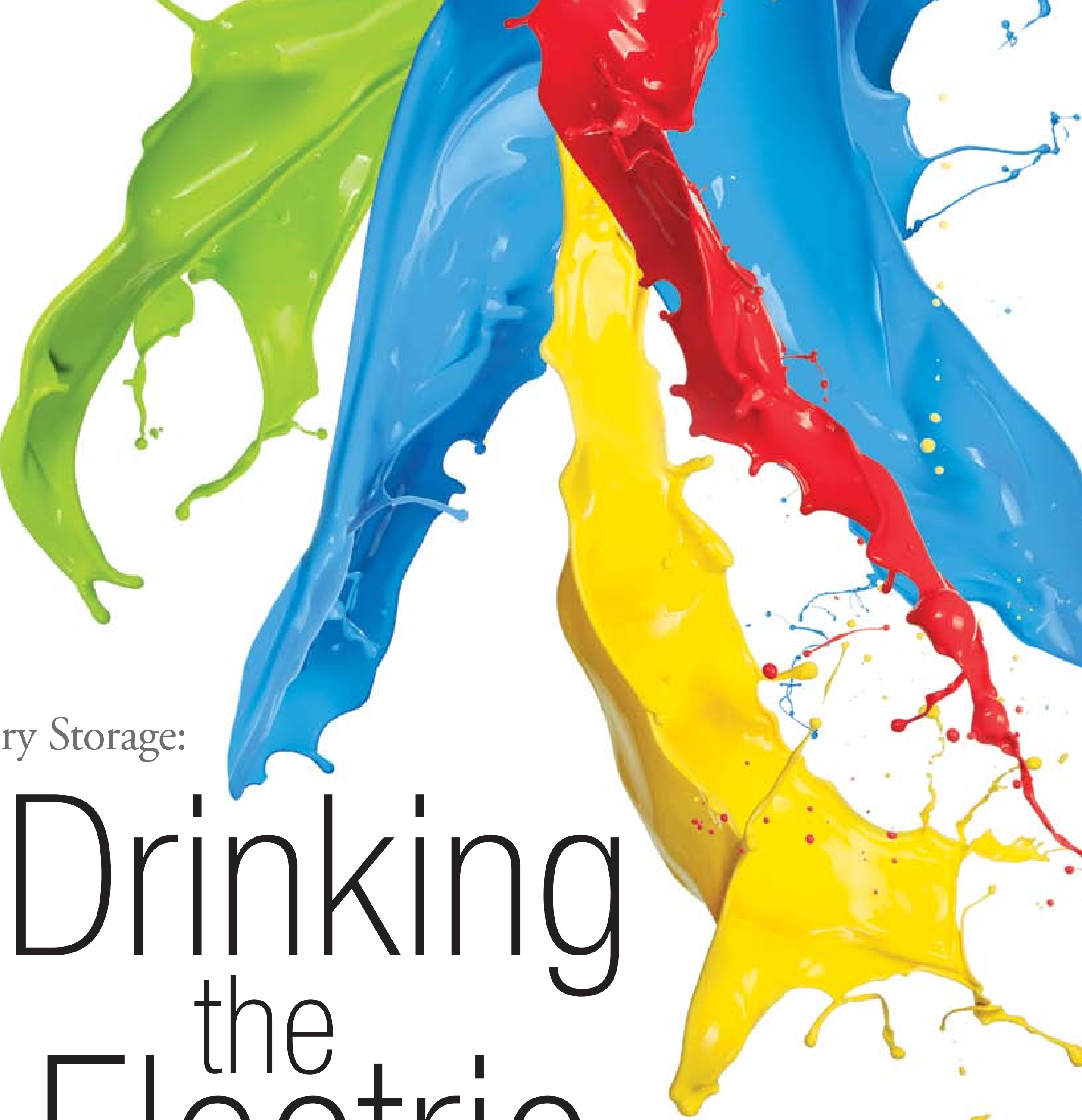

Battery Storage:

Drinking the Electric Kool-Aid

By Steve Huntoon

First came Powerwall, the home battery introduced by Elon Musk. Now comes utility-scale battery storage, touted as the next big thing for the electric grid. But as with Powerwall, the hoopla far exceeds the reality.[1]

The risk isn't that venture capital takes its chance and fails. That's what venture capital gets paid (or not paid) to do. The risk is that utility customer and/or taxpayer money gets committed to projects that don't make sense, and the money vanishes.[2] That is what we need to guard against.[3]

The big payoffs for battery storage – the supposed "killer apps" – are 1) capacity and 2) energy arbitrage. Capacity would provide "back-up" to ensure resource adequacy. Energy arbitrage would involve daily cycling of storage injections and discharge to capture differences in energy prices. One could cite other potential applications, like frequency regulation or deferral of transmission/distribution expansion, but they don't rise much above niche relevance, as we'll see.

In this article, I'll explain why the two potential killer apps are not yet ready for prime time, and in fact may never be. I'll address some common misconceptions that have contributed to the unwarranted hoopla, and discuss some of the flaws that often occur in a typical study claiming large benefits. Finally, I'll explain how even in those cases grid-scale energy storage might appear to make sense, battery storage still faces stiff competition from other storage technologies and resources.

The risk is that public money gets committed to projects that don't make sense. Battery storage would need to cut costs by four-fold to compete in providing capacity.

1. For a technical critique of the Powerwall, http://www.catalyticengineering.com/top-ten-facts-about-teslas-350kwh-powerwall-battery/, and for a business critique, http://www.bloomberg.com/news/articles/2015-05-21/your-home-doesn-t-matter-for-tesla-s-dream-of-a-battery-powered-planet. This author's take on the Powerwall is here, http://spark.fortnightly.com/fortnightly/old-musk-magic.
2. For example, battery makers A123 Systems and Ener1 cost the federal taxpayer a reported $129 million and $118 million, respectively, https://en.wikipedia.org/wiki/A123_Systems#cite_note-3 and http://abcnews.go.com/Blotter/ener1-parent-obama-backed-green-company-files-bankruptcy/story?id=15456414. California utility customers face an enormous tab for mandatory storage purchases of 1,325 MW without a cost-benefit or market-need analysis to support that mandate, http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M078/K929/78929853.pdf, page 21 ("[California law] AB 2514 is silent on any requirement to conduct or apply a system need determination as a basis for procurement targets. As such, we are not prevented from establishing procurement targets, based on our expertise and authority, in the absence of a system needs determination."). Thus far, the CPUC has approved 264 MW of battery projects for Southern California Edison, including 50 MW, at an estimated cost of $100 million, in battery projects by a two year old company headed by an industry insider, http://www.sandiegouniontribune.com/news/2015/jun/29/ams-susan-kennedy-picker-email-ex-parte/, and now backed by the Terminator himself, http://blogs.wsj.com/venturecapital/2015/07/13/tesla-battery-customer-advanced-microgrid-raises-18m-series-a/. The actual price to be paid by Southern California Edison's customers will not be disclosed for up to three years, http://www.sandiegouniontribune.com/news/2015/nov/19/ams-energy-storage-edison-cpuc/, so it may be a long time before customers find out exactly how much all this is costing them.

