Applied Energy 159 (2015) 422–432

Contents lists available at ScienceDirect

Applied Energy

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

Estimating the value of electricity storage in an energy-only wholesale market

Dylan McConnell [a,b,*], Tim Forcey [a], Mike Sandiford [a]

[a] Melbourne Energy Institute, University of Melbourne, Australia
[b] Australian German College of Climate and Energy Transitions, University of Melbourne, Australia

HIGHLIGHTS

- Storage devices effectively provide a similar service to peak generators.
- The capacity value of storage was found to be insensitive to the round trip efficiency.
- Storage devices may compete with traditional peak generation technologies.
- The ability to derive additional revenue from energy arbitrage provides a competitive advantage to storage devices.

ARTICLE INFO

Article history:
Received 12 May 2015
Received in revised form 14 August 2015
Accepted 2 September 2015

Keywords:
Electricity storage
Arbitrage
Volatility
Pumped hydro
Energy-only market

ABSTRACT

Price volatility and increasing renewable energy generation have raised interest in the potential opportunities for storage technologies in energy-only electricity markets. In this paper we explore the value of a price-taking storage device in such a market, the National Electricity Market (NEM) in Australia. Our analysis suggests that under optimal operation, there is little value in having more than six hours of storage in this market. However, an inability to perfectly forecast wholesale prices, particularly extreme price spikes, may warrant some additional storage. We found that storage devices effectively provide a similar service to peak generators and are similarly dependent on and exposed to extreme price events, with revenue for a merchant generator highly skewed to a few days of the year. As a consequence of this finding, and in contrast to previous studies, the value of storage was found to be relatively insensitive to the round trip efficiency. We also found that the variability of revenue and exposure to extreme prices could be reduced using common hedging strategies, such as those currently used by peak generators. We present a case study that demonstrates storage technologies using such strategies may have a competitive advantage over other peaking generators in the NEM, due to the ability to earn revenue outside of extreme peak events. Similar to traditional peak generators, a main driver for storage options in an energy-only electricity market is extreme prices, which in turn is dependent on capacity requirements. However storage technologies can receive additional revenue streams, which may be improved by increased integration of renewable energy.

1. Introduction

Volatile prices are a common feature of competitive wholesale electricity markets, and especially energy-only markets [1]. While market structures vary considerably from country to country, electricity prices in energy-only markets invariably demonstrate significant short term variation. This is a function of the underlying characteristics of electricity supply: consumption and production must instantaneously match – a novel feature for a commodity market [2].

Electricity has generally been considered a non-storable commodity [3]. The lack of options to cost-effectively store electrical energy on a significant scale means that electricity systems are sized to meet the maximum potential peak demand, and electricity markets rely on the real-time balance of supply and demand.

A common feature of electricity markets with limited or no storage is price volatility with extreme price spikes. Rapid variations in demand over short periods, outages of generators or transmission lines, and generator bidding behaviour result in highly volatile prices [4]. Historically, flexible generators such as Open

* Corresponding author at: Melbourne Energy Institute, University of Melbourne, Australia
E-mail address: dylan.mcconnell@unimelb.edu.au (D. McConnell).

http://dx.doi.org/10.1016/j.apenergy.2015.09.006
0306-2619/

Cycle Gas Turbines (OCGT) have been used to provide peak capacity and respond to these rapid changes in demand and price. Due to its high flexibility, gas is also often considered to be an ideal partner for variable renewable generation [5].

Electricity storage technologies can also provide peak demand capacity in addition to grid reliability and assist the integration of renewable energy sources [6]. Large-scale electricity storage offers an alternative to gas for power system balancing, as variable renewable generation continues to expand [7]. In Australia the market operator (AEMO) recently undertook a study exploring an Australian market powered entirely by renewable energy [8]. This study found that significant energy storage was crucial to such a system in minimising cost while maintaining reliability and security standards.

In this paper we analyse the current value of electricity storage deployed in Australia's National Electricity Market (NEM), recognised as one of the better designed and implemented energy-only markets [9,10]. Unlike many studies, this work includes both an evaluation of the value of time shifting energy, capitalising on arbitrage opportunities *and* the value of providing peak capacity, with a case study comparison to OCGT's. We focus on the South Australian (SA) market region which has one of the highest penetrations of wind power in the world, with 31% of the electricity generated coming from wind in the 2013–14 financial year [11]. As such, this study provides interesting and useful insight into the energy and capacity value of storage in an energy-only electricity market in a system with high renewable energy penetrations.

1.1. Literature review

Energy storage technologies have historically been uneconomic to install and operate, with the exception of pumped hydro. Increasing penetrations of variable renewable energy technologies, such as wind and solar, have renewed interest in evaluating the arbitrage opportunities [12,13].

