

Potential Arbitrage Revenue of Energy Storage Systems in PJM during 2014

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Abstract— The price of electricity in the Mid-Atlantic (PJM) region of the United States increased during the “Polar Vortex” at the beginning of 2014. Transmission lines were congested because of high demand during the extreme cold weather. The natural gas price for electricity generation increased more than 35% at the end of 2013. Energy Storage Systems (ESS) would have helped the system to overcome many difficulties during that period. Other opportunities in energy arbitrage define the greatest scale for storage applications. Real-time and Day-ahead markets in PJM provide alternative arbitrage opportunities. Considering the prices in 2014 for 7,395 locations in PJM, results show the potential revenue for ESS for normal arbitrage and for extreme cold weather events.

Index Terms— Arbitrage, electricity market, energy storage, linear optimization, power system economics, real-time price.

I. INTRODUCTION

The benefits provided by Energy Storage System (ESS) have been described as related to energy time shift, ancillary services, upgrade deferral, power quality, reliability and variable generation smoothing [1],[2]. The United States (including all territories) have already installed 52 units (or 411 MW) of electrochemical ESS over 1MW of rated power [3]. There are 14 units over 1 MW operating in PJM (123 MW of power capacity), making them one of the most engaged Regional Transmission Operator (RTO) in the United State. Those installed ESS operate with different purpose, mainly including bill management, energy time shift, frequency regulation and reserve capacity. Flow battery and sodium based battery technologies are the most promising for time shift and peak shaving applications [2],[4].

The prices of electricity went down since 2008, because of increased natural gas supply from fracking. However, the average electricity prices in Real-time markets and Day-ahead markets in 2014 were the highest since then (section II will discuss those values). Ancillary services costs are relatively limited, about \$2/MWh in PJM compared to the energy costs of \$50/MWh per unit of system load [5]. Hence, the largest impact of storage would be through energy arbitrage. Energy time shift can create revenue during periods of low prices

(buying opportunity) and high prices (selling opportunity). An estimation of the potential arbitrage revenue for a selected nodes in PJM from 2002 to 2007 in DAM is presented in [6]. The authors found that perfect foresight is a reasonable approximation of the actual possible capture. We present related analysis using a generic model to represent EES technologies with more recent and more granular data.

In section II, an electricity price overview of PJM is presented. Section III shows the potential arbitrage of ESS for a perfect forecast scenario of electricity prices in PJM wholesale market in 2014 and evaluates the influence of energy capacity (or hours of storage) in the potential arbitrage revenue. The main conclusions are presented in section IV.

II. ELECTRICITY PRICES IN PJM IN 2014

PJM Interconnection is a Regional Transmission Organization (RTO) that coordinates an organized wholesale electricity market in 13 states and the District of Columbia. The total installed power capacity in PJM at the end of 2014 was 183 GW and the electricity generation was 780 TWh.

There are two options of electricity energy market in PJM with separate settlements based on Locational Marginal Price (LMP): Day-ahead market (DAM) and Real-time market (RTM). This section is dedicated to discuss the wholesale electricity in 2014.

A. Day-ahead market (DAM)

The DAM produces bid-based schedules with market settlement performed on hourly-based LMP [7] determined by an economic dispatch algorithm that follows operational security constraints. Fig. 1 shows the day DAM electricity price in PJM in 2014, calculated for every two months, - including 7,395 locations for which we have complete hourly data. The daily price curve for January and February shows two high peaks, the first in the early morning and the second late afternoon. In March and April, prices start to return to be close to the year average, which aggregates very different seasonal patterns.

B.1 Real-time market (RTM)

The Real-time market is a physical market with a 5-minute interval price. Both DAM and RTM settlements are performed on hourly-based LMPs, but the RTM is based on actual system condition deviations from the Day-ahead schedule [7]. Fig. 2 shows the RTM average price in PJM in 2014, for the 7,395 locations.

