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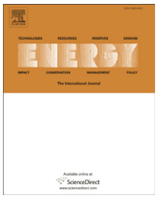

Economic assessment of a price-maker energy storage facility in the Alberta electricity market[☆]

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ABSTRACT

Dynamic price fluctuations in the Alberta electricity market bring potential economic opportunities for electricity energy storage technologies. However, storage operation in the market could have significant impact on electricity prices. This paper evaluates the potential operating profit available through arbitrage operation for a price-maker storage facility in Alberta. Considering a five-year period from 2010 to 2014, hourly generation and demand price quota curves (GPQCs and DPQCs) are constructed to incorporate price impact as an input to the self-scheduling problem of a price-maker storage facility. The self-scheduling model is applied to the historical hourly GPQCs and DPQCs of the Alberta electricity market to investigate the potential economic performance of a price-maker energy storage facility.

1. Introduction

The implementation of large-scale energy storage systems has been shown to be technically feasible in the province of Alberta [1]. Such systems are able to provide load-shifting [2] and potentially provide the necessary flexibility to deal with uncertainties associated with the growing penetration of renewable resources [3–5]. Load shifting is one of the best-comprehended and analyzed applications of energy storage, i.e., to buy and store electricity at low demand, low price periods, and sell at high demand, high price periods [6]. This is referred to as energy arbitrage. It has been shown that the dynamics of the Alberta electricity market and relatively high price variations provide desirable opportunities for energy arbitrage [7]. As an example, the hourly electricity prices in this market for 2013 are shown in Fig. 1. Over the year, electricity prices averaged $80.20/MWh. For 3208 h, the price was below $25/MWh and for the remaining hours, the average price was over $115/MWh with 204 h settling between $800/MWh and $1000/MWh, the market price cap. As a result of this variation, energy storage systems have attracted the attention of investors; in 2014, a 160 MW compressed air energy storage (CAES) plant was filed with the Alberta Electric System Operator (AESO) in 2014 [8]. It is important for the investors to know the potential profitability of a large-scale investment in bulk energy storage; economic feasibility is the deciding factor for developing new energy storage facilities. Projects must be attractive to capital from the investors' viewpoint and it is crucial to evaluate the potential profit available to be earned through energy arbitrage in the Alberta electricity market.

The profitability of providing energy arbitrage by energy storage systems in various electricity markets are shown in Refs. [6,9–14]. These studies assume that the energy storage facility is a ”price-taker”, i. e, storage operation in the market does not affect the pool price [15,16]. However, in the case of a large-scale energy storage facility it can be assumed that charging and discharging operations change the net demand and supply. As a consequence, a large-scale energy storage facility can be expected to be a price-maker, i.e., its actions could affect the market price. A few studies have modeled the impacts of energy storage operation on market price. The operation of large-scale price-maker energy storage systems is optimized in Ref. [17]. The profitability of energy arbitrage for a price-maker energy storage in the PJM [6], the Iberian Electricity Market [18,19] and the Alberta electricity market [20] is investigated. In Ref. [20], one representative supply curve is considered for all the hours. The impact of energy storage charging and discharging operation on market prices should be accurately formulated and historical hourly data should be employed to achieve a better understanding of the energy storage profitability in the

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Nomenclature

Indices

t	Index for operation intervals running from 1 to T.
s	Index for the steps of generation price quota curves from 1 to n_t^d.
s'	Index for the steps of demand price quota curves from 1 to n_t^c.

Parameters

μ	Roundtrip storage efficiency.
VOM^d	Variable operation and maintenance cost of discharging.
VOM^c	Variable operation and maintenance cost of charging.
P^d_{max}	Maximum discharging capacity.
P^c_{max}	Maximum charging capacity.
E_{min}	Minimum level of energy storage.
E_{max}	Maximum level of energy storage.
E_{int}	Initial level of energy storage.
$\pi^d_{t,s}$	Price corresponding to step number s of the GPQC at hour t.
$\pi^c_{t,s'}$	Price corresponding to step number s' of the DPQC at hour t.
$q^{d,min}_{t,s}$	Is the summation of power blocks from step 1 to step $s-1$ of GPQC for hour t.
$q^{c,min}_{t,s'}$	Is the summation of power blocks from step 1 to step $s'-1$ of DPQC for hour t.
$b^{d,max}_{t,s}$	Size of step s of the GPQC at hour t.
$b^{c,max}_{t,s'}$	Size of step s' of the DPQC at hour t.