There are now many studies that investigate the economic viability of electricity storage in electricity markets around the world. This analysis is predominantly limited to assessing the arbitrage value only, capturing the price differential resulting from electricity market volatility.[1]

Typically the economic viability of storage has been evaluated with a price-taker model, using historical market prices [14], sometimes referred to as a 'small device' energy arbitrage model. For example, in the U.S., Sioshansi et al. [15] analysed the PJM interconnection, Walawalkar et al. [16] analysed the NYISO interconnection and Bradbury et al. [12] analysed the value of storage in seven U.S. wholesale markets. These approaches do not consider non-arbitrage value, but both Bradbury et al. [12] and Sioshansi et al. [15] recognised that energy storage may have additional value in the ancillary services and capacity markets.

Internationally, Figueiredo et al. [17] investigated and compared the economics of 14 power markets. Graves et al. [18] looked at the arbitrage opportunities of storage in the U.S., and compared these to international markets. Connolly et al. [19] compared optimal arbitrage profits across 13 electricity spot markets. These papers also papers consider different operational strategies to evaluate 'real-world' arbitrage opportunities, incorporating the uncertainty of future electricity prices.

Increasingly, attempts have been made to model the dispatch of storage devices by co-optimising energy arbitrage with provision of energy reserves. Drury et al. [20] quantified the additional value of reserves for a Compressed Air Energy System (CAES) in several markets. More recently, Das et al. [14] analysed the co-optimised value of storage in both the energy market *and* the ancillary service market, using a market modelling approach. This paper utilised a storage dispatch model based on arbitrage opportunities across energy and ancillary service markets ("cross-arbitrage"), with the simulation results applied to a Compressed Air Energy Storage (CAES) system.

While the Das et al. [14] paper co-optimises across the different services, the economic dispatch formulation uses both a *Unit Commitment* (UC) and *Economic Dispatch* (ED) program. The UC is run a day-ahead and the ED is run once the commitments decisions have been made. At the same time, the capacity is considered separate to the energy market (as a regulation service), with bid price parameters capped at $350/MW. Drury et al. [20] also used reserve price data, separate from the energy market data, to optimally dispatch the storage devise.

In this paper, we extend the literature by investigating both the arbitrage value and capacity value of storage in an energy-only market with a high penetration of renewable energy. Unlike the Das et al. [14] work we use historic market data in an energy only-only market, with a single market for both energy and capacity. However we also explore the capacity value separate to the arbitrage value, which is often missing from historic price-taker analysis.

This paper is organised as follows: Firstly, we describe some of the key characteristics of the NEM. Then we characterise the basic relationship between storage capacity and the arbitrage value of energy storage, using a small-device energy arbitrage approach, assuming optimal operating regime and *'perfect foresight'* of electricity price. Thirdly, we determine the value using wholesale price forecasts in order to assess the impact of the uncertainty of future electricity prices and estimate the accuracy of perfect foresight analysis. Finally we analyse how hedging strategies typically used in the supply of *capacity* to the market might effect the value. We finish with a discussion of the implications of the analysis and how the value may evolve over time.

1.2. The Australian electricity market

The Australian National Electricity Market (NEM) is a gross pool, energy-only market along the Eastern seaboard of Australia, supplying electricity to approximately 90% of the Australian population. It is often held up as a exemplar of an energy-only market [10], with a price cap explicitly based on the Value of Lost Load (VOLL). The price cap is currently one of the highest in the world at $13,100/MWh, about 300 times the volume weighted price average of around $45 [9].[2] The market has a floor price of −$1000/MWh. Historically, prices have often reached the price cap during periods of scarcity, and the market has been noted as one of the most volatile commodity markets in the world [21].

The NEM consists of five interconnected regions, with the dispatch process centrally managed by the market operator AEMO. Wholesale Regional Reference Prices (RRP) are calculated for each region and set the settlement price for all generators in the region. All transaction is the NEM are settled against a half-hourly spot price. However, dispatch within the NEM is optimised by the operator on 5 min intervals, and as such is considered a 'fast market'. Fast markets (with short dispatch intervals) provide incentives for dispatchable, flexible capacity rather which would otherwise be met by regulation reserves [22]. This is reflected in the relative small size of the Frequency Control Ancillary Services (FCAS) market relative to wholesale spot market. In 2014, payments through

[1] Buying power when power prices are low, and reselling it at a higher price, hours or days later.

[2] The price cap changed over the period analysed increasing from $10,000, to $12,500 in 2010, to $12,900 in 2012 and then to $13,100 in 2013.