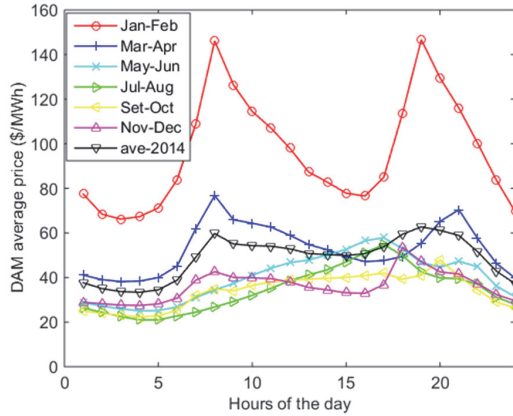


Fig. 1 DAM hourly-based average price in PJM in 2014 including 7,395 locations.

The expected prices of the RTM at the beginning of the year were not as high as DAM and the peak periods were longer. The difference between these two markets should be small in normal conditions [5].

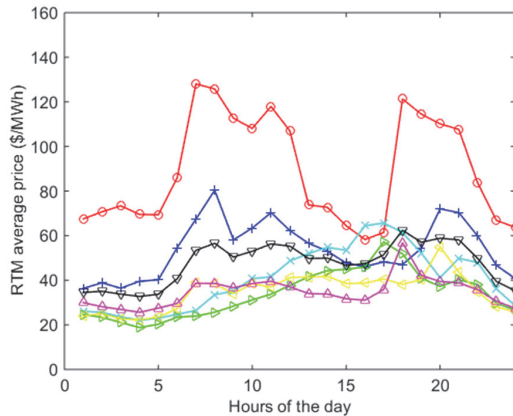


Fig. 2 RTM hourly-based average price in PJM in 2014 including 7,395 locations (see legend in Fig. 1).

C.1 Volatility of electricity prices in PJM in 2014

Price volatility influences the arbitrage revenue of ESS and can be affected by gas prices and also because of high demands and contingencies on the electric grid. With no volatility, there is no arbitrage opportunity. The best conditions for arbitrage involve volatility over the day. The standard deviation of process is a measure of the volatility [8]. The standard

deviations were calculated for all the 7,395 nodes and the results per period of two months are shown in Fig. 3. We can see very high values in all the examined nodes in January and February. March and April also suffered the impact of cold weather. The standard deviation calculated for the whole year (in blackened triangulated line) reflect the effect during extreme conditions.

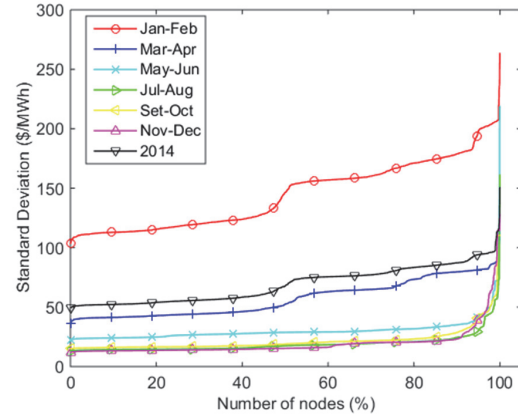


Fig. 3 Standard deviation of RTM prices in PJM (7,395 analyzed nodes), the values are calculated by period and are independently sorted.

The highest standard deviation value in the first period of 2014 happened in a load bus in Delaware (the U.S. state), price node number 49984 and node name NEWMERED69 KV N-MERD. The standard deviation and the average price per day for this node are presented in Fig. 4.

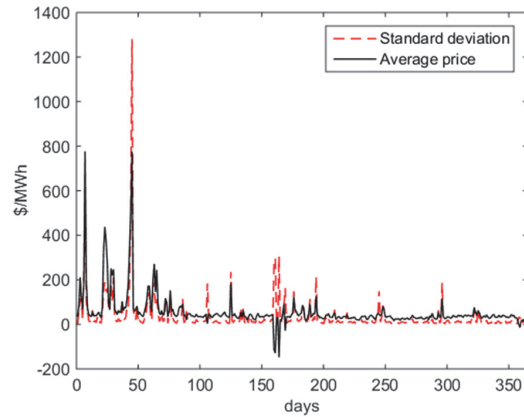


Fig. 4 The daily-based standard deviation and average price at the price node NEWMERED69 KV N-MERD during 2014.

The prices at the beginning of year were not uniformly high, showing high volatility. Negative prices and high volatility were observed in summer.