   Elsewhere, Texas utility Oncor is seeking to rate base a large battery purchase, http://www.utilitydive.com/news/whatever-happened-to-oncors-big-energy-storage-plans/404949/, putting customers at risk regardless of the economics. Batteries are a standard component of "microgrids" being promoted across the country, which would be subsidized by other customers; the author's take on microgrids is here, http://www.fortnightly.com/fortnightly/2015/11/microgrids-wheres-beef.

   Batteries are not the first high-tech electric storage system to have their day in the sun: Remember fuel cells, flywheels, hydrogen?
3. Two-thirds of the country operates under competitive wholesale markets that can function as a check on bad ideas being charged to captive customers (of course captive taxpayers remain at risk). Where a new resource cannot get traction in the competitive wholesale markets it should be a canary in the mine for the rest of the country. A Rocky Mountain Institute study explains the importance of competitive markets in determining true value: "Utilities in non-restructured areas are not required to unbundle and publicly disclose the value of ancillary services, like spin and non-spin reserves, from published contract prices. … This makes energy storage valuation in non-restructured states challenging and oftentimes forces third parties to overlay wholesale market data from restructured states onto non-restructured ones when estimating value." http://www.rmi.org/electricity_battery_value (page 23). This article focuses on the lack of true value of grid batteries in the competitive wholesale markets where value can be objectively assessed.

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If there's a recurring theme here, it's that the hoopla is based on hypothetical use and value when the reality is quite different.[4] Take it from me: don't drink the Kool-Aid.

These Killer Apps Won't Hunt

Let's first consider capacity as a potential killer app. Capacity is the ability to provide energy on demand.[5] Battery storage is the ultimate in "pure" capacity – if it is charged it provides electric energy at the push of a button.

The low end of the range for battery system cost currently runs about \$2,000,000/MW.[6] One projection of future capital cost is \$1,000,000/MW – half the low-end of the range for current cost.[7]

Let's assume that this lowball projection of \$1,000,000/MW can be achieved. To keep it simple we can pencil in 15 percent per year for pre-tax return of and on capital and for operation and maintenance expenses,[8] for an annualized capital cost of \$150,000/MW. In contrast, capacity in PJM's most recent auction cleared at a base price of \$60,141/MW-year, with the highest-cost area in eastern PJM at \$82,278/MW-year.[9] So the projection of future battery cost is about *twice* the highest clearing price in the last PJM capacity auction. That means that a four-fold decrease in the current cost of battery storage would be necessary before it could potentially compete.[10]

And that is not the end of the cost comparison. In comparing

4. Most of the analysis in this article is based on PJM Interconnection, L.L.C. ("PJM") markets. PJM is the transmission operator and market operator for the largest, most sophisticated, and most transparent power grid in the nation. And, as important, it has welcomed rather than resisted energy storage, as acknowledged by the Electricity Storage Association, "PJM has welcomed competition." http://www.pjm.com/~/media/committees-groups/committees/pc/20131010/20131010-item-03-energy-storage-snapshot-broader-market-potential.ashx (last slide). Thus, if the fundamentals of battery storage cannot make it in PJM they are unlikely to make it anywhere (although it is possible that economics elsewhere could be so different that grid batteries make sense there).
5. Or more literally, "on command." The command comes from the grid operator when supply becomes tight relative to demand.
6. Brattle Group, "The Value of Distributed Electricity Storage in Texas" (March 2015) (hereafter Brattle Study), http://www.brattle.com/system/publications/pdfs/000/005/126/original/The_Value_of_Distributed_Electricity_Storage_in_Texas_-_Proposed_Policy_for_Enabling_Grid-Integrated_Storage_Investments_Full_Technical_Report.pdf?1426377384, page ii, footnote 2, citing fellow consultancy Navigant: "… current storage costs for a four-hour battery are \$720–\$2,800/kWh depending on the scale of the battery."

   Four important notes about capital costs: First, battery capital costs are frequently quoted in \$/MWh or \$/kWh instead of \$/MW or \$/kW. As Brattle explains (at footnote 35): "Many storage developers quote costs on a per kWh or MWh basis. This represents the capital cost in terms of how much energy it can store, as opposed to the maximum instantaneous power output that would be quoted in kW terms. For example, a 300 kWh device at \$350/kWh would have a capital cost of \$105,000. The capacity that it can output instantaneously depends on the energy to power (or kWh:kW) ratio of the device, which we assume to be 3:1 in our study." So, taking the low-end of the Brattle/Navigant per kWh cost of \$720, the per kW cost is \$2,160 (three times the per kWh cost), and the per MW cost is \$2,160,000. Lazard's Levelized Cost of Storage Analysis also explains this concept in terms of "instantaneous power capacity" (MW) and "potential energy output" (MWh), https://www.lazard.com/media/2391/lazards-levelized-cost-of-storage-analysis-10.pdf (page 1), and has an implied minimum per MW cost of 4:1 lithium battery storage of \$2,052,000 (battery with 100 MWh of stored energy times the lowest cost of \$513,000/MWh divided by 25 MW of power rating ("capacity"), page 21).

   Second, battery costs are sometimes quoted on a battery stand-alone basis and sometimes on a battery system basis (*i.e.*, including what sometimes is called "balance of plant" or "power conversion system"). The latter is substantially larger than the former, Brattle Study, footnote 36, and the latter is, of course, what matters.

   Third, it is not clear if reported unit costs generally include the DC-AC conversion loss factor in battery discharge – if not then nominal capacity should be discounted by that loss factor, ballpark 5% (this is a one way loss factor from DC to AC; a round-trip loss factor from AC to DC to AC would be twice that or more).

