leq 1$. The buffered energy may also increase and decrease independent of the grid through exogenous power flows $p_t^+ \geq 0$ (addition) and $p_t^- \geq 0$ (removal), e.g., water inflow and evaporation in the upper reservoir for pumped-hydro storage (PHS) plants. The general power balance of storage plants that consume electric power $p_t^c \geq 0$ and generate electric power $p_t^d \geq 0$, and store it in an energy buffer $e_t \geq 0$, is then:

$$\underbrace{\frac{de_t}{dt}}_{\triangle\text{ Energy buffer}} = \underbrace{\underbrace{p_t^c \cdot \eta^c}_{\text{Addition}} - \underbrace{p_t^d / \eta^d}_{\text{Removal}}}_{\text{Electric origin}} + \underbrace{\underbrace{p_t^+}_{\text{Addition}} - \underbrace{p_t^-}_{\text{Removal}}}_{\text{Exogenous origin}}. \quad (1)$$

In recent years there has been a renewed interest in electricity storage due to the liberalization of electricity markets and the

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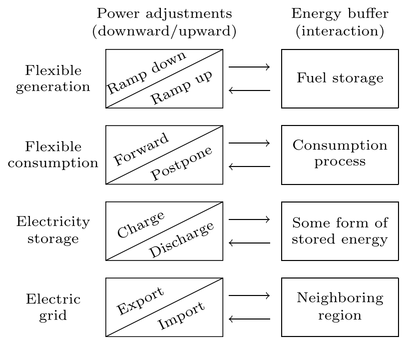

Fig. 1. Overview of power system flexibility sources.

integration of variable renewable energy sources (RES). Their expected and unexpected variability results in an increased need for flexibility, which is the ability to provide power adjustments to deal with temporary imbalances between generation and consumption of electric energy [2,3]. Electricity storage plants can provide this flexibility by charging and discharging through interaction with an energy buffer. However, flexibility can also be provided by flexible generation and consumption, but also by the electric grid through which flexible capacity in neighboring regions can be accessed (Fig. 1). Market participants are only incentivized to integrate new flexible resources when the investment is profitable. Although electricity storage plants can be used for many applications (e.g., arbitrage, portfolio optimization, frequency control, voltage support, black-start service [4,5]) and maximizing the value of storage requires the aggregation of different applications, one of the most studied and well-known applications is arbitraging day-ahead (DA) market electricity prices [6,7]. This article focuses on the arbitrage application as the sole revenue source.

1.2. Scope and approach

Classic definitions of arbitrage denote making a riskless profit by simultaneously buying and selling a similar commodity with net zero investment. However, in a broader context any activity in which a player buys a commodity at a relatively low price and sells a similar commodity, or commodity in which the former can be converted, at a relatively high price for profit can be referred to as arbitrage. This broader definition allows to include initial investments, does not require simultaneity of the purchase and sale, and furthermore does not require a single commodity either (i.e., so-called cross-commodity arbitrage) [8]. In the context of this article, arbitrage is defined as the capturing of price spreads over time in a single market, being the DA market, by means of electricity storage plants. Although the arbitrage value is directly related to the presence of these price spreads, it also depends on the price-effect of (dis)charge actions, as additional storage capacity generally reduces price spreads by increasing off-peak prices when charging as well as decreasing on-peak prices when discharging.

In contrast to cost-based unit commitment (UC), which refers to the scheduling of generation capacity to meet system load at minimum cost, the scheduling of units with the objective to maximize profit based on price signals is referred to as price-based unit commitment (PBUC) [9]. The arbitrage application is widely discussed in the literature, both from a system (e.g., [10–15]) and from an individual storage plant's PBUC perspective, the latter being the focus of this article. Generally, there are two important assumptions in PBUC arbitrage models: the first is related to the storage operator's assumed knowledge of future prices, i.e., the (im)perfect price foresight assumption, while the second is related to whether they recognize that their (dis)charge actions may affect those prices, i.e., the price-taking or price-making assumption [16,17].

A large share of the existing PBUC work assumes perfect foresight of future prices and the storage plant to be small enough to be a price-taker in the considered market (e.g., [18–23]). Ref. [18] provides an estimate of the arbitrage value in 14 deregulated markets, Ref. [19] considers the Danish market, Ref. [20] analyzes the arbitrage value in the PJM, ERCOT, and CAISO markets in the United States (US), Ref. [21] considers different markets in the US and compares them with the United Kingdom (UK), Norway, Canada, and Australia, Ref. [22] focuses on the UK and Wales, and finally Ref. [23] considers the UK market for arbitrage purposes.

In addition, quite some studies discuss a relaxation of the perfect price foresight assumption (e.g., [16,24–29]). Refs. [16,24] use a backcasting approach and analyze the PJM market. The method used in [25,26] is based on average prices of a user-specified period around which a price at which is bought and at which is sold is defined, and is applied to 13 day-ahead markets in [25] and to Denmark in [26]. In [27] a price forecast method is applied to Ontario, while [28] studies the NYISO market and forecasts the peak hours based on historical data. Finally, Ref. [29] includes a variety of random normally distributed forecast errors and uses data from the standard IEEE 118-bus test system.

Although quite some studies discuss a relaxation of the perfect price foresight assumption, less attention has been given to the relaxation of the price-taking assumption in PBUC arbitrage models. However, either large-scale or multiple small-scale storage plants that are operated cooperatively could benefit from considering the price-effect of (dis)charge actions. Even when deciding on the (dis)charge schedule as a price-taker, considering the price-effect in the ex-post calculation of the realized profit is important for owners of large storage capacities as arbitrage may reduce effective price spreads. First, Refs. [16,30] introduce a method to account for this price-effect based on an observed linear relationship between the system load and price. Second, Ref. [31] introduces a constant so-called market resilience factor to represent the price-effect of (dis)charge actions. Third, Refs. [32,33] propose methodologies to relax the price-taking assumption by taking into account the residual inverse demand function. Although these methodologies provide insight in the arbitrage value and operation of large storage capacities, due to a lack of market data or a different research scope they are based on rather conceptual and simplified price-effects and therefore result in (1) a suboptimal (dis)charge schedule and accompanying arbitrage value with respect to the actual price-effect, and (2) an ex-post gap between the expected and realized profit.

Therefore, this article focuses on relaxing the price-taking assumption by including real-world market resilience data, which illustrates the impact on the DA price of a change in offer or demand volume for each hour, published by several European power exchanges.[1] This data represents the most detailed available price-effect data, as it is obtained by the power exchange running the market-clearing algorithm again for alternative scenarios, and thus takes into account (1) the hourly aggregated supply and demand curves, (2) interaction with neigboring markets through market-coupling, and (3) the presence of complex orders. This article focuses on the arbitrage value of additional storage capacity in the DA market, but does not aim to provide bidding strategies for storage plants (e.g., [35]). Instead, the storage operator is assumed to self-schedule its (dis)charge actions against a set of DA prices

[1] In contrast to the considered market resilience data, the price elasticity of demand refers to the relative change in demand as a result from a relative change in the price, and is typically negative as the demand for most commodities decreases as the price increases [34].