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ENVIRONMENT IMPACTS OF RENEWABLE ENERGY SOURCES

Potential revenue and breakeven of energy storage systems in PJM energy markets

Maurício B. C. Salles[1] · **Taina N. Gadotti**[1] · **Michael J. Aziz**[2] · **William W. Hogan**[3]

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Abstract

The operation in energy arbitrage markets is an attractive possibility to energy storage systems developers and owners to justify an investment in this sector. The size and the point of connection to the grid can have significant impact on the net revenue in transmission and distribution systems. The decision to install an energy storage system cannot be based only on the cost of the equipment but also in its potential revenue, operation costs, and depreciation through its life cycle. This paper illustrates the potential revenue of a generic energy storage system with 70% round trip efficiency and 1–14 h energy/power ratio, considering a price-taking dispatch. The breakeven overnight installed cost is also calculated to provide the cost below which energy arbitrage would have been profitable for a flow battery. The analysis of the potential revenue was performed for 13 locations within the PJM Real-time market. We considered hourly data of day-ahead and real-time locational marginal prices over 7 years (2008–2014). Breakeven installed cost per MW ranged from \$30 (1 MW, 14 MWh, 2009) to \$340 (1 MW, 1 MWh, 2008).

Keywords Electricity markets · Energy arbitrage · Energy storage · Flow battery · Real-time market · Breakeven

Introduction

Energy storage systems (ESS) are expected to be used extensively in the near future and to be a game changer for the grid operation (Tsagkou et al. 2017; Usera et al. 2017). Technological and financial issues are still challenges to be overcome. New York State has announced a target of 50% renewable energy by 2030. The State of California has also announced targets on renewable energies and on ESS, including distributed energy resources (DER). The ESS would replace old peaking plants because in many cases they are already a cheaper option to reduce emissions (Silverstein 2017).

Natural disaster and man-made attacks challenge the resiliency of local electrical systems. The operators and the consumer (or prosumer) will have to deal with extreme weather events due to climate change (Bie et al. 2017), (Schneider et al. 2016) and using distributed generation combined with ESS can make the local system more reliable. The benefits that come with the use of ESS are related to reliability, energy price, power quality, flexibility, and lowering emissions (Eyer and Corey 2010), (Akhil et al. 2013).

As of 2017, there were 48 grid-connected electrochemical ESS with between 1 and 10 MW power capacity in the USA (US Department of Energy—DOE 2017). The installations were dominated by lithium-ion batteries (39 units), followed by sodium-sulfur batteries (10), lead-acid batteries (2 units), zinc air batteries (3 units), flow batteries (1 unit), and two other lithium-based batteries. Figure 1 shows the distribution of these ESS inside the organized electricity markets in the USA, ranked within each region by energy/power ratio, or

Responsible editor: Philippe Garrigues

✉ Maurício B. C. Salles
mausalles@usp.br

Taina N. Gadotti
taina.gadotti@usp.br

Michael J. Aziz
maziz@harvard.edu

William W. Hogan
william_hogan@harvard.edu

[1] Laboratory of Advanced Electric Grids - LGrid, Polytechnic School, University of São Paulo – USP, São Paulo, Brazil

[2] John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, USA

[3] John F. Kennedy School of Government, Harvard University, Cambridge, USA

discharge duration at rated power. Twenty-five of these ESS are connected to CAISO (California Independent System Operator) and 11 to PJM (Pennsylvania, Jersey, Maryland Interconnection). NYISO (New York Independent System Operator) and ERCOT (Electric Reliability Council of Texas) each have 4; MISO (Midcontinent Independent System Operator) and ISO-NE (Independent System Operator New England) each have only 2. In addition, it is important to notice that 51% (31 units) of these batteries are utility-owned, whereas 38% (23 units) are third-party-owned and 11% (7) are customer-owned.

The analysis performed in this paper intends to evaluate the potential arbitrage revenue of a generic ESS using real-time and day-ahead prices from 2008 to 2014, including 13 different locations in PJM. Five out of the 13 locations are among the highest in potential revenue and nine locations are already equipped with an ESS in PJM. This paper extends the work presented previously in (Salles et al. 2016, 2017a, b).

The organization of the paper is as follows. In the next section, the electricity markets and the selection of the nodes with electricity prices from 2008 to 2014 in PJM are discussed. The subsequent sections discuss, in turn, the potential arbitrage revenue of ESS for a minimum scenario of forecast in PJM wholesale markets; the break-even overnight installed cost for various hours of discharge duration; and the main conclusions. We focus on PJM because it has been very engaged on ESS integration and has inspired other markets even outside the United States (Steel 2017).

Organized wholesale electricity markets

The wholesale electricity markets must produce energy at the cheapest price to meet demand and to guarantee the system reliability. The price of the energy is determined by bids and offers submitted via a web-based platform by market participants balancing the supply and the demand continuously. The locational marginal pricing (LMP) is used by the independent system operators (ISOs) and the regional transmission organizations (RTOs) to price the congestion of the transmission systems, the losses, and the marginal cost of energy. The real-time and day-ahead markets are current in all ISOs/RTOs in the USA.

The real-time market (RTM) is a physical market with a 5-min interval price. Both day-ahead market (DAM) and RTM settlements are performed on hourly-based Locational Marginal Price (LMP), but the RTM is based on actual system condition deviations from the Day-ahead schedule (Ott 2003; Fan et al. 2008; Litvinov 2010).

Locations analyzed in PJM

The analysis was performed for 13 selected nodes in PJM with full hourly price data from 2008 through 2014, displayed in Table 1. The first five locations have the potential revenue at

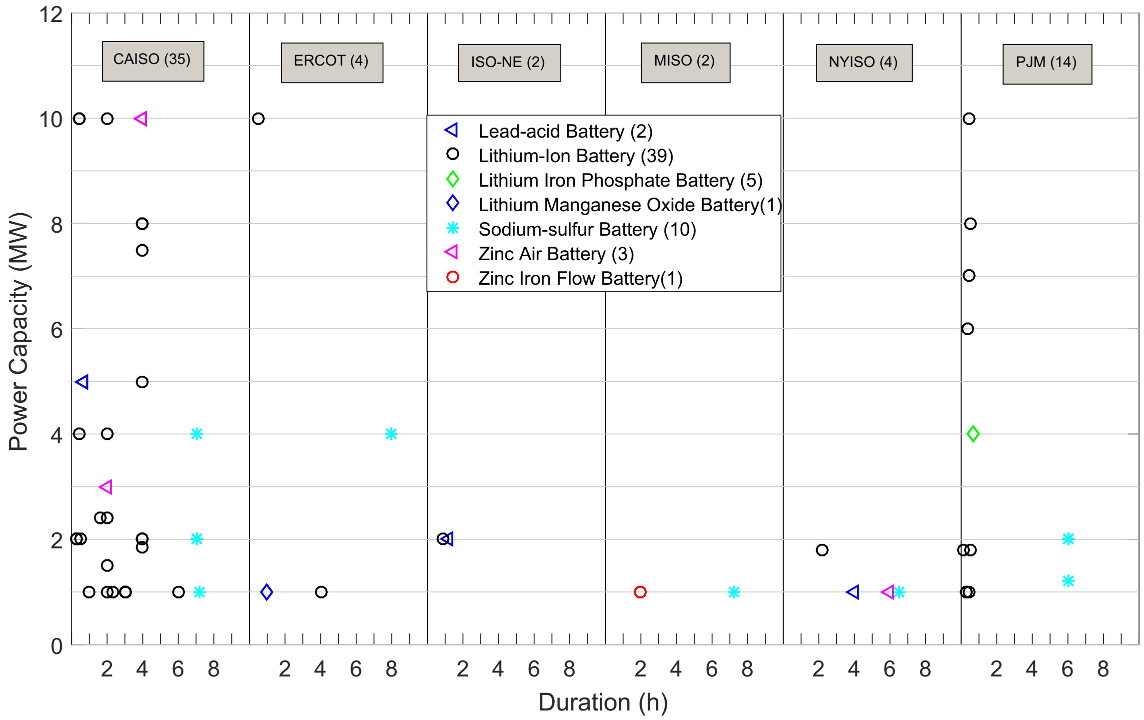


Fig. 1 Electrochemical ESS installations between 1 and 10 MW in the USA (September 2017), based on the data provided in (US Department of Energy—DOE 2017)

Table 1 Selected locations (or nodes) in PJM classified from high to low potential revenue

Node ID	City	State	Zip code
724	Rockville	Maryland	20850
2227	Harpers Ferry	West Virginia	25425
2583	Hagerstown	Maryland	21740
733	Washington	District of Columbia	20019
793	Vineland	New Jersey	08360
1505	Blairstown	New Jersey	07825
3434	DeKalb	Georgia	60112
2971	McHenry County	Illinois	60102
3123	Joliet	Illinois	60431
6454	Moraine	Ohio	45439
712	Mead Township	Pennsylvania	16313
2196	Cumberland	Maryland	21502
660	Somerset County	Pennsylvania	15411

the high end of the distribution of 7395 nodes in PJM; the other eight locations are distributed in lower percentiles. More details are giving in the following sections.

Nine locations already have an ESS unit in operation, as shown in Table 2. Energy arbitrage as a first service appears only in three ESSs (two pumped hydro and one Lithium Ion Battery), frequency regulation appears in 4 and capacity in 2.

The daily average profile of the prices in RTM is presented for each node in Figs. 2 and 4 for 2008 and 2014, respectively.

The daily profile prices shown in 2008 (Fig. 3) are higher than the prices in 2014 (Fig. 3) mainly because the natural gas prices for electricity generation were higher in 2008. However, it is interesting to verify that the prices in 2014 had very high values all over PJM nodes at the beginning of the year, as shown as an example in Fig. 4 for Rockville.

In Fig. 5, the prices for the selected nodes are shown for 2008 and 2014 for the highest-priced 500 h of the year. The high price in the LMPs can be verified for all the selected nodes for a very few hours of the year. Both characteristics could result in high potential revenues and will be discussed in the following sections. Vineland had its maximum LMP of 800 \$/MWh and the rest of the selected nodes had between 1600 and 2000 \$/MWh.

Potential arbitrage revenue in selected nodes

The evaluation of the potential arbitrage revenue was performed for each of the 13 nodes considering a generic storage model. The historical price data for RTM and DAM were available on the PJM website and a linear programming method was applied using AMPL software with CPLEX solver to optimize the charge and discharge profile of the ESS to maximize the revenue per year. The approach adopted considered the linear optimization of a price-taking system knowing the future price (also known as the perfect forecast method).

The reviewer has pointed out a very good point. The maximum revenue that an energy storage system could achieve in arbitrage is in the real-time market with a perfect price forecast. The minimum acceptable revenue in arbitrage would be captured in the day-ahead market dispatching the energy storage system in the next day knowing the next day price settlement in advance. In any real implementation, however, the price forecast has imperfections and would fail to achieve this maximum. We proposed (Salles et al. 2017a) that the day-ahead prices' settlement is taken to optimally schedule the dispatch of the energy storage system for the next day. On the next day, the energy storage system will be dispatched as previous scheduled; however, the negation will be in the real-time market. This simple approach provides a reasonable revenue without any complex strategy and necessity for external data analysis. The ESS owner could implement this method relatively easy and would capture between 70 and 85% of the revenue existing in the RTM (Salles et al. 2017a).

The ESS optimization model

The generic linear optimization model of a price-taking ESS considering perfect forecast for hourly based price data was presented in (Salles et al. 2016), (Salles et al. 2017a), (Sioshansi et al. 2009). The flow battery was chosen to be modeled, considering a round trip efficiency of 70% and the possibility of fully charge and discharge (Luo et al. 2015). The price-taking model assumes that the individual ESS has no impact on the settlement price. The adopted model utilizes Eq. (1):

$$\underset{c,d,s}{Max}\sum_{t=1}^{T} p_t(d_t - c_t)\, s_t = s_{t-1} + \eta c_t - d_t d_t,\, c_t \in [0,\kappa] s_t \in [0, h\kappa] \quad (1)$$

where

T number of hours in dispatch horizon
η round trip efficiency of storage device
p_t energy price in hour t
κ power capacity of storage device
h number of hours of discharge at rated power
d_t discharge power in hour t of storage device
c_t charge power in hour t of storage device
s_t state of charge in hour t of storage device

The rated power for charge and discharge is equal to 1 MW for all analyses. The optimal solution tends to charge or discharge at either zero or the maximum rated power. A round trip efficiency of 70% was chosen to represent a flow battery, considering the battery losses, the induction motor-based pump to circulate the electrolytes inside the system and the converter losses (Luo et al. 2015; Turker et al. 2013; Choi et al. 2016). Some storage technologies

Table 2 Main characteristics of the ESS in operation at selected nodes in PJM

Node ID	Technology	Rated power (kW)	First service
2583	Lithium-ion battery	2000	Electric energy time shift (arbitrage)
1505	Open-loop pumped hydro storage	400000	Electric energy time shift (arbitrage)
3434	Lithium-ion battery	20000	Frequency regulation
2971	Lithium-ion battery	19800	Electric supply capacity
3123	Lithium-ion battery	19800	Frequency regulation
6454	Lithium-ion battery	20000	Frequency regulation
712	Open-loop pumped hydro storage	440000	Electric energy time Shift (arbitrage)
2196	Lithium-ion battery	10000	Electric supply reserve capacity
660	Lithium-ion battery	10400	Frequency regulation

can have efficiency over 90% (Luo et al. 2015; Zhang et al. 2018).

This model provides an estimate of net revenues that would be captured through price arbitrage.

The battery capacity fade

Only fell publication that analysis the energy storage systems for arbitrage consider the capacity degradation/fades during the life cycle, even for lithium-ion. Two examples of very cited papers that do not include degradation are Sakti et al. (2017) and Sioshansi et al. (2009).

It does not mean that the degradation/fades during the life cycle do not affect the revenue and the results. In (Wankmüller et al. 2017), the impact on the revenue for two degradation models of lithium-ion is analyzed considering different C-rates. It has been shown that the reduction in revenue due to degradation is in the 12–46% range depending on the degradation model and end of life criteria.

The flow battery has no significant degradation/fades during the 20 years of operation, but it could happen after long-term operation. The negative electrolyte can be transferred to the positive side and the energy capacity fading occurs inevitably. However, this process is reversible and can be performed during regular maintenance, the improvement of the membrane can also reduce the electrolyte imbalance (Tang et al. 2011). Considering these facts, we decided not to include capacity fade in the analysis. An improvement of this model for future work could considering a semi-permanently capacity fade.

Revenue through energy arbitrage

A method to capture the equivalent of more than 100% of the potential revenue available in the DAM was presented in (Salles et al. 2017a). Using the DAM settlement prices as a forecast, an optimal dispatch schedule can be determined for the next day, then the known charge and discharge plan can be

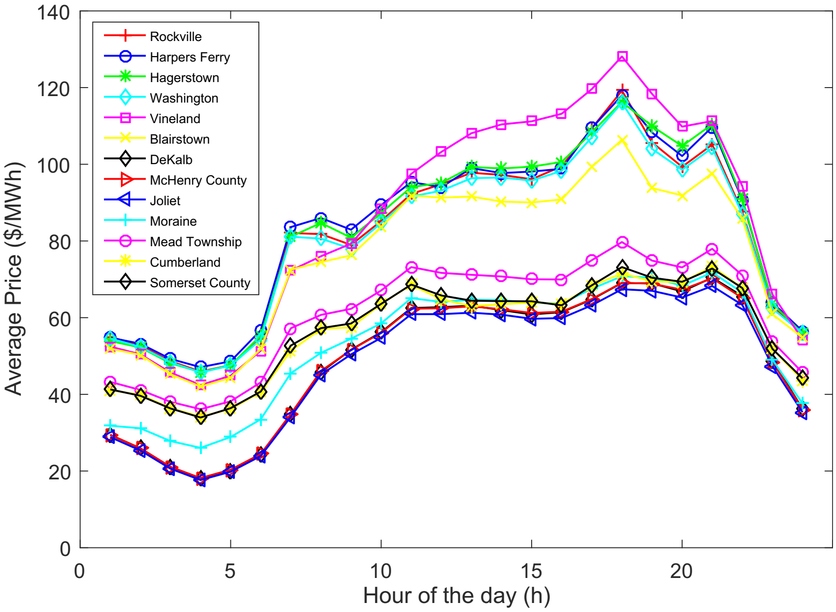
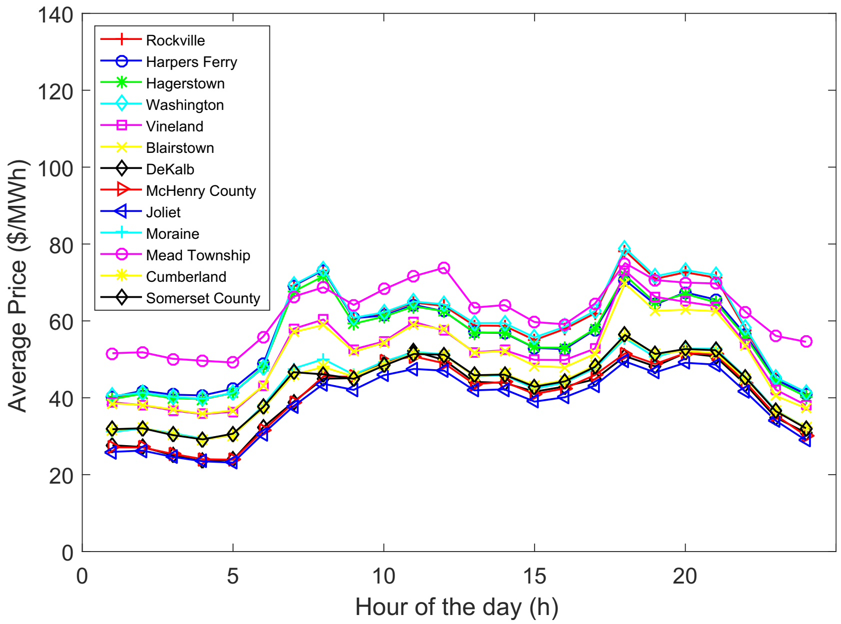


Fig. 2 RTM hourly-based average LMP price in PJM in 2008 in the selected nodes

Fig. 3 RTM hourly-based average LMP price in PJM in 2014 in the selected nodes



used to participate in real-time. The proposed method is feasible under the PJM market rules.

The evaluation of the potential annual revenue of an ESS for the years 2008 through 2014 was performed encompassing all 7395 nodes of PJM with complete data over this period. In Fig. 6, the horizontal axis represents the percentiles of the nodes analyzed classified from the lowest average revenue of the period to the highest (the vertical axis is revenue). There are three curves of average revenue for 4, 8, and 12 MWh of energy capacity. The selected nodes from Table 1 are represented over the curves in its relative position classified among the other 7935 nodes. Hagerstown and Blairstown are two best nodes among the nodes with an installed ESS (Table 2) and the third and sixth position among all other selected nodes.

The selection of these best five nodes intentionally considers high potential revenue during the period of analysis in different locations (percentile between the 93th and 97th), as shown in Fig. 6. The group of high revenue nodes is formed by as follows: Rockville, Maryland; Harpers Ferry, West Virginia; Hagerstown Maryland; Washington, District of Columbia; Vineland, New Jersey.

There are two more groups of nodes: intermediate (five nodes from 25th to 70th percentiles) and low (3 nodes below 9th percentile) revenue potentials. These nodes do not represent a significant revenue in the period; however, as shown in

Fig. 4 Classified RTM hourly-based LMP per month in PJM in 2008 and 2014 in Rockville, Maryland

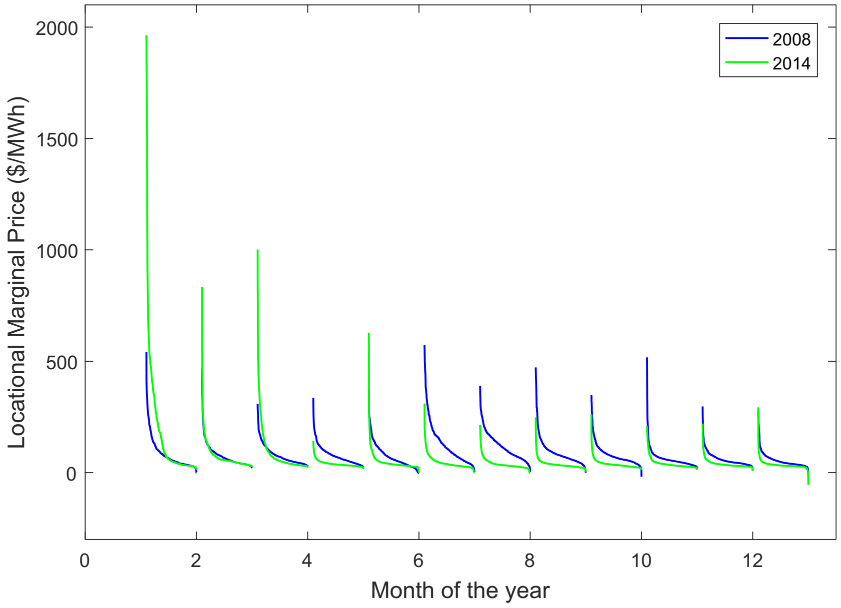


Fig. 5, there is still potential in days when high spikes on LMPs appears (Salles et al. 2016).

In Fig. 7, a detail from the high-revenue end of Fig. 6 is presented. The percentile of the node changes for different energy capacity.

In Fig. 8, the average potential revenue from 2008 to 2014 for the 13 selected nodes is presented. The sensitivity to the energy/power ratio can be seen. The increment in revenue for an ESS gets smaller for each increment in energy capacity. This occurs because, with increasing energy/power ratio, there are fewer additional opportunities to discharge over increasingly long durations without the opportunity to recharge for some time in the middle.

In Figs. 9 and 10, the potential revenue vs. energy/power ratio for each year is presented for the group of high and intermediate potential revenue nodes, respectively. The difference between the best year (2008) and the second-best year (2014) is large in both groups. Higher prices distributed throughout the year have more impact on total year revenue than very high prices in few days.

Breakeven overnight installed cost

The net revenue vs. energy capacity determined in the previous section is used to evaluate the breakeven overnight installed cost of an ESS for each of the selected nodes. The adopted methodology does not depend on the ESS technology and can be applied to other types of ESS. This methodology calculates the annualized capital recovery factor (CRF), considering the life time of the project and the net installed costs (after taxes and depreciation). The present value of the investment can be determined with the CRF. The CRF is compared with the net revenues (Denholm et al. 2010) discussed in the previous section.

The analysis of a different EES technology would give different results because the parameter values are also different. For the analysis presented here, the life of the flow battery project is considering to be 20 years, as discussed in (Lazard 2017), and no subsidies are included. The NR (Net Operating Revenue Before Corporate Taxes) can be considerate equal to the values of PJM net potential revenue determined in the previous section for the selected locations and the different years.

The value of 2% of initial capital costs for flow batteries was used as reference (Lazard 2017) to represent the annual Fixed Operating and Maintenance Cost (OM). The Annual Energy Outlook of the Energy Information Administration (US Energy Information Administration 2014) was the base reference for tax rates and other financial parameters in the calculations. The quantities were implemented in real terms, except where is specified:

i Nominal corporate borrowing rate = 7.1%
τ Corporate tax rate = 38%
d Share of investment financed by debt = 45%
E Risk adjusted real return on equity = 9.3%
π Expected inflation rate = 2.0%

The calculation of the Real Corporate Discount Rate ($\tilde{r}$~) is implemented by Eq. (2):

$$\tilde{r} = d(i(1-\tau)-\pi) + (1-d)E \tag{2}$$

The study presented in (Lazard 2017) suggested the depreciation (Internal Revenue Service 2017) to be set for 7 years. The Investment Tax Credit (ITC) is not

Fig. 5 Classified RTM hourly-based LMP in 2008 and in 2014 for the selected nodes for the 500 h with the highest values

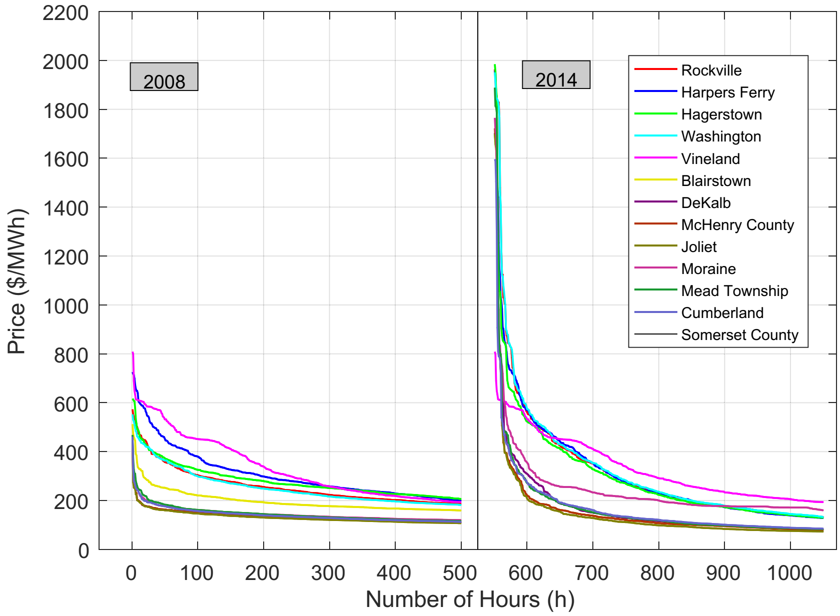
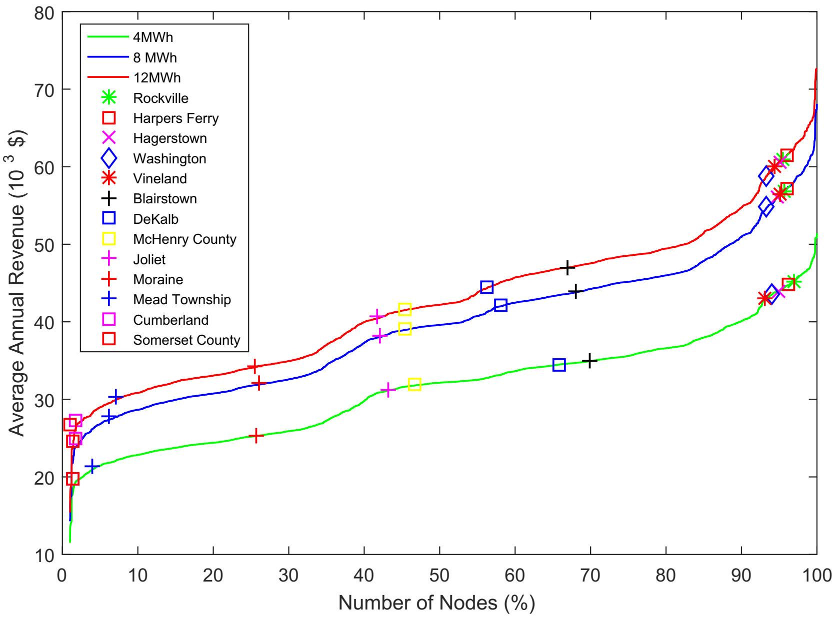


Fig. 6 The curves represent a yearly based average potential arbitrage revenue from 2008 to 2014 of a ESS with 70% round trip efficiency and 1 MW of rated power for RTM in PJM using the DAM price settlement as forecast, encompassing 7395 nodes. The abscissa is the percentage of nodes with revenue less than the value given by the ordinate; the values are independently sorted. We included the 13 nodes from Table 1 to show their percentile of average annual revenue among all the analyzed nodes



considered in this analysis, $\rho_{ITC} = 0\%$. The assumptions can be summarized as 0% *ITC*, a 20-year project life and a 15-year tax depreciation life. The Adjusted Capital Recovery Factor (*ACRF*) is equal to 8.66%; a detailed calculation is discussed in (Salles et al. 2017a). The calculation of the breakeven installed cost can be done by Eq. (3):

$$\text{Breakeven }(\$/\text{kWh}) = \frac{\text{Revenue }(\$/\text{year})}{\text{ACRF.1000.Discharge duration(h)}} \tag{3}$$

The overnight breakeven installed cost was calculated and is given in $/kWh for simplifying the comparison with other studies. The cost of a flow battery can be represented as a linear combination of the marginal cost per unit of power capacity and the marginal cost per unit of energy capacity.

The evaluation of the breakeven was performed considering the ESS doing arbitrage in RTM using the DAM settlement price as forecast and the main assumptions are the 70% round trip efficiency and the 20-year project life for all selected nodes. Figure 11 presents the distribution of breakeven overnight installed costs for the average revenue (from Fig. 8) with dependence on storage capacity. The breakeven rapidly decline when the energy/power ratio increases.

The returns increase in absolute value when the energy capacity increases but decrease in revenue/kWh. The cost/kWh of flow batteries drops when increase the discharge duration by enlarging the electrochemical storage tanks to accumulate more electrolyte.

Fig. 7 Detail of the high potential revenue group of five nodes from Table 1 for 4, 8, and 12 MWh of energy capacity. The rated power is 1 MW

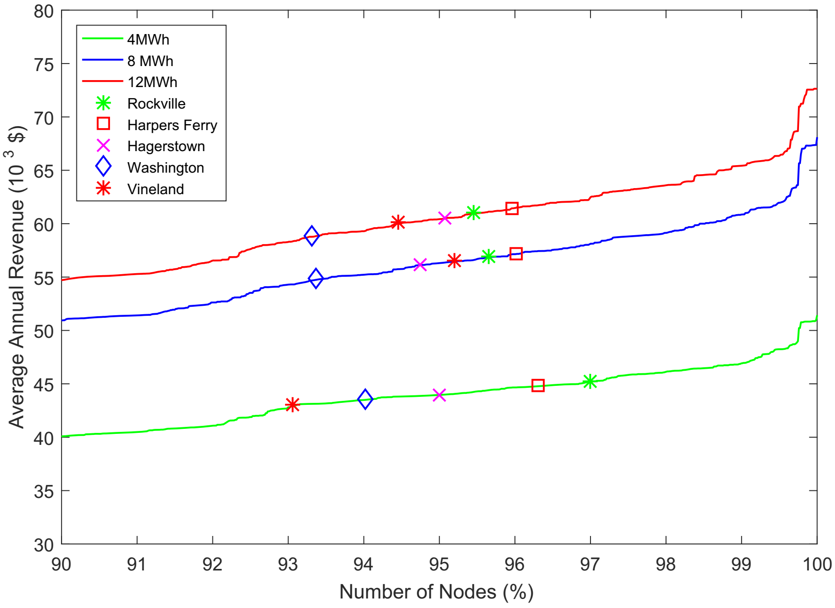
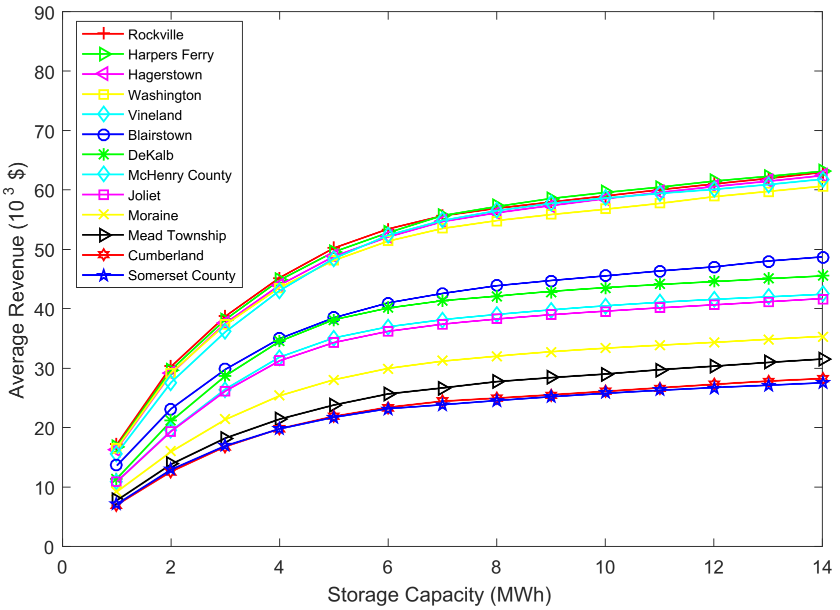


Fig. 8 The curves represent a yearly based average potential arbitrage revenue from 2008 to 2014 of a ESS with 70% round trip efficiency and 1 MW of rated power for RTM using the DAM prices settlement as forecast, encompassing the 13 selected nodes. The abscissa is the energy capacity, varying from 1 to 14 MWh



It is an indication that further evaluation should be performed to verify the ideal discharge duration. A flow battery with a specific discharge duration might achieve breakeven before others.

The additional evaluation for the group of the high potential revenue is shown in Fig. 12. For 2008, the highest breakeven value would have achieved between 320 and 370 \$/kWh. For the group of intermediate potential revenue, the highest values decreased to between 220 and 263 \$/kWh (Fig. 13). The price evolution of energy storage systems has been dropping. However, it is still unclear when this application will become economically viable and what would be the right service to make then become profitable.

Revenue considering stacking services

There are many studies on the literature that include the multiple services (multi-purpose or value stacking) for the energy storage systems to make its use more intense and become

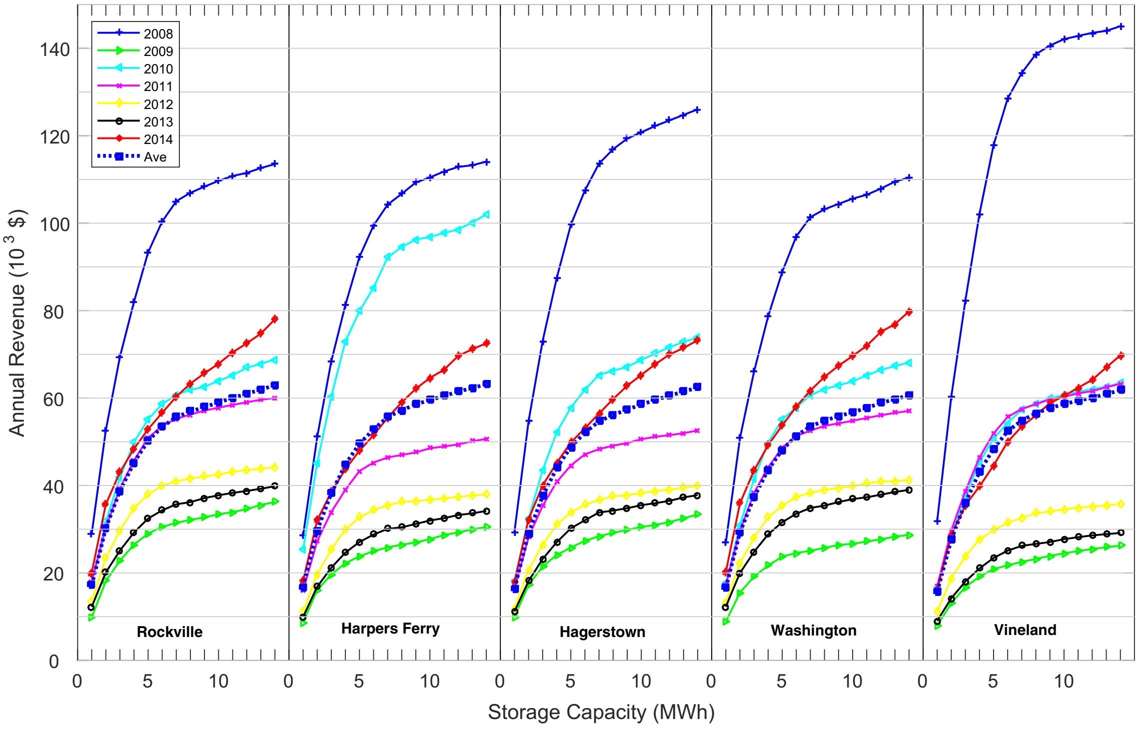


Fig. 9 The curves represent the potential arbitrage revenue in the group of high potential revenue nodes from 2008 to 2014 of a ESS with 70% round trip efficiency and 1 MW of rated power for RTM in PJM using the DAM prices settlement as forecast. The abscissa is the energy capacity from 1 to 14 MWh

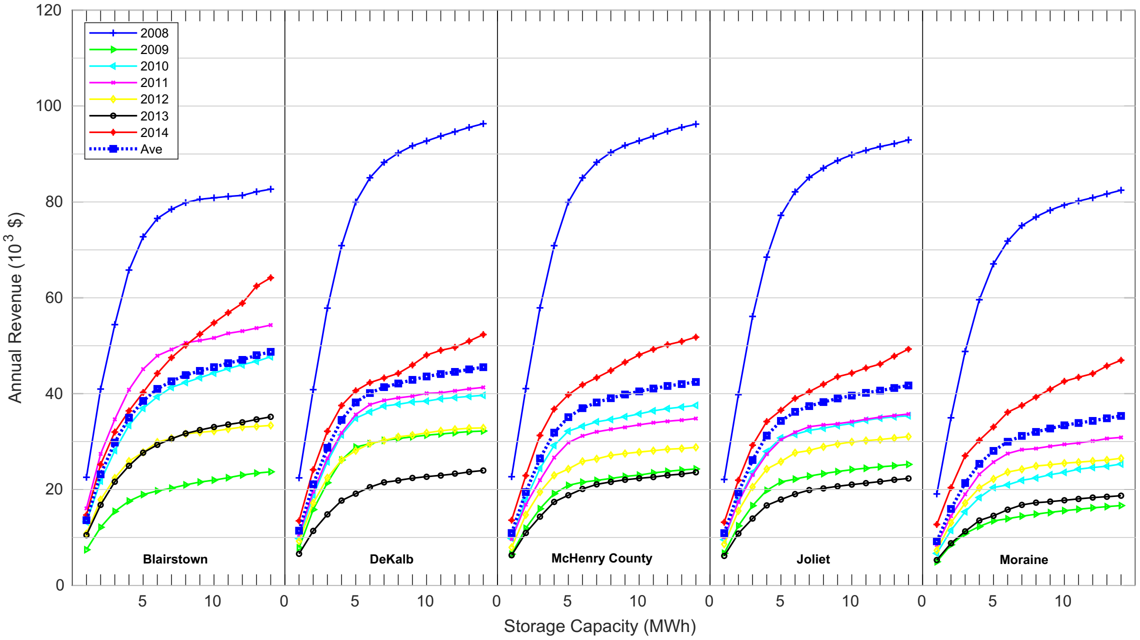


Fig. 10 The curves represent the potential arbitrage revenue for the group of intermediate potential revenue nodes from 2008 to 2014 of a ESS with 70% round trip efficiency and 1 MW of rated power for RTM in PJM using the DAM prices settlement as forecast. The abscissa is the energy capacity from 1 to 14 MWh

profitable. In (Fitzgerald et al. 2015), they found out that is already possible to have positive net present value, however, there are still barriers to be overcome in regulation and in the stakeholder's behavior. In (Byrne and Silva-Monroy 2012), the authors analyzed two potential cases of income: energy arbitrage only and energy arbitrage combined with the frequency regulation. Their analysis founded that participation in the regulation market would produce four times the revenue compared to arbitrage in the CAISO market using price data from 2010 and 2011. The value in frequency regulation

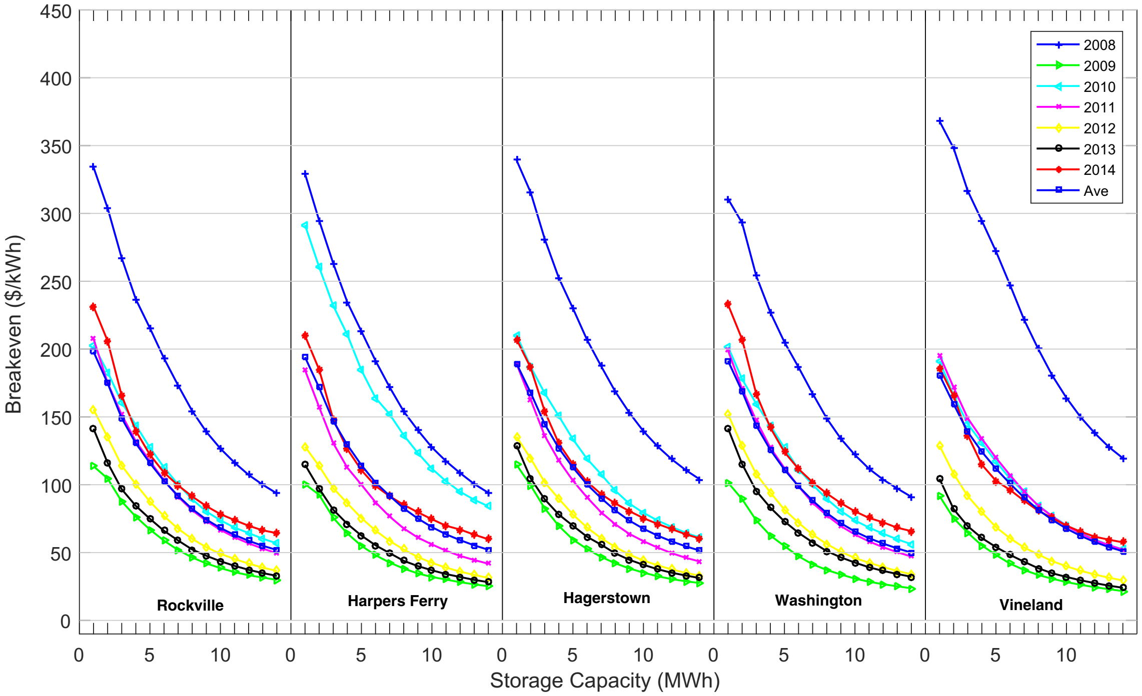


Fig. 11 Distribution of breakeven overnight installed cost for the average revenue vs. energy capacity (1 MW, 1–14 MWh) of the selected nodes in the PJM RT-Market using DAM as a forecast. Assumed round trip efficiency is 70% and project lifetime is 20 years for 1 MW of rated power

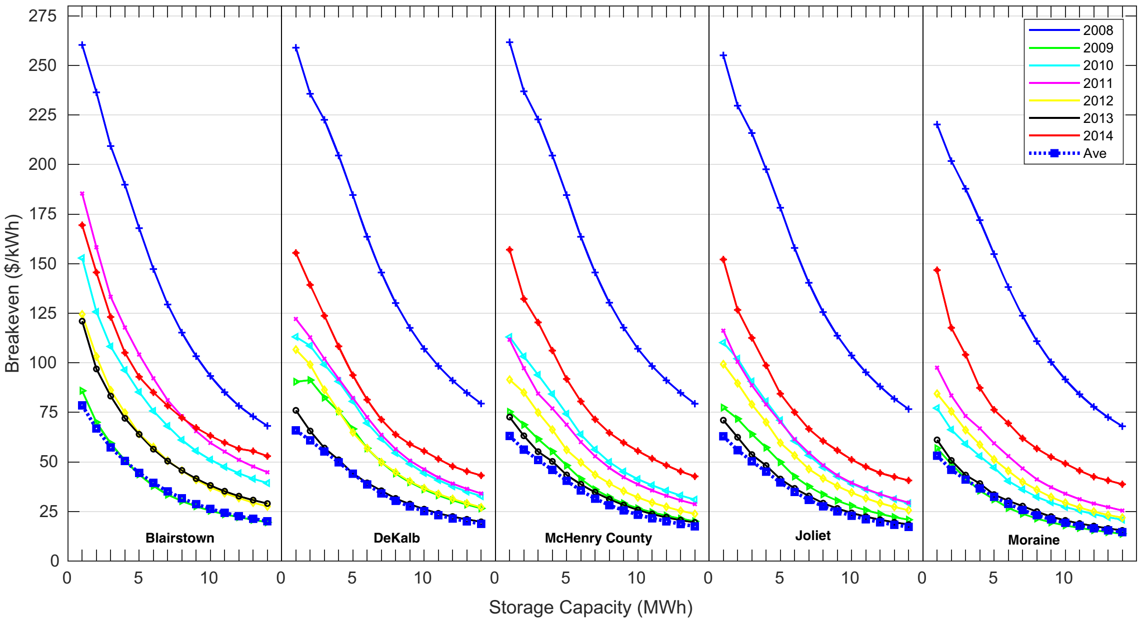


Fig. 12 Distribution of breakeven overnight installed cost for the group of high potential revenue nodes in the PJM RT-Market using the DAM settlement prices as forecast, for a 1 MW of rated power ESS vs. energy capacity (1–14 MWh) for each year between 2008 and 2014. Assumed round trip efficiency is 70% and project lifetime is 20 years

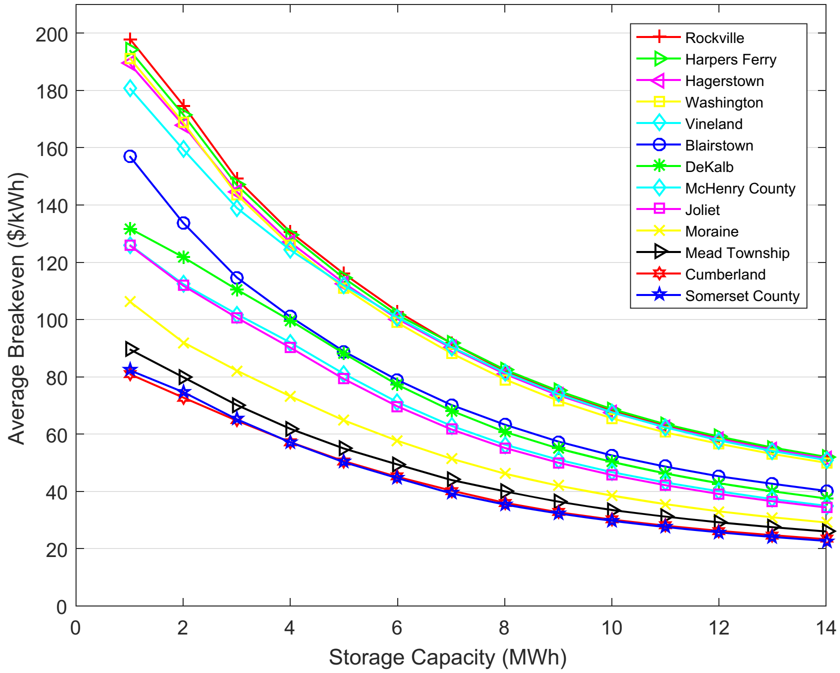
markets has dropped significantly in last years, mainly because this market is small compared to the energy market.

In a temporal utilization perspective, it makes more sense to optimally use the battery including different services (Hesse et al. 2017). This paper analysis only one application for the battery, considering that the control of a storage system for multiple applications and simultaneously meet the regulation of the markets is still a challenge.

Conclusions

The evaluations presented in this paper focused on the potential arbitrage revenue of an energy storage system with fixed power capacity of 1 MW and a varying energy capacity (1 to 14 MWh) in PJM for a price data set from 2008 to 2014, considering the settlement price in the Day-ahead market as a forecast to make the next day schedule of the charge and discharge for the Real-

Fig. 13 Distribution of breakeven overnight installed cost for the group of intermediate potential revenue nodes in the PJM RT-Market using the DAM settlement prices as forecast, for a 1 MW of rated power ESS vs. energy capacity (1–14 MWh) for each year between 2008 and 2014. Assumed round trip efficiency is 70% and project lifetime is 20 years



time market. The main contribution of this paper is to give a realistic perspective about a reasonable revenue for different locations in PJM, considering three groups of nodes with different potential revenues (high, intermediate and low). Most of the papers on the literature focus on the perfect foresight that represents an upper limit of revenue. This paper provides achievable values using the DAM settlement prices as a forecast to optimally schedule the dispatch for the next day; however, the negation will be in the real-time market. The degradation is not included for the breakeven analysis as it can be minimized with good maintenance for the flow battery.

In the group of high potential revenue, the revenue and the breakeven had similar behavior; however, 2010 in Harpers Ferry was almost as good as 2008 and in Vineland, 2008 in Vineland was even better than 2008 in the other nodes. In the group of intermediate potential revenue, Blairstown had almost in all years the highest value but 2009.

Considering the breakeven about 200 $/kWh, the equivalent LMP profiles of all the five nodes in the group of high potential revenue for 2008 and four nodes for 2010 and 2014 would have achieved profitability. Current ESS costs are not low enough for profitability, but recent ESS cost reductions are expected to continue and might bring the best nodes into profitability in the foreseeable future.

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