   Fourth, battery makers are not bashful about claims for performance of forthcoming batteries. A good compilation is here, http://cleantechnica.com/2015/05/09/tesla-powerwall-powerblocks-per-kwh-lifetime-prices-vs-aquion-energy-eos-energy-imergy/. It's important to recognize the variables involved: discharge capacity trades off for storage capacity, physical life and cycles vary, efficiency varies, degradation varies, capital cost varies, etc. Your mileage may vary.
7. Brattle Study, footnote 37, citing "… \$350/kWh projection of the installed cost of a battery system," which would convert to about \$1,000/kw, and \$1,000,000/MW, at a 3:1 ratio of storage capacity to discharge capacity. Lazard's Levelized Cost of Energy Analysis provides a "next generation" (2017) projection of capital cost at \$300/kWh for 6 hours of storage capacity, https://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf, which would be \$1,800,000/MW, but its more recent Levelized Cost of Storage Analysis, *supra,* projects a significant capital cost decrease over the next five years, especially for lithium batteries (page 17).
8. For example, PJM uses a 16.2% "levelized annual carrying chart rate" to evaluate the market efficiency of transmission projects, http://pjm.com/~/media/committees-groups/committees/teac/20140410/20140410-market-efficiency.ashx, slide 14.
9. http://pjm.com/~/media/879A2FA2A1794C7887A98686A70336D2.ashx, page 2. The "Rest of RTO" clearing price of \$164.77/MW-day is \$60,141/MW-year and the "EMAAC" (Eastern MAAC) clearing price of \$225.42/MW-day is \$82,278/MW-year. PJM capacity prices may increase in the future, but it should be noted that some new natural gas peaking units offer and clear at current prices, http://pjm.com/~/media/markets-ops/rpm/rpm-auction-info/2018-2019-base-residual-auction-report.ashx (page 23). It is also important to recognize that where battery and natural gas peaking units have the same installed capacity cost that natural gas units have the inherent advantage of receiving energy market revenues in addition to capacity revenues, and these energy market revenues have ranged from \$17,000/MW-year to \$51,000/MW-year depending upon the specific area in PJM, http://pjm.com/~/media/markets-ops/rpm/rpm-auction-info/2018-2019-bra-planning-parameters.ashx (Net CONE tab). As discussed in more detail later a battery storage unit that attempts to collect energy revenues by discharging at a time of high energy prices runs the risk of being unable to fully perform if called on as a capacity resource.
10. New natural gas peaking units offer and clear at these prices, more than 1,000 MW in the most recent PJM auction. http://pjm.com/~/media/markets-ops/rpm/rpm-auction-info/2018-2019-base-residual-auction-report.ashx (page 23).

the cost of generation[11] with the cost of battery storage, the lump-sum capital cost is of course important but also important is the relative life of the facility. Generation facilities are very long-lived, 30-40 years or more without material degradation in rating. The life of battery storage is usually measured in cycles, and for this application the cycles would presumably be low so it would be necessary to know the physical life under low cycling as well as the rate of degradation in discharge capacity.

Data for these two characteristics are difficult to find. One data point for physical life is that Tesla is providing a 10-year warranty for the Powerwall.[12] Another data point is Sanyo's report of recoverable capacity from a lithium ion battery. Sanyo's finding assumes a full battery charge lasting for 12 months, but with some capacity lost during that time due to "self-discharge" before the battery then again is fully re-charged, making for a permanent loss of capacity of about 10 percent.[13] If these data points are indicative then battery storage has serious disadvantages relative to generation facilities, both in terms of physical life and in terms of capacity degradation.

But being way out of the money and having physical life and capacity degradation disadvantages don't mark the end of problems for batteries in capacity markets. Another huge obstacle arises because a battery generally can't sustain output for more than several hours (this characteristic has been termed "energy limited").[14] A rule of thumb is one hour of maximum energy output for every three hours of stored energy (this guide reflects battery characteristics as well as conversion losses).[15] Generally speaking, to qualify as a capacity product a resource has to be capable of generating whenever and for as long as directed, as there are large penalties for a failure to do so. Battery storage does not qualify under this general principle.[16]

In sum there are fundamental bars to battery storage successfully competing as a capacity resource.[17]

Now let's consider the second potential killer app, energy arbitrage, which we can describe as the daily cycling to arbitrage between low wholesale energy prices in the wee hours of the morning and high wholesale energy prices in the late afternoon/early evening. We can illustrate this arbitrage opportunity in Figure 1, which tracks average hourly energy prices in PJM as seen in 2014.[18]

Charging at Hours 3-5 at an average \$35/MWh and discharging at Hours 18-20[19] at an average \$60/MWh yields an average margin of \$25/MWh which, less conversion losses of 10 percent,[20] would produce a net average hourly margin of \$22.50/MWh. Annual revenue would be 3 hours x \$22.50/MWh x 365 days

11. This article refers to generation resources, the largest of which are natural gas, coal, nuclear and hydro generating units. It should be noted that demand response resources also participate in various wholesale markets and would be competing with battery storage as well.
12. http://www.teslamotors.com/powerwall. Interestingly, when Powerwall was first announced Tesla said it would offer "an optional 10 year extension." http://rameznaam.com/2015/04/30/tesla-powerwall-battery-economics-almost-there/. That offer has disappeared. Tesla offers an 8 year warranty on the batteries in the Model S. http://www.teslamotors.com/blog/infinite-mile-warranty. Battery maker BYD offers a 3 year warranty on its battery (guaranteeing 80% capacity retention), and a 2 year warranty on the power conversion system. http://www.byd.com/energy/ess.html.
13. http://www.rathboneenergy.com/articles/sanyo_lionT_E.pdf, Figure 2-11. Another source reports 20% loss after 12 months if at full capacity at 25 degrees Celsius (6% loss at full capacity at 0 degrees Celsius). http://batteryuniversity.com/learn/article/how_to_prolong_lithium_based_batteries.
14. It is of course possible to say, double, the number of hours of discharge of a given battery but that can only be done by halving the MW capacity value and thus doubling the cost per MW.
15. Brattle Study, footnote 35 (previously quoted).
16. In PJM an accommodation has been made for storage and for intermittent (renewable) resources such that qualifying offers could be based on expected performance during defined peak period hours. Most of the peak period hours are in the summer and are six hour stretches each day. http://elibrary.ferc.gov/idmws/common/opennat.asp?fileID=13773611 (page 23). A battery that has three hours of stored energy for its rated capacity could thus achieve a 50% capacity credit and receive a capacity payment discounted by that 50%. This doubles the bar (again) at which battery storage would be competitive as a capacity product (assuming it qualifies in the first place).
17. Lazard recently released a Levelized Cost of Storage Analysis that warrants discussion. Lazard shows battery storage as being uncompetitive with a natural gas peaking unit at current battery costs (page 9), and even after assuming future potential cost reductions (page 18), https://www.lazard.com/media/2391/lazards-levelized-cost-of-storage-analysis-10.pdf (for some battery technologies the low end of the cost range with potential cost reductions overlaps the cost of a gas peaker). Even assuming the potential cost reductions there are other generous elements in Lazard's modeling: (1) Assumption of a 20-year project life for batteries (pages 20-21), when the expected useful life for most battery technologies is indicated to be 5-15 years (page 4); (2) apparent assumption of a gas peaker life of 20 years (Levelized Cost of Energy Analysis, *supra,* page 18) when expected life may be twice that; (3) in computing levelized cost apparently using a capacity factor of 16% for battery storage (35,000 MWh annual use divided by 8,760 hours divided by 25 MW/hour capacity) versus the 10% capacity factor for a gas peaker in its Levelized Cost of Energy Analysis (page 18); (4) not offsetting a gas peaker's capacity cost with energy market revenue (this is significant as discussed earlier); (5) not recognizing that the modeled battery in only supplying energy for four hours at maximum output would not qualify as a capacity resource (as discussed earlier); and (6) while acknowledging that its alternatives analysis is limited to a gas peaker (page 18, note c), not modeling these other alternatives of capacity that may be less costly than a gas peaker. In other words, even with optimistic assumptions of future cost reductions there are significant questions as to whether battery storage would approach the net capacity cost of alternatives.
18. http://monitoringanalytics.com/reports/PJM_State_of_the_Market/2014/2014-som-pjm-volume2-sec3.pdf (page 125).
19. This reflects the 3 to 1 storage capacity to maximum discharge ratio previously discussed.
20. This may be a conservative assumption for AC-DC-AC conversion losses. See, for example, https://www.neces.com/assets/NEC_Grid_Brochure_MD100120-02-5.pdf (footnote on fourth page), in contrast to Lazard's assumption of 15-25% losses, https://www.lazard.com/media/1777/levelized_cost_of_energy_-_version_80.pdf, page 17, note c.