Functions

$\pi^d_t(P^d_t)$	Stepwise decreasing function that indicates the market price as a function of the price-maker discharge quantity at time t.
$\pi^c_t(P^c_t)$	Stepwise increasing function that indicates the market price as a function of the price-maker charge quantity at time t.

Variables

P^d_t	Discharging power of the storage unit at hour t.
P^c_t	Charging power of the storage unit at hour t.
OC_t	Operation cost of the plant at time t.
E^s_t	Level of energy storage at time t.
u^x_t	Unit status indicator in either modes x, i.e., discharging (d) or charging modes (c) (1 is ON and 0 is OFF).
$b^d_{t,s}$	The fractional value of the power block corresponding to step s of the GPQC to obtain discharging quota P^d_t in hour t.
$b^c_{t,s'}$	The fractional value of the power block corresponding to step s' of the QPQC to obtain charging quota P^c_t in hour t.
$x^d_{t,s}$	Binary variable that is equal to 1 if step s of GPQC is the last step to obtain discharging quota P^d_t in hour t and 0 otherwise.
$x^c_{t,s'}$	Binary variable that is equal to 1 if step s' of DPQC is the last step to obtain charging quota P^c_t in hour t and 0 otherwise.

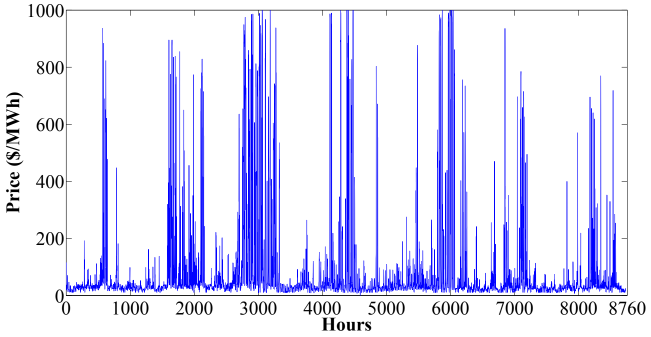

Fig. 1. Hourly electricity price during 2013 in the Alberta electricity market.

Alberta electricity market.

Several efforts have been devoted in modeling of price-maker generation companies (Gencos). The developed modeling methods can be divided into two categories: game based and non-game based. Game based methods aim to calculate the Nash Equilibrium in a market with a single or multiple price-maker Gencos using the mathematical program with equilibrium constraints (MPEC) approach and binary expansion techniques [21–24]. In Refs. [21,22], the bidding strategy problem of a price-maker Genco is initially formulated as a bi-level optimization problem, consisting of bidding strategy and market clearing problems in the upper and lower levels, respectively. Then, using Karush-Kuhn-Tucker (KKT) optimality conditions, the problem is converted to its equivalent single nonlinear MPEC problem. Binary expansion is used in Ref. [22] to transform the nonlinear MPEC problem to a mixed-integer linear programming (MILP) form and then solve the bidding strategy for one price-maker thermal generator in an electricity market. In Ref. [23], this work is further extended to find the Nash equilibrium for a market with multiple price-maker firms. Bakirtzis et al. [24] apply the approach in Ref. [22] to construct multi-step price-quantity offer curves for a single price-maker producer.

In non-game based methods, the impact of a participant's operation on the market price is modeled by generation price quota curves (GPQCs) [25]. The GPQC for a given hour, is a stepwise decreasing curve that indicates the market price as a function of the total accepted production of the price-maker generator. Fig. 2-(a) shows an example of a GPQC with steps of 10 MW up to 100 MW. The use of GPQCs enables self-scheduling of price-maker producers to be formulated efficiently [26–29]. In Ref. [26], the self-scheduling problem of a price-maker thermal producer is addressed using a MILP approach with PQCs. This work illustrates the efficient and proper functioning of the proposed formulation. PQCs are used to address the short term operation planning of a price-maker hydro producer in a day-ahead electricity market [27,28]. A mid-term self-scheduling model for a price-maker hydro producer is developed in Ref. [29], in which PQCs are used to model the producers interaction with other market participants.

This paper addresses the economic assessment of energy arbitrage for a large-scale energy storage facility in the Alberta electricity market, considering its impact on pool prices. Self-scheduling of a merchant price-maker storage plant is proposed, using an approach which incorporates the impact of storage operation on market clearing price by means of price quota curves. The impact of large-scale energy storage discharging activities in the market is modeled by hourly GPQCs. However, the storage plant must decide not only when to sell electricity to the market, but also