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Use of battery storage systems for price arbitrage operations in the 15- and 60-min German intraday markets

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ABSTRACT

Over the last few years, electrical storage and especially battery systems have seen a strong rise in interest. In several countries, as for instance in Germany, lithium-ion batteries are now commonly deployed in end-consumer installations to shift local generation from photovoltaic systems in time. A further application for storage is price arbitrage, which corresponds to an operation strategy benefitting from price differentials. In this work, we describe a Mixed Integer Problem to optimize the storage dispatch considering both the 15- and the 60-min auctions in use in Germany. Furthermore, in addition to the calendric lifetime, the limitation to a certain number of cycles is considered in the evaluation. Last, it was conducted a sensitivity analysis to identify the price volatility level that is required to generate a profit from arbitrage operations. Therefore, a market price process with adjustable parameters has been implemented.

1. Introduction

As the share of renewable, non-dispatchable and intermittent generation is continuously growing, its integration in power systems becomes increasingly challenging. Apart from further increases in demand flexibility and additional investments in grid infrastructures to enable the integration of renewable generation, storage systems are considered as a potential solution. A recent classification for the usage of storage systems is provided in Refs. [1–3]. One of the most prominent applications is arbitrage, which describes an operation strategy where an agent aims at benefiting from price differentials by buying energy at a low price and selling it at a higher price. It can be implemented on a spatial and/or temporal scale. Spatial price differences occur between two different markets, when prices for a particular time period are lower in one market than in the other market. In that case, one can profit by purchasing at the market with the lower price and simultaneously selling at the higher price market. As the traded energy is not transferred in time, but only between different markets, no storage is required. Inter-temporal arbitrage refers to shifting energy in time and hence requires storage. In this case, energy is purchased, stored for a temporary time-span, and sold back to the market at a later point in time. The profit of the agent is determined by the revenues from selling energy (by discharging the storage device) minus the purchasing cost (to charge the storage device). Furthermore, efficiency losses and the capital cost of the storage system have to be considered in order to conduct a proper economic evaluation.

The existing literature widely recognizes that arbitrage operations did not break-even in the recent past. Steffen [4] analyzed the prospects of pumped hydro storage installations in Germany looking at the years 2002–2010 and found that revenues showed a high volatility and declined over the last few years. He concluded that the expected profit from arbitrage operations is not sufficient to justify a commitment by a typical utility. Kloess [5] analyzed arbitrage profits in the Austrian market from 2007 to 2011 and found a decline of revenues of about 60% over the time horizon. Zakeri and Syri [6] conducted a similar analysis in the Nordic market from 2009 to 2013 and concluded that arbitrage revenues are very volatile and not sufficient to break-even. Barbour et al. [7] identified a similar variability of returns in the UK market as well as a decrease in annual revenues of 75% along two years. Woo et al. [8] compared the revenues across several markets for the years 2005–2009. In line with the previous authors, they found high variations, both between markets as well as among individual years. Looking at historical data from 2007 to 2011 for the Nord Pool, EEX, UK, the Spanish and the Greek markets, Zafirakis et al. [9] determined that arbitrage revenues vary widely between markets and are not sufficient to justify storage investments. McConnell et al. [10] looked at the Australian market over the years 2004–2014. Even though they did not take investment cost into account, a strong decrease in revenues was obvious. Bradbury et al. [11] considered seven U.S.

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markets and investigated the year 2008 as it exhibited high price volatility. Nonetheless, most technologies they compared would not have been able to break even.

Overall, in the recent past arbitrage was not able to deliver sufficient returns in any of these markets to justify a storage investment. However, several market places have experienced important structural changes over the last few years for instance related with the wide spread occurrence of negative electricity prices. Furthermore, in the German market, a 15-min auction was introduced in addition to the existing 60-min auction. These auctions introduce extra flexibility mechanisms allowing agents to adjust their positions. The experience since 2011 shows that these are important instruments in a system highly driven by renewables and that the volumes traded on the 15-min auctions are strongly correlated with the intermittence of solar generation.

Both factors are likely to increase the arbitrage opportunities and therefore the theoretical revenue potential. However, negative prices might lead to unpredicted outcomes in storage dispatch models. After fully charging the storage device, simultaneous charge- and discharge operations – which are not feasible from a technical perspective – are the economic optimal solution once the storage device is fully charged due to the occurring efficiency losses and resulting monetary gains. In existing evaluation models, this situation is oftentimes not yet considered.

Furthermore, the participation in a second simultaneous market is usually difficult to be integrated in existing models thus justifying the development of new models as well as the re-evaluation of the results previously reported on this issue.