D.1 Negative prices of electricity in PJM

The LMP price can be negative, for example, if consumption of electricity in a specific node can have

significant impact on the grid flowing energy to attenuate losses or/and decrease the marginal cost of electricity. PJM has also modified its energy market rules in 2009 to allow the submission of negative price offers from all generator units [9]. The renewable power plant bids could be negative in order to guarantee that it will be running and receiving the Production Tax Credit (PTC) and the possibility to sell renewable energy credits (RECs) for each generated MWh. Nuclear power plants can also pay the grid operator to take its production to avoid shut-down and start-up costs [10].

Fig. 5 shows the hours of negative RTM prices in PJM during two-months period and the total hours in 2014. We can see that May-July were the period with most hours and 17% of the nodes had around 60 hours of negative prices. Very few nodes (164 nodes) had more than 200 hours of negative price in 2014.

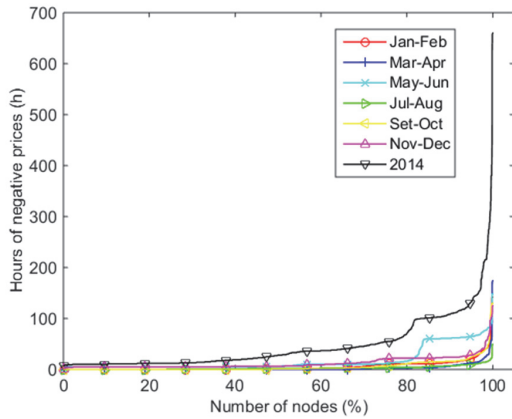


Fig. 5 Hours of negative prices per period in 2014, independently sorted per period.

The optimization strategy would remain the same in the presence of negative prices, buying (charging) when the prices are low and selling back (discharging) when the prices are higher.

III. POTENTIAL ARBITRAGE REVENUE IN PJM

We adopt a generic linear optimization model of price-taking ESS to maximize arbitrage revenue considering perfect forecast of a year hourly-based price data, as presented in [6]. A round trip efficiency of 95% was chosen to represent the upper limit of high efficient ESS technologies (for example some Li-ion batteries, Flywheels and Supercapacitors) [4]. The maximum power capacity of charge and discharge is 1MW for all analysis. The number of cycles per day depends on energy capacity (the energy accumulated inside the device). A ratio of energy to power capacity around 5 hours or more is more likely to have 1 cycle per day, whereas smaller values are likely to cycle twice per day.

A. The energy arbitrage revenue

The potential arbitrage revenue of an ESS in PJM in 2014,

considering a perfect forecast approach in DAM, is presented in Fig. 6. We can see that for low hours of storage (or low values of MWh) the difference of potential revenue is small among the nodes. However, these difference increase for 50% of the nodes for higher hours of storage. Less than 1% of the nodes have very high potential revenue.

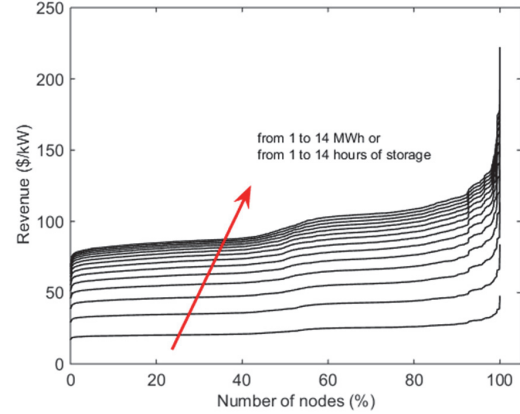


Fig. 6 Potential revenue in DAM in 2014 for different energy capacity (1 to 14 MWh), considering 7,395 nodes with price-taking and perfect forecast.

The same analysis was also performed for RTM and it is shown in Fig. 7. The tendency of these curves follow the ones presented in Fig. 6. However, the curves have higher slope.

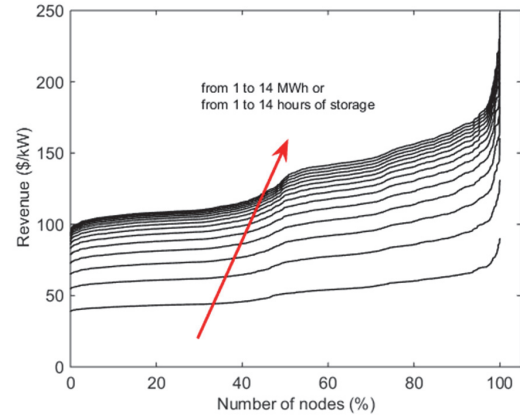


Fig. 7 Potential revenue in RTM in 2014 for different energy capacity (1 to 14 MWh), considering 7,395 nodes with price-taking and perfect forecast.