= $24,600 per year. That's a small fraction of an annualized capital cost of $150,000.

Using the above as a "base case" we should consider factors that could make the $24,600/MW-year too high or too low. First, it could be *too high* due to degradation in capacity with the number of cycles.[21] One commentator states that lithium ion batteries cannot be frequently discharged below 30 percent of capacity without a large reduction in battery life.[22] The economics of energy arbitrage would need to be adjusted for any such operating limit by reducing revenue proportionate to the practicable operating range of the battery system.

Second, the $24,600/MW-year revenue estimate could be *too low* if storage could improve on the pair of three-hour periods we have set for charging and discharge, by successfully projecting the three highest-priced hours and the three lowest-priced hours each day, and offering into the PJM energy market accordingly. It also is conceivable that specific locations could be identified with larger differences in high and low prices.[23]

What all this means is that a simple base case for energy arbitrage does not come close to being economic, and that there are large uncertainties around the base case, both to the downside and to the upside. This is not an attractive value proposition.

Common Misconceptions

Advocates for grid-scale battery storage sometimes suggest that different applications can be made additive, or that storage can be paired profitably with generation to "add value," or that battery storage is "green" because it will displace the dirtiest generation. Let's take these claims one at a time.

Additive Applications. The hoopla for battery storage often portrays revenue from different applications as potentially additive.[24] That might prove possible with regard to some of the niche applications discussed later, but not for the two killer apps discussed above.[25] That's because the battery system has to be fully charged 24x7 to "stand by" its obligation to provide the full capacity commitment. Any discharge for purposes of energy arbitrage would compromise the ability of the battery system to meet its capacity commitment and would risk large penalties if the battery system were to be called upon.

This example shows also why battery storage cost per MW is not equivalent to other capacity resource costs per MW in terms of return on investment. Battery storage operating as a capacity resource will be compensated solely by capacity market revenue. But a natural gas peaking unit operating as a capacity resource will be compensated by capacity market revenue plus energy market revenue.[26] This contrast arises as an inherent consequence of the fact that the fuel source of battery storage is the limited amount of energy stored in the battery itself – but which must be held continuously in storage to qualify as a capacity resource – whereas the fuel source of a natural gas peaking unit comes from an the external, continuous supply of natural gas.[27]

Some say storage helps wind displace coal. That's a misconception, because wind is the last fuel to become marginal.

Strategic Pairing. Notions have developed that battery storage can add value from strategic pairing with generating resources. In other words the whole can be greater than the sum of the parts.

One notion has battery storage pairing with renewables,[28] and another notion has battery storage pairing with natural gas peaking units. There is some irony in this because wind and

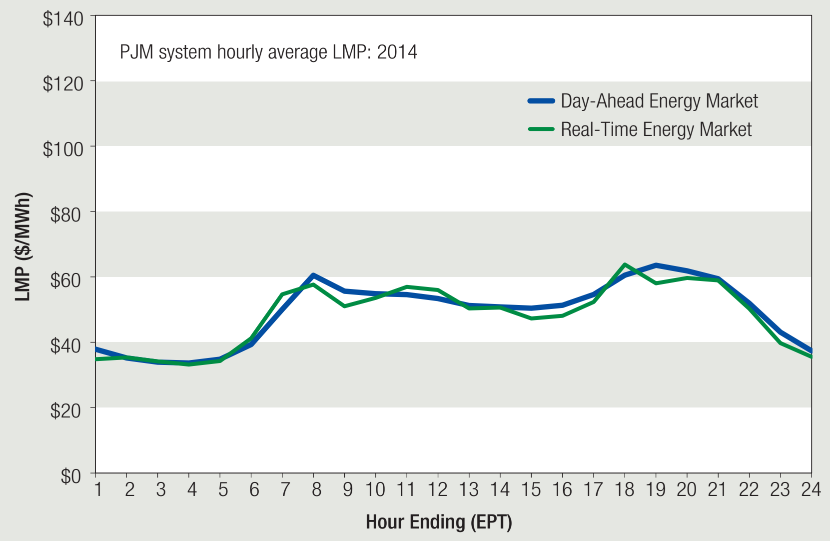
21. See, for example, the charts at http://www.byd.com/energy/technology.html.
22. http://reneweconomy.com.au/2015/how-cheap-can-energy-storage-get-pretty-darn-cheap-77700.
23. It should be noted that this is not necessarily the same as locations with higher prices generally due to transmission constraints that cause "congestion" because, as discussed later, such locations may have above-average prices in high-priced periods and above-average prices in low-priced periods.
24. See, for example, http://www.utilitydive.com/news/whats-the-value-of-energy-storage-its-complicated/407498/.
25. An example of combining a killer app, energy arbitrage, with a niche application, frequency regulation is here, http://elibrary.ferc.gov/idmws/common/opennat.asp?fileID=13916373. The referenced discussion focuses on co-optimizing the combination, *i.e.*, minimizing the tradeoff involved. But the underlying problem remains that even if no trade-off were involved and the revenue streams were purely additive, energy arbitrage annual revenue of $24,600/MW-year cannot support deployment of battery storage at an annualized capital cost of $150,000, and the frequency regulation market is itself small.
26. The energy market net revenue is called "infra-marginal" and arises from the resource being paid the difference between the clearing price and its variable cost. As noted earlier these energy market revenues have ranged from $17,000/MW-year to $51,000/MW-year depending upon the specific area in PJM.
27. There is a misconception that energy-only wholesale markets would be less attractive for battery storage than dual energy-capacity markets. In a properly designed energy-only market the value of capacity must be reflected in energy prices, and these energy prices necessarily will exceed energy prices in a dual energy-capacity market (all else equal). If the physical characteristics of battery storage disqualify it from a capacity market, or greatly discount its nominal value because it is energy limited, then the expected revenue from an energy-only market would be expected to exceed that from a dual energy-capacity market (again, all else equal).
28. "Battery storage technology paired with renewables such as wind and solar has the power to transform the energy landscape," said Rep. Mark Takano (D-CA), announcing the "Congressional Battery Energy Storage Caucus." http://www.utilitydive.com/news/bipartisan-coalition-launches-congressional-battery-storage-caucus/408096/?utm_source=Sailthru&utm_medium=email&utm_campaign=Issue:%202015-10-28%20Utility%20Dive%20Newsletter&utm_term=Utility%20Dive.

peaking units are opposites in terms of their variable costs of generation. In any event, both notions are wrong.

Let's envision 1 MW of battery storage paired with a wind project. Our base case is battery storage by itself, charging when the energy price is $20/MWh and discharging when the energy price is $60/MWh for net revenue of $40/MWh. Now let's consider this battery storage paired with a wind project. Same wholesale prices, and the wind generation is used to charge the battery at $0/MWh in variable cost. The battery nets $60/MWh, but the wind project gave up $20/MWh that it could have received from selling in the wholesale market instead of selling to battery storage at $0/MWh. So the combined revenue is $60/MWh for the battery less the $20/MWh in revenue foregone by the wind project for net of $40/MWh. This is the same as battery storage by itself.[29] The whole is not greater than the sum of the parts.[30]

FIG. 1 ARBITRAGE VIA DAILY CYCLING

Average hourly energy prices (Day-Ahead vs. Real-Time) in PJM during 2014.



Now let's envision a similar pairing of battery storage with a natural gas peaking unit. The base case is battery storage by itself, charging when the energy price is $20/MWh and discharging when the energy price is $60/MWh for net revenue of $40/MWh. Now let's consider this battery storage paired with a natural gas peaking unit. When the variable cost for the natural gas peaking unit falls below $60/MWh it will be selling into the wholesale market – not to battery storage, which is waiting for the low prices of the wee hours of the morning. And when variable cost for the natural gas peaking unit rises above $60/MWh it would make no sense to use the peaking unit to charge the battery when wholesale energy is available for charging at $60/MWh (assuming battery storage would ever charge at a time of peak prices). Revenue of battery storage and the natural gas peaking unit is in all cases determined by the wholesale energy price, and that revenue is independent of whether the battery storage is paired with or without the natural gas peaking unit.[31]

The 'Green' Myth. The PJM hourly price chart discussed earlier *(see Fig. 1)* also helps show why battery storage is not "green." To the extent battery storage is used for energy

29. It is sometimes thought that negative energy prices, such as those reported by the *New York Times*, http://www.nytimes.com/2015/11/09/business/energy-environment/a-texas-utility-offers-a-nighttime-special-free-electricity.html?emc=edit_tnt_20151108&nlid=39266840&tntemail0=y&_r=0, somehow change the fundamentals for pairing. But that is not so. Let's consider a base case of battery storage by itself, charging when the energy price is -$20/MWh and discharging when the energy price is $60/MWh for net revenue of $80/MWh. Now let's consider this battery storage paired with a wind project. Same wholesale prices -- the wind generation with $0/MWh in variable cost will not be used to charge the battery because the negative energy price is less than $0. And the wind generation won't sell to the grid because that would lose money at the negative energy price. So the pairing doesn't change the economics, the wind generation isn't sold and the battery nets the same $80/MWh. We can vary this scenario for the impact of a $23/MWh production tax credit for wind that incents wind to generate even when the energy price is negative. The wind generation can be used to charge the battery at $0/MWh cost to the battery and the wind generator keeps the $23/MWh PTC. The battery loses the value of the negative $20/MWh energy price so it nets $60/MWh. The wind generator without the battery would have netted $3/MWh ($23/MWh PTC less the –$20/MWh energy price), and with the battery gets the entire PTC for a net increase of $20/MWh. Combined value of the pairing is still $80/MWh.

It should be noted that negative energy prices are a predictable consequence of a national policy to subsidize renewable energy through the PTC (which is not to take a position on that policy but to simply observe that this consequence is not anomalous). Negative energy prices certainly do not warrant the installation of uneconomic battery storage to "correct" the prices. To the extent negative energy prices should be addressed the simplest way is that described in the *Times* article, let the negative wholesale prices be passed through to the consumer, such as in the form of "free" electricity at night. Then consumers will provide the cheapest form of storage: the "storage" of their demand during the day and the release of that stored demand at night.

30. There can be synergy when other factors are introduced such as a possible transmission constraint resulting in significant curtailment of wind project output, https://www.purdue.edu/discoverypark/energy/assets/pdfs/SUFG/publications/Wind%20with%20energy%20storage%20valuation.pdf, but that is not a significant factor in PJM, http://www.pjm.com/~/media/committees-groups/subcommittees/irs/20150921/20150921-item-04-wind-curtailment-statistics.ashx, and even if it were it is likely that relieving the transmission constraint would be more cost effective than installing battery storage.

31. Actually that is not entirely the case. Co-locating battery storage with the natural gas peaking unit would tend to suppress the energy price in that location. So the net effect of co-location could be negative for both resources.

arbitrage/cycling,[32] the energy for battery charging at hours of low prices is generally coming from coal generation that is "on the margin" at those hours, and the battery discharge at hours of high prices is displacing natural gas generation that is "on the margin" at those hours.[33] Thus, as a general matter, battery storage displaces natural gas generation with coal generation – the opposite of green.

There is a misconception that wind is often the marginal resource at hours with low prices, and therefore battery storage enables wind to displace fossil fuel generation. Notwithstanding this occurring from time to time in areas with very high wind penetration such as Texas, this is rarely the case generally because wind has a negative marginal cost due to the production tax credit and thus is the last resource to become marginal.

Finally, there is a belief that battery storage ultimately will be needed for deep decarbonization of electricity. This belief fuels a view that battery storage should be subsidized and/or imposed now in order to support development for this future need. A recent Harvard study concludes that this is not the case for two reasons. First, bulk storage isn't necessary for deep de-carbonization and second, even if it were, battery storage is not the economic choice for storage.[34]

As for *total* decarbonization – a zero-emission future – J.P. Morgan estimates that total reliance on wind, solar, and storage would result in a cost between $280/MWh and $600/MWh.[35] Ouch.

