Journal of Energy Storage 7 (2016) 82–92

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Auction-based allocation of shared electricity storage resources through physical storage rights

Tom Brijs [a,b,d,*], Daniel Huppmann [c,d], Sauleh Siddiqui [d,e], Ronnie Belmans [a,b]

[a] Department of Electrical Engineering, University of Leuven (KU Leuven), Heverlee, Belgium
[b] EnergyVille Research Institute, Genk, Belgium
[c] International Institute of Applied Systems Analysis (IIASA), Laxenburg, Austria
[d] Department of Civil Engineering, The Johns Hopkins University, Baltimore, MD, USA
[e] Department of Applied Mathematics and Statistics, The Johns Hopkins University, Baltimore, MD, USA

ARTICLE INFO

Article history:
Received 12 March 2016
Received in revised form 13 May 2016
Accepted 17 May 2016
Available online

Keywords:
Electricity storage
Shared storage resources
Auction-based allocation
(Generalized) Nash equilibrium
Mixed complementarity problem

ABSTRACT

This article proposes a new electricity storage business model based on multiple simultaneously considered revenue streams, which can be attributed to different market activities and players. These players thus share electricity storage resources and compete to obtain the right to use them in a dynamic allocation mechanism. It is based on the design of a new periodically organized auction to allocate shared storage resources through physical storage rights between different market players and accompanying applications. Through such a flexibility platform owners of flexible resources can commercialize their flexible capacity over different applications, while market players looking for additional flexibility can obtain this through a pay-per-use principle and thus not having to make long-term investment commitments. As such, they can quickly adapt their portfolio according to the market situation. Alternatively, through such an allocation mechanism players can effectively share storage resources. Players may be incentivized to participate as they can share the investment cost, mitigate risk, exploit economies of scale, overcome regulatory barriers, and merge time-varying and player-dependent flexibility needs. The mechanism allocates the limited storage resources to the most valuable application for each market-clearing, based on the competing players' willingness-to-pay. An illustrative case study is provided in which three players share storage resources that are allocated through a daily auction with hourly market-clearings.

1. Introduction

The integration of variable renewable energy sources (RES) is a major challenge for the operation of the power system. Their limited controllability and predictability results in an increased need for power system flexibility, while flexible conventional power plants currently experience decreasing profitability as a result of low electricity prices and a limited number of operating hours [1]. Flexibility is the ability to provide up- and downward power adjustments to deal with temporary imbalances between generation and consumption of electric energy [2,3]. This flexibility can be provided by flexible generation and consumption, and electricity storage, but can also be activated in neighboring regions through interconnection capacity and the further integration of adjacent markets (Fig. 1). Electricity storage has the ability to compensate temporary power surpluses and shortages by decoupling the generation of electric energy from its consumption over time. The extent of this compensation is limited by its storage capacity.

Although there is a need for flexibility because of its increasing demand and decreasing supply, market participants are only incentivized to integrate new flexible resources if the investment is profitable. In addition, the value of storage is often underestimated due to the focus on operation strategies based on only a single application, usually price arbitrage between off-peak and on-peak hours. However, determining the true value of electricity storage will likely require the aggregation of multiple applications while accounting for the interdependence between potential revenue streams [4–6]. The value of individual applications cannot simply be added together, but need to be co-optimized since different storage services can conflict with each other [7].

* Corresponding author at: Department of Electrical Engineering, University of Leuven (KU Leuven), Heverlee, Belgium. Tel.: +32 485826161.
E-mail addresses: tom.brijs@esat.kuleuven.be (T. Brijs), huppmann@iiasa.ac.at (D. Huppmann), siddiqui@jhu.edu (S. Siddiqui), ronnie.belmans@esat.kuleuven.be (R. Belmans).

http://dx.doi.org/10.1016/j.est.2016.05.009
2352-152X/

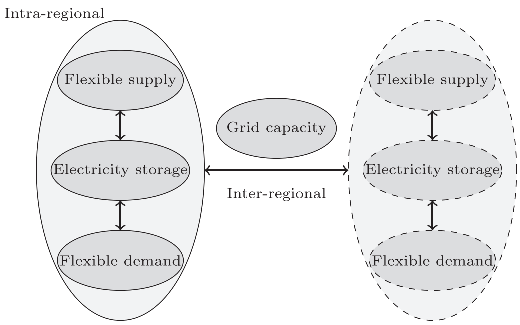

Fig. 1. Overview of power system flexibility sources.

Therefore, this article considers a new storage business model based on multiple simultaneously considered revenue streams, which can be attributed to different activities in the market and can thus be the focus of different market players. As such, these market players share electricity storage resources and compete to use the shared storage resources. The allocation is based on the design of a periodically organized auction with sequential market-clearings, in which the right to use storage resources is traded between different players.

1.1. Electricity storage applications

Electricity storage refers to systems, bidirectionally coupled with the power system, which buffer energy. This includes both systems in which the charging and discharging side is physically located at one location, e.g., pumped-hydro storage plants and battery storage systems, or at multiple locations, i.e., power-to-gas systems in combination with a gas turbine. This definition distinguishes electricity storage from the broader concept of energy storage, which may, e.g., also include stock-piling fuel at the supply side of the power system.[1]

Historically, electricity storage plants were considered as an alternative for investing in peak-load generation, by charging during off-peak and discharging during on-peak moments. However, due to the liberalization of electricity markets and the integration of RES, distinct valorization paths for different applications of storage emerged [8–11]. These can be categorized in *energy*, *network*, and *reliability* services.

Energy services include arbitrage and portfolio optimization of market participants. Arbitrage is based on price differences over time: electricity is bought and stored when the price is low, and is sold and generated again when the price is higher. Portfolio optimization is performed at different time scales, i.e., investment, scheduling, and operation, and covers generation investment deferral, inter-temporal energy shifting, and capacity firming, respectively. Through inter-temporal energy shifting generators optimize the value of generation by decoupling generation and physical injection, while consumers optimize the cost of consumption by decoupling consumption and physical withdrawal. Capacity firming can indicate the ability to smoothen the generation or consumption output, resulting in less volatile power profiles, or to follow predetermined output schedules to reduce imbalanced positions in real-time. *Network services* include the provision of frequency control (i.e., primary, secondary, tertiary),[2] voltage support, congestion management, and black-start capabilities to the transmission system operator (TSO). In the future, some of these will likely be provided to the distribution system operator (DSO) as well. *Reliability services* include the provision of reliability on both the local and system level.

This multitude of applications makes electricity storage plants an interesting asset for a wide range of market participants. However, operating a storage plant to provide just one or a few of these services might not always result in a positive business case; profitability may require the aggregation of multiple applications.

1.2. Motivation

Although some studies focus on the co-optimization of different storage applications (e.g., [5,7,12]), most existing work focuses on only a single application or allocates the available storage resources a-priori when considering multiple applications, instead of applying a periodically performed optimization process. In addition, the sharing and operation of storage resources by different players has only been studied to a limited extent, except for the work done by [4]. As such, the contribution of the auction-based allocation described in this article is that it does not a-priori define the applications or even the market player that the storage resources will serve at a certain moment in time. This can be accomplished by the development of a centralized platform where periodical auctions with sequential market-clearings take place to allocate the right to use (dis)charge power capacities and energy storage capacity. These auctions can serve both settings where (1) multiple players share common storage plants and (2) multiple suppliers of storage resources and prospective consumers meet to trade physical storage rights. Whereas the presented allocation mechanism allows to simultaneously include multiple resource suppliers and players competing for the right to use them, and to simultaneously consider their offers, the method discussed in [4] considers a sequential allocation to players which express their need for flexible resources at different time scales. In addition, the presented allocation mechanism auctions physical (dis)charge power rights and storage capacity rights, whereas the allocation in [4] is based on actual utilization profiles.

Market players can have multiple incentives to share, contract, or offer storage resources by means of a periodically organized auction. First, this may allow them to exploit economies of scale, i.e., increasing the plant size at a reduced cost per unit of power and energy. Second, they can share the investment cost and associated risk, especially when considering large-scale storage plants. Third, as flexibility needs vary throughout the year and even throughout the day, and across market players, they may have different (possibly complementary) storage utilization patterns, providing an incentive to share resources.

From a system point of view, there are additional reasons to share storage resources. First, as storage resources are usually limited due to geographical requirements, they should be allocated to the most valuable services at each point in time. Second, due to the introduced competition to use storage resources strategic under- or overusage [13] is likely to occur less frequently. Third, although pumped-hydro storage is currently the most mature storage technology, rapidly decreasing costs and technological advancements are making battery storage systems increasingly competitive [14]. To overcome barriers for such small-scale storage resources to participate in the market, the development of a centralized platform allows owners of these resources to offer flexibility to market players that aggregate them. Finally, regulatory barriers might prevent storage operators to provide certain services simultaneously. In the United States storage plants can either provide market-based or regulated services (e.g., congestion management to avoid grid upgrades), but they are

[1] Power plants may have significant fuel reserves, e.g., the natural gas grid with its storage capabilities for gas-fired power plants, coal piles at classic thermal power plants, and nuclear fuel at nuclear power plants.

[2] In the ENTSO-E synchronous zone operating reserves are categorized into frequency containment reserves (FCR), frequency restoration reserves (FRR), both automatic (aFRR) and manual (mFRR), and restoration reserves (RR).