The rapid changes in energy demand, transmission line congestion, generators or transmission lines outages, generator bid strategies and extreme climate events can affect the price volatility of the RTM and DAM, however the volatility in the RTM is higher. The daily average prices in RTM and DAM do not vary as much. There is more potential arbitrage revenue in the RTM than in the DAM for an energy storage system, as can be seen in in Fig. 7. How much more an ESS can receive in the RTM depends on its energy capacity (or hours of maximum

energy storage), as shown in Fig. 8. For 1 MWh of energy capacity, the additional revenue in RTM is more than 100% of revenue in DAM and it can achieve more than 140% in 10% of the nodes.

It would be an easy matter to exactly capture the average DAM price arbitrage opportunity, such as by dispatching in real-time according to the known DAM prices. By contrast, capturing the deviations in the real-time market presents a high payoff but a greater challenge in optimizing the storage profile.

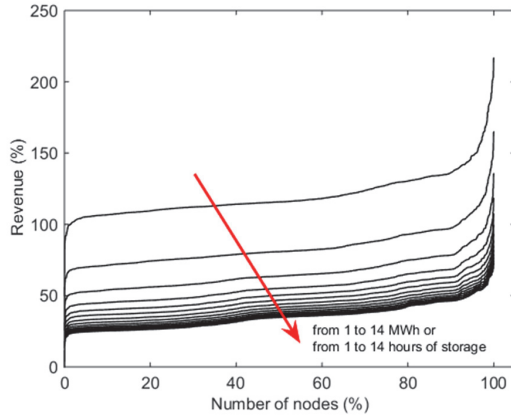


Fig. 8 Additional revenue in energy arbitrage in RTM related to DAM in 2014, for different energy capacity (1 to 14 MWh).

The additional revenue decreases with increase in energy capacity. We have found that the gain in revenue increasing the energy capacity of the ESS is very small above 10 MWh, considering Fig. 6 to Fig. 8.

Another way to analyze the impact of different values of energy capacity of ESS in potential arbitrage revenue is the use of revenue per kWh curves. It is the approach that cost analysis of ESS technologies usually adopt. Fig. 9 shows the same results presented in Fig. 7, however, the curves are divided by its energy capacity.

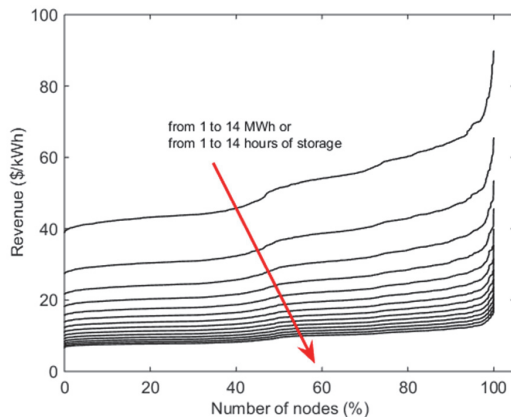


Fig. 9 Potential revenue per kWh of energy capacity (from 1 to 14 MWh) in RTM in 2014, considering 7,395 nodes with price-taking and perfect forecast.

We can see that the potential revenue per kWh decreases for an increment of energy capacity (the opposite of revenue per kW curves) and it is more than 9.4 \$/kWh for the higher potential 50% of the nodes for 14 MWh.

B.1 The round trip efficiency sensitivity

A round trip efficiency of 95% can be understood as each 10 hours of charge you can have 9.5 hours of discharge, both at rated power capacity. The sensitivity to round trip efficiency is shown in Fig. 10.