Apart from changes on the market framework, the available storage technologies also experienced important developments in recent years. Driven by significant investment cost reductions and technological advances, lithium-ion battery storage systems experienced a strong rise in interest, with several installations already deployed for the provision of primary reserve control. Contrary to pumped-hydro systems, which have been widely analyzed in the past, the lifetime of battery systems is typically not only limited by a calendric lifetime limit, but also by an operational lifetime limit. While some papers recognize the need to include the degradation resulting from storage operations (e.g. [12,3]), this effect has only recently been internalized in evaluation models. As an example, Shang and Sun [13] studied the installation of batteries in electric vehicles and found that when considering degradation, revenues from arbitrage operations are no longer sufficient to overcome implicit cost. Wankmüller et al. [14] suggest that storage systems deployed for arbitrage purposes should pursue only the most profitable opportunities to increase the net present value. Given the high relevance and the significant impact on the financial evaluation, the dual limitation by the calendric as well as the operational lifetime should therefore be incorporated in the models.

In this work, the previously mentioned shortcomings of existing research are addressed. Accordingly, the paper describes an optimization framework to identify the profit maximizing dispatch, admitting the occurrence of negative prices, the existence of two parallel markets – the 15- and the 60-min auctions as already in operation in Germany – as well as the dual lifetime limitation. In addition, an approach is described and applied to estimate the price volatility level that is required for storage devices to break-even.

2. Dispatch model

2.1. Mixed integer formulation

In order to determine the optimum dispatch of the storage device, a Mixed Integer Problem (MIP) was developed. The simulation is performed in discrete time steps. Index t refers to the individual simulation time steps and T to the time horizon of the simulation. The duration of each time step Δt is expressed as fraction of an hour and set to 0.25, as we will be considering 15-min intervals. Power flows are assumed to be constant during each time step and no ramping rates or response times are considered. Table 1 summarizes the relevant simulation parameters and variables.

Table 1
Simulation parameters and variables.

t, T, Δt	[-, -, h]	Index, simulation horizon and duration of each time step
$E_{Storage}(t)$	[Wh]	Current charge of the storage device
$P^{In}_{Storage}(t)$,$P^{Out}_{Storage}(t)$	[W]	Power absorbed/supplied by the electric storage device
$P_{15}(t)$, $P_{60}(t)$	[W]	Participation in the 15-/60-min auction and resulting power exchange with the grid
P^{Limit}_{15},P^{Limit}_{60}	[W]	Power limit for the participation in the 15-/60-min auction
$R_{15}(t)$, $R_{60}(t)$	[EUR/Wh]	Market price of the 15-/60-min auction
Hurdle	[EUR/Wh]	Hurdle rate
$\eta^{In}_{Storage}$, $\eta^{Out}_{Storage}$	[%]	Charge/discharge efficiency
$E^{Capacity}_{Storage}$	[Wh]	Rated energy capacity of the storage device
$P^{Capacity}_{Storage}$	[W]	Rated power capacity of the storage device
$\delta_{Storage}$	[%]	Maximum depth of discharge
$b_1(t)$, $b_2(t)$, $y(t)$	–	Binary variables

The power flows of the storage device are represented by $P^{In}_{Storage}(t)$ and $P^{Out}_{Storage}(t)$. The former represents charging power flows and can only assume negative numbers. Discharging power flows are represented by the latter and can only assume positive numbers. The objective of the storage agent is the maximization of his gross profit, that is the revenues obtained from the energy injected in the grid minus the cost of buying the energy taken from the grid. Therefore, the power flows for the charging and discharging operations are weighted by the current market prices. To consider the simultaneous participation in the 15- and in the 60-min auctions, the associated variables are differentiated by the subscript $_{15}$ and $_{60}$. A positive value for $P_{15}(t)$ or $P_{60}(t)$ represents power taken from the grid during the time period t in the 15-min/60-min market, whereas negative values indicate power injected in the grid. The market prices for each time period t is $R_{15}(t)$ for the 15-min auction and $R_{60}(t)$ for the 60-min auction. For our analysis, we will assume perfect knowledge of future prices. In addition, we assume that market agents act as price takers, hence a market participation does not cause any feedback reaction on the market price. As each transaction covers only a short time horizon, the time value of money is not considered in this dispatch problem. Furthermore, additional operational costs besides the immediate energy cost are not considered. While these are important issues to consider in an implementation, they would further complicate the analysis and are therefore not considered in this document.

However, as even small price differentials would be exploited under the described objective and the assumption of no operating cost, this dispatch could result in a very large number of operations. This might be undesirable due to a premature wear-down of system components as well as further transaction costs. The problem becomes more complex for storage technologies such as batteries, whose lifetime is typically limited both by a limited amount of energy throughput during their lifetime as well as calendric aging. If the storage device is dispatched very frequently, it will soon be at the end of its operational lifetime not profiting from attractive arbitrage opportunities during the remaining theoretical calendric lifetime. On the other hand, if the storage device is dispatched too restrictively, its calendric aging will be the determining factor and not sufficient arbitrage opportunities will be pursued. Therefore, an additional term ("hurdle") is included