Comparing the Upfront Costs of Energy Storage

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With the advent of energy storage for use in utility grid applications and in so-called "behind-the-meter" applications, its cost is a critical factor in determining whether an application makes economic sense or not. However, there are layers of complication in the discussion of cost, and an understanding of both performance parameters as well as the mode of operation is required to enable potential users of energy storage to focus on the appropriate cost-based metrics.

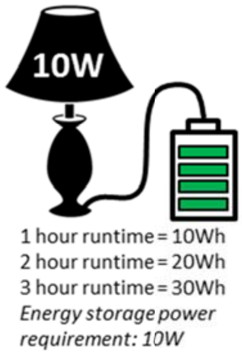
Introduