



Techno-economic evaluation of battery energy storage systems on the primary control reserve market under consideration of price trends and bidding strategies

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ARTICLE INFO

Article history:

Received 29 September 2017

Received in revised form 19 December 2017

Accepted 18 March 2018

Available online xxx

ABSTRACT

With declining prices on the German primary control reserve (PCR) market and simultaneously decreasing battery cell and system prices, it is unclear whether an investment in a battery energy storage system (BESS) providing PCR will be profitable. In order to address this issue, we outline different bidding strategies for PCR auctions and analyze their impact on revenues and battery aging. Furthermore, following a net present value (NPV) approach, we investigate how the development of PCR prices and battery system prices affects the attractiveness of BESS providing PCR.

The results show that the bidding strategies developed in this paper allow for reasonable revenues from PCR provision. A higher willingness of the bidder to take risks is not rewarded with higher revenues in the scenario presented in this paper. Furthermore, the impact of the choice of the bidding strategy on battery aging seems negligible. However, the development of PCR market prices and battery system prices is crucial for the attractiveness of BESS providing PCR. Investments come with a high risk due to the volatility of PCR market prices and the uncertainty of future battery system prices. A strong drop in PCR prices would make investments unattractive, even in the case of an optimistic estimate of the BESS price development. However, if PCR prices decrease moderately, an investment in a BESS providing PCR lead to a positive NPV over the system lifetime under the assumptions made in this study.

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1. Introduction

Stabilizing the electricity grid is a major challenge for system operators, particularly with a growing share of intermittent renewable energy sources feeding into the grid. Since the electricity grid is not capable of storing energy, control reserve is required to balance feed-in and consumption. Primary control reserve (PCR) is the product with the fastest response time and the shortest deployment period in the interconnected grid of the

European Network of Transmission System Operators (ENTSO-E) Regional Group Continental Europe. PCR is tendered by the responsible transmission system operator and traded on separate markets with specific regulatory frameworks.

This paper focuses on the German PCR market, which has undergone a dynamic development in recent years. This includes the integration of neighboring countries and an increasing share of stationary battery energy storage systems (BESS) providing PCR. In 2016, a rapid drop in PCR capacity prices could be observed. This development raises the question whether providing PCR is an attractive business model for BESS operators.

We aim to investigate the attractiveness of BESS providing PCR in the given framework, focusing on bidding strategies of BESS operators in PCR auctions on one hand, and on possible paths of PCR price and BESS price development on the other hand.

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Nomenclature

A_{week}	Weekly annuity of investment (€)
BESS	Battery energy storage system
CAP_{min}	Power plant minimum load (MW)
CAP_{PCR}	Amount of PCR capacity provided (MW)
C_{BESS}	Battery capacity (MWh)
C_{var}	Variable costs (€/MWh)
E	Energy (MWh)
I	Initial investment (€)
i	Discount rate (–)
OC	Opportunity costs (€)
PCR	Primary control reserve
P_{DA}	Price on the day-ahead market (€/MWh)
P_{PCR}	Price on the primary control reserve market (€/MW)
P_{PCRbid}	Price bid on the PCR market (€/MW)
P_{PCROC}	Minimum price bid due to opportunity costs (€/MW)
P_{PCmax}	Maximum PCR price forecast (€/MW)
P_{PCmin}	Minimum PCR price forecast (€/MW)
$P_{\text{PCRannuity}}$	Price bid on the PCR market based on weekly annuities (€/MW)
P_{PCRwa}	CAP_{PCR} – weighted average PCR price forecast (€/MW)
R	Cash flow (€/year)
SoC	State of charge (%)
T	System lifetime (years)
t	Time (index)
w	Week (index)
ΔE_{DU}	Energy exchanged due to deadband utilization (MWh)
ΔE_{OF}	Energy exchanged due to overfulfillment (MWh)
ΔE_{PCR}	Energy exchanged due to PCR provision (MWh)
ΔE_{SC}	Energy exchanged due to self-consumption (MWh)
ΔE_{ST}	Energy exchanged due to schedule transactions (MWh)
η_{ch}	Charging efficiency (–)
η_{dis}	Discharging efficiency (–)

1.1. Literature review

Providing PCR has been found to be a high-value application field for stationary BESS owners [1]. The impact of primary frequency control provision by energy constrained units, such as BESS, on the power system has been analyzed by Borsche et al. [2]. A key finding is that PCR provision by BESS is as reliable as PCR provision by conventional power plants with additional advantages for the system due to fast ramp rates and the decoupling of control power provision and energy production. Furthermore, using BESS instead of conventional power plants is a promising option to reduce environmental impacts of PCR provision [3]. In the literature, different aspects of PCR provision by BESS are investigated. A number of publications deal with operation strategies for charge level control of stationary BESS providing PCR and their impacts on energy throughput and charge levels [4–8]. In [9], an operation strategy and a sensitivity analysis for PCR provision by a large scale hybrid BESS fully applicable to the current regulation in Germany is presented. While most papers consider market based measures for charge level control (e.g. intraday trading). Henninger et al. present a combined approach considering direct coupling of a BESS with renewable energy

sources which directly provide the energy for charge level control [10]. An approach for sizing a BESS for combined grid inertial response and PCR provision is provided in [11]. A performance analysis of energy storage systems within existing regulatory frameworks for PCR provision and an analysis quantifying the design and operational requirements is carried out by [12] and applied to Great Britain as a case study.

Further papers discuss battery aging and economic aspects of PCR provision by battery systems. Hollinger et al. compare cost structures of BESS and conventional power plants [13]. Based on a simulation model, Fler et al. evaluate battery aging and the economic feasibility of a BESS providing PCR in a case study for Germany [14]. Świerczynski et al. investigate performance degradation of lithium-ion cells and economic feasibility of BESS providing PCR on the Danish electricity market [15,16]. The impact of different operation strategies for charge level control on battery aging and lifetime is evaluated in [17]. The impact of a market entry of large numbers of BESS in the PCR market is discussed in [18] and [19]. Steber et al. investigate the possibility of providing PCR using distributed household PV BESS [20]. The application of BESS for PCR provision in (island) microgrids has been discussed in a number of papers [21,22]. The design and the operation of a hybrid storage system consisting of a BESS in combination with a SMES for PCR provision in a small island microgrid with high shares of renewable energies is presented in [23].

1.2. Development of the German PCR market

The German market for balancing power is divided into three sections, of which PCR is the product with the highest requirements in terms of reaction times and accuracy of regulation. The other two products traded are secondary control reserve and minute reserve (tertiary control reserve). BESS work well for PCR provision as they offer short response times, precise controllability, high efficiencies and can be dimensioned in a flexible manner. The regulatory framework of the market including prequalification requirements for technical units providing PCR is described in [24–28]. Table 1 summarizes the product characteristics of PCR in Germany.

In recent years, the German PCR market has developed from a bilateral oligopolistic market with five providers in 2007 to a more competitive market with 22 prequalified providers in 2016. As of January 2017, 603 MW of PCR are tendered in the German control area. TSOs from the Netherlands, Belgium, Switzerland, France and Austria also use the German auction platform to tender parts of their PCR demand, which results in an effectively bigger market size (see Table 1) [29].

Fig. 1 illustrates the development of the average PCR capacity price from 2008 to 2016. From 2008 till 2011 prices fluctuated on a relatively high level between approx. 3300 and 3900 €/MW. In 2012, the average price dropped by 24%–2779 €/MW. In the following three years, the prices recovered, reaching a value of 3464 €/MW in 2015. In 2016, the second price drop occurred. This

Table 1
Product characteristics of primary control reserve in Germany (joint market area) [29].

Primary control reserve (PCR)	
Tender period	one week
Minimum bid size	1 MW
Increment of bid size	1 MW
Call for tender	capacity price [€/MW] merit-order
Remuneration	pay-as-bid (capacity price)
Market size	approx. 1250 MW (joint tender of German, Dutch, Belgian, Swiss, French and Austrian TSOs)

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