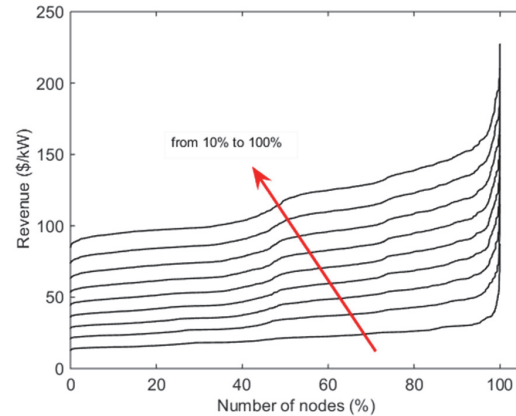


Fig. 10 Round trip efficiency sensitivity (10% to 100%) in RTM for 10 MWh.

The influence on potential revenue is practically linear at most of the nodes. A similar result related to round trip efficiency as also presented in [11].

C.1 Daily analysis of potential revenue

We have also calculated a daily-based potential revenue at the price node NEWMERED69 KV N-MERD during 2014. The difference between the captured revenue in 2014 between 10 and 5 MWh is small for this specific node (199,396 and 171,847 US dollars, respectively).

The daily revenue capture for both energy capacities are almost the same, as shown in Fig. 11. We can see that the spikes in potential revenue coincide with the spikes in standard deviation of the price, shown in Fig. 4. The potential revenue can be very limited during these price spikes if a small energy capacity device is chosen (such as 1 MWh), the opportunity will not be fully captured by the ESS.

Fig. 12 shows the potential revenue of a 1 MWh device at the first 70 days of 2014 when cold weather happened. The figures from this section show that the potential arbitrage revenue during cold weather events and during negative prices with high price volatility has greater potential than the average. Recently, a similar finding has also been reported in the literature [12]. The ESS would provide an analogous service to peak generators and would also depend on extreme price events.

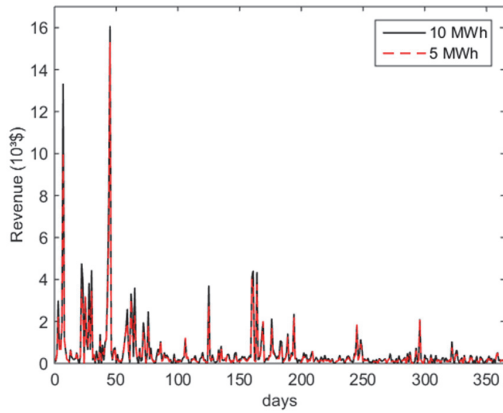


Fig. 11 Daily-based potential revenue in RTM in 2014 at the price node NEWMERED69 KV N-MERD during 2014.

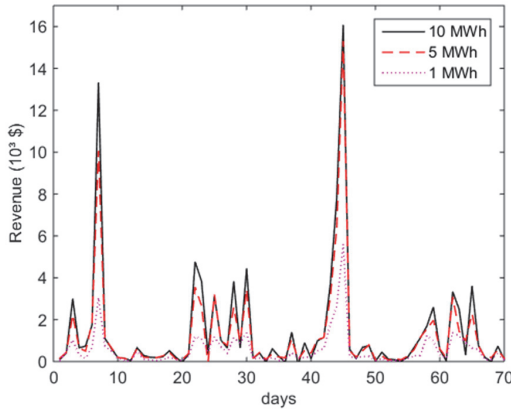


Fig. 12 Daily-based potential revenue in RTM of the first 70 days of 2014 at the price node NEWMERED69 KV N-MERD.

The potential arbitrage revenue in RTM in 2014 considering the 10 best days at the price node NEWMERED69 KV N-MERD would have captured 33.62%, 32.96% and 27.37% of the total year revenue, respectively for 10, 5 and 1 MWh of energy capacity. The cold weather at the beginning of the year (between January 1st and February 28) would have been responsible for 45.11%, 45.03% and 42.14%, of year's revenue, respectively for 10, 5 and 1 MWh of energy capacity.

IV. CONCLUSIONS

This article has discussed the potential arbitrage revenue of energy storage systems in PJM in 2014 for 7,395 locations. The large potential opportunity for energy arbitrage through storage arises from the scale of the energy market and the volatility of prices. A granular analysis of the prices in PJM in 2014 reveals the importance of forecasting to exploit real-time prices, the dependence on location, and the importance of few periods with the largest price volatility.

The forecast is less important for large energy capacity devices. An ESS with energy to power ratio less than 5 or 6 hours would be much more dependent on the forecast and it may miss opportunities in arbitrage on the few days when volatility is high.

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