A Niche Is Just That

Let's examine some niche applications for battery storage. Most of these are referred to as "ancillary services" and as the term implies they are ancillary to the major wholesale markets, energy and capacity. A study from the Rocky Mountain Institute ("RMI") has listed a number of functions as ancillary services: frequency regulation, spin/non-spin reserves, black start, and voltage support (aka reactive service).[36] RMI listed other potential storage value from transmission and distribution deferral and transmission congestion relief, which we'll discuss as well.

Even where storage might make sense, batteries must compete with pumped hydro, compressed air, and flywheels.

Frequency Regulation. Regulation marks the ancillary service that battery boosters have focused on most. It involves rapid changes in output at the direction of the grid operator.[37] Battery storage is well suited to provide this service, but regulation remains a small niche application. [38]

PJM's resource requirement for regulation service provided during on-peak hours is 700 MW and during off-peak hours is 525 MW.[39] There are about 185,000 MW of generating capacity in PJM, so the regulation requirement is about 0.4 percent of total generating capacity.

Traditional electric generators also provide this ancillary service, as shown in *Figure 2,* which presents a chart prepared by PJM.[40]

The term "REGD" in Figure 2 refers to Reg D, Dynamic Regulation ("fast moving response") resources, which are more highly valued and paid than the traditional "REGA" (Reg A)

32. This application, and the strategic pairing application discussed in the previous section, are the only applications that could be claimed to be green.
33. The Energy Information Administration has a dispatch curve illustrating this, http://www.eia.gov/todayinenergy/detail.cfm?id=7590#. Decreasing natural gas prices have increased the competition between coal and natural gas units at low prices, but it remains that there is more coal/less natural gas on the margin at low prices than there is at high prices.
34. "We draw two policy-relevant conclusions from this work. First, large-scale adoption of bulk electricity storage compared to variable renewables and gas turbines is neither technically required nor cost effective as a means to reduce carbon emissions even when variable renewables play a large role. In other words, intermittent renewables need not to wait for the availability of cheap bulk storage to become an effective tool for decarbonization. … Second, at their current costs, adiabatic CAES and PHS [non-battery storage] show the most appealing prospects in lowering the decarbonization cost among other BES [bulk electricity storage] technologies due to their low energy-specific capital costs and despite their much higher power-specific capital costs." Safaei and Keith, "How Much Bulk Energy Storage Is Needed to Decarbonize Electricity?," Energy & Environmental Science, December 2015, http://pubs.rsc.org/en/content/articlepdf/2015/ee/c5ee01452b (page 3415). The basic study conclusion is not sensitive to a large reduction in the assumed price of storage (*id.*).
35. https://www.jpmorgan.com/cm/BlobServer/Brave_New_World_-_Annual_energy_piece.pdf?blobkey=id&blobwhere=1320687247153&blobheader=application/pdf&blobheadername1=Cache-Control&blobheadervalue1=private&blobcol=urldata&blobtable=MungoBlobs (page 17) (cost range is from modeling California).
36. http://www.rmi.org/Content/Files/RMI-TheEconomicsOfBatteryEnergyStorage-FullReport-FINAL.pdf, pages 5 and 15.
37. The grid operator provides an Automatic Generation Control ("AGC") signal to the frequency regulation resource. FERC Order No. 755 describes this ancillary service in detail. http://elibrary.ferc.gov/idmws/common/opennat.asp?fileID=12795735.
38. The largest battery storage facility in PJM is a 32 MW installation at a wind project near Elkins, West Virginia. It should be noted that battery storage size is sometimes referred to by its "range" of, in this case, discharging up to 32 MW and charging up to 32 MW for a total of 64 MW. This is particularly misleading in the context of capacity and energy arbitrage where only the discharge capacity is relevant. And it can be misleading in the context of regulation because the ability to provide regulation at any point in time depends on the charge level of the battery at that time. For example, if a battery with 32 MW of discharge capacity is charged at 20 MWh when "up regulation" is needed then the battery can only provide that 20 MWh, and a battery that is fully charged cannot provide "down regulation."
39. http://www.pjm.com/~/media/committees-groups/task-forces/rmistf/20151016/20151016-item-03-regulation-market-overview.ashx, slide 16.
40. *Id.,* slide 9.

resources.[41] The figure shows also that existing Reg D resources of 684 MW by themselves approximate the PJM regulation requirement of 525-700 MW, raising the question of what additional market demand might exist for additional battery storage in PJM.[42] The PJM Market Monitor has criticized the PJM regulation market design, which it says has caused overpayment resulting in the market becoming "saturated."[43] Thus, the market opportunity for additional battery storage in PJM's regulation market has disappeared or is disappearing.

FIG. 2 **ANCILLARY SERVICES**

Types of electric generators and other resources that typically provide the need for frequency regulation within PJM.

Resource	REGA MW	REGD MW	Dual Qualified
Steam	3103	0	0
Hydro	970	420	420
CT	1194	80	20
Energy Storage	0	176	0
DSR	4	8	2
Total MW	**5271**	**684**	**442**

Notes. The term "REGD" in the chart above refers to Reg D, Dynamic Regulation ("fast moving response") resources, which are more highly valued and paid than the traditional "REGA" (Reg A) resources. "CT" denotes combustion turbine generators. "DSR" denotes demand-side resources.

Reactive Service. Another ancillary service that battery storage can provide is reactive service which supports grid voltage.[44] Reactive service is compensated on a traditional cost-of-service basis via rate filings by generators at FERC. Total reactive service costs in PJM in 2014 represented 0.6 percent of the total wholesale price of power,[45] so if the reactive capability of battery storage is in line with other resources, the contribution of reactive service revenue to battery storage earnings would be negligible.

Black Start. Battery storage potentially could provide black start service, which is the ability to support restoration of the grid in the event of an outage.[46] However, a black start unit typically must be able to maintain its rated output for 16 hours,[47] which battery storage could only do by having a MWh:MW ratio of 16:1 or more, at a per-MW cost roughly five times more than the optimistic assumption of $1,000,000/MW that was noted earlier.

With some added data we can estimate potential black start revenues for battery storage. With annual black start service charges in PJM projected at $80 million,[48] and given the 8,000 MWs of black start capacity,[49] we can project average compensation of about $10,000/MW per year for battery storage providing black start service. Note also that battery storage would have to compete with other sources of black start service in an RFP process that occurs infrequently. Thus, this potential source of revenue is small and problematic relative to an optimistic capital cost for this application around $5,000,000/MW.

Transmission Deferral. Another potential benefit of battery storage might come from deferring (or eliminating) a need to expand the transmission system. Such grid expansion might become necessary, for example, when growth in customer demand or loss of an existing generating unit makes the existing transmission and generation system unable to reliably serve a particular area.

41. *Id.,* slide 13. The greater value of Reg D resources diminishes with an increase in the percentage of Reg D resources, i.e., there is diminishing marginal value. http://www.pjm.com/~/media/committees-groups/committees/oc/20150811/20150811-item-03-regulation-clearing-and-benefits-factor-calculation.ashx, slide 6.
42. The percentage of qualified MW that participates in a given hour varies, http://www.pjm.com/~/media/committees-groups/committees/oc/20150701-rpi/20150701-regulation-problem-statement-education.ashx, slides 6-7, but the fact remains that the regulation market is small and has significant existing resources.
43. "This inefficient market signal has contributed to a significant amount of storage capacity (Table 10-28) appearing in PJM's interconnection queue, despite operational evidence that the RegD market, as currently implemented, is saturated." http://www.monitoringanalytics.com/reports/PJM_State_of_the_Market/2015/2015q3-som-pjm.pdf, page 381. A PJM task force is evaluating changes in the regulation market design.
44. PJM Market Monitor report, http://monitoringanalytics.com/reports/PJM_State_of_the_Market/2014/2014-som-pjm-volume2-sec10.pdf.
45. http://monitoringanalytics.com/reports/PJM_State_of_the_Market/2014/2014-som-pjm-volume2-sec1.pdf, page 16, Table 1-9. This table also shows the relative significance of energy, capacity, transmission, and all other cost components of the wholesale system. Energy, capacity and transmission are more than 95% of all costs.
46. "Black start service is necessary to ensure the reliable restoration of the grid following a blackout. Black start service is the ability of a generating unit to start without an outside electrical supply, or the demonstrated ability of a generating unit to automatically remain operating when disconnected from the grid." PJM Market Monitor, http://monitoringanalytics.com/reports/PJM_State_of_the_Market/2014/2014-som-pjm-volume2-sec10.pdf, page 384.
47. http://www.pjm.com/~/media/committees-groups/task-forces/srstf/20130709/20130709-rto-wide-five-year-selection-process-request-for-proposal-for-bss.ashx (page 6).
48. *Id.* at page 386.
49. http://www.pjm.com/~/media/committees-groups/committees/mic/20140709/20140709-item-07a-pjm-rto-wide-five-year-selection-process-rfp.ashx, slide 4.

In this circumstance the traditional response has been to expand transmission and/or generation resources as necessary to maintain reliability.[50] Battery storage might offer a potential alternative. And make no mistake, the *potential* market is enormous. PJM, for example, has directed $27.8 billion of transmission upgrades over the last 15 years, and the MISO has directed $20.2 billion.[51]

A threshold challenge, however, is the same one that battery storage faces in providing capacity generally. Transmission planners will insist, at a minimum, that a substitute resource be able to provide energy over the peak hours of a day, which in the case of PJM in the summer is six hours. A battery can deliver its discharge capacity for perhaps three hours, meaning that it would take twice the battery capacity to meet the six-hour requirement.

Battery storage thus is handicapped as a transmission/generation substitute. That does not rule out battery storage entirely, but it would require an even greater improvement in capability than that forecasted. Should that happen the outcome becomes an empirical one, cost of transmission expansion versus cost of generation expansion versus cost of storage, with batteries being one form of storage.

In comparing the cost of a transmission upgrade versus the cost of battery storage, the lump-sum capital cost needs to be adjusted for the relative life of the facility. Transmission facilities are extremely long-lived – 50 years or more without material degradation in rating along the way. The life of battery storage is usually measured in cycles, however, and for this application the cycles would presumably be low in number, so it would be necessary to know the physical life under low cycling as well as the rate of degradation in discharge capacity. If, as discussed earlier, physical life is 10 years, let's say, and there is degradation in discharge capacity over the physical life, then the effective cost of battery storage would be a multiple of a transmission upgrade, even if both had the same lump-sum capital cost.[52]

Consolidated Edison's Brooklyn/Queens Demand Management Program is cited often as an example of grid batteries supporting deferral of traditional grid expansion.[53] However, the New York Public Service Commission did not evaluate the cost-benefit value of grid batteries on a stand-alone basis, and instead conducted a "portfolio level" analysis of a total 52 MW of load reduction measures, of which a grid battery will make up only 2 MWs.[54]

Bottom line? Battery storage is not economic for deferring transmission expansion.[55]

Transmission Congestion. This potential application is based on high energy prices in specific locations due to transmission constraints where the constraint is not so severe as to cause a reliability problem. It is not certain that the value proposition would be greater than that for energy arbitrage generally because the transmission-constrained locations may post above-average prices in both high-priced *and* low-priced periods, such that the arbitrage value may or may not be more than average arbitrage value.[56]

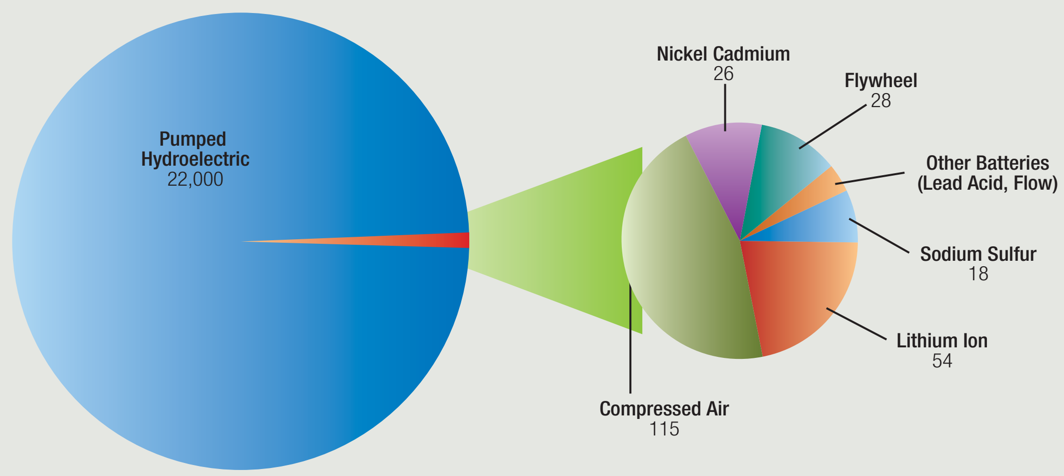
Where do studies go awry? They look at system-wide savings, not the revenue stream that accrues to storage itself.

Assuming there is an incremental arbitrage opportunity from relatively high energy prices in a given location, nevertheless it is a *raison d'etre* of locational marginal pricing in energy markets to attract new generation resources to the high-priced locations to capture that higher price. This incentive can be expected to bid down the price premium over time, making

50. As a general matter a transmission upgrade has been the standard and least-cost solution to a local capacity deficiency.
51. http://www.pjm.com/~/media/committees-groups/committees/teac/20151008/20151008-pjm-teac-board-whitepaper.ashx, page 1; https://www.misoenergy.org/Library/Repository/Study/MTEP/MTEP14/MTEP14%20Executive%20Summary.pdf.
52. It is also worth noting that transmission upgrades are basically passive and require little in the way of maintenance. Battery storage will require active management and maintenance, at a cost for both.
53. http://www.greentechmedia.com/articles/read/con-ed-looks-to-batteries-microgrids-and-efficiency-to-delay-1b-substation.
54. The NY PSC Order is here, http://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={83594C1C-51E2-4A1A-9DBB-5F15BCA613A2} (pages 18-19). ConEd was given discretion to select among load reduction alternatives, apparently deciding on 2 MWs of grid batteries, http://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={43168D9B-2F0A-4DC8-B319-3E772BDFAC42} (page 25). ConEd reports a cost of $12 million for the 2 MWs in a 12 MWh (6:1) configuration, http://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId={8EE6660B-304E-4B49-87DF-7DF3D6A9B623} (CapEx tab), which is $6,000,000/MW. This would be $3,000,000/MW at a 3:1 configuration (12 MWh/4 MW).
55. Lazard's Levelized Cost of Storage Analysis (page 18) shows battery storage as uneconomic for this purpose, even with future forecasted cost declines, but understates just how uneconomic battery storage would be by (1) overstating battery capability relative to a gas peaker, (2) assuming battery storage life to be equal to that of a gas peaker (instead of less than half), and (3) not making a cost comparison to transmission expansion itself (the likely least cost solution).
56. The highest price area in PJM tends to be the southern portion of the Delmarva Peninsula as shown by the map here (slide 10), http://pjm.com/~/media/committees-groups/committees/mc/20151116-webinar/20151116-item-05-imm-report.ashx. The Tasley substation is a location (node) in the middle of that area. At Tasley, for the 12 months ended October 2015, Hours 3-5 have averaged $58.05/MWh and Hours 18-20 have averaged $88.47/MWh for an average difference of $30.42/MWh that would provide annual revenue of $33,310 ($30.42/MWh times 3 hour cycle each day times 365 days; this is before losses).

Fig. 3 **Energy Storage Technologies**

2011 U.S energy storage capacity by resource technology (in MWs).



a long-term investment in battery storage based on that price premium very risky.

In addition, grid operators like PJM actively target areas of high prices and evaluate the economics of transmission upgrades that would reduce or eliminate the congestion. PJM has recently approved a number of such upgrades at relatively low cost.[57]

Thus, the transmission congestion niche application must identify locations where the location-specific arbitrage value is greater than the average system arbitrage value, and where that value can be expected to persist against the incentive of new generation to locate there and of the mandate of grid operators to mitigate congestion when economic to do so. A heavy lift indeed.

Indeed, much of the hoopla around battery storage implicitly assumes that battery storage is the principal means of storing electric energy. That assumption is wrong. In those limited circumstances where storage makes sense battery storage must compete with pumped hydro, compressed air, and flywheels.

Figure 3 puts matters in a proper perspective. This chart, taken from a report by the State Utility Forecasting Group (a research arm of Purdue University), shows that 2011 there were 22,000 MWs of pumped hydro in the U.S., and all other storage technologies were less than 300 MWs. [58]

Where Studies Go Awry

Admittedly, one can uncover studies of battery storage that find or imply value. Where do they go awry? Let's take a study from DOE's national Renewable Energy Laboratory (NREL) completed two years ago. For starters the study "… assumes a single 300-MW device, with eight hours of capacity at full output."[59] As discussed earlier, a realistic ratio of discharge capacity to stored energy is more like three hours of capacity at full output.

'It's tough to make predictions, especially about the future.'

– Yogi Berra

The NREL study also treats as a benefit any *system* price reduction from storage, instead of considering just the revenue that accrues to storage itself.[60] That's an erroneous approach in a competitive market where investment necessarily is based on what the resource owner expects to achieve, and markets clear on the basis on those investments. No resource owner is entitled to the system price reduction caused by the resource, and no investment can be supported on that basis.

57. http://pjm.com/~/media/about-pjm/newsroom/2015-releases/20151015-board-approves-transmission-projects.ashx.

58. http://www.purdue.edu/discoverypark/energy/assets/pdfs/SUFG/publications/SUFG%20Energy%20Storage%20Report.pdf. The California mandated storage procurement excluded large pumped hydro on grounds that it may best other storage technologies ("However, the sheer size of pumped storage projects would dwarf other smaller, emerging technologies; and as such, would inhibit the fulfillment of market transformation goals."), http://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M079/K533/79533378.PDF.

59. "The Value of Energy Storage for Grid Applications," http://www.nrel.gov/docs/fy13osti/58465.pdf, page 10.

60. "In this case, the 300-MW device would have purchased a total 613 GWh at a cost of $15.4 million, while selling 465 GWh, with revenues totaling $20.6 million. As a result the net revenue of the storage plant in a market setting is $5.2 million, or only about 50% of the reduction in operational costs produced when adding storage to the base system. The combination of incomplete capture of system benefits and price elasticity presents additional challenges to storage devices in restructured markets, as noted previously by Sioshansi et al. (2012) and Kirby (2011)." *Id.* at page 18. As noted in the text this is flawed analysis in a market environment where no resource is entitled to the reduction in system price resulting from its existence. The study appears to partially concede this on page 34.

The NREL study also assumes that the values of different applications are additive.[61] That also is not valid. As discussed earlier, capacity value cannot be added to energy arbitrage value because a capacity resource must be fully charged at all times.

The NREL study also estimates benefits ("value") without regard to competing alternatives, as expressed in market prices. In a market, "value" is based on the lowest-cost alternative, not on a theoretical value from a model.

The NREL study also does not consider the physical life of battery storage and the degradation of capacity over time, relative to transmission and generation facilities with long lives and no material degradation. As discussed earlier these are serious disadvantages of battery storage.

And even with all these flaws the NREL study still finds only a limited value for battery storage, mostly in providing regulation and in assuming that value from energy arbitrage and from capacity can be added to the regulation value.[62]

What can we take away from all this?

The electric industry no doubt faces serious threats in the near and medium term, but battery storage isn't one of them. Grid batteries might eventually make sense, but as Yogi Berra said, "It's tough to make predictions, especially about the future."

61. "The monetized capacity value of a storage plant can be added to its operational value to derive an estimate of its total annual value." *Id.* at page 21. "We examine the value of an energy storage device as the sum of its operational and capacity values." *Id.* at page 34.

62. *Id.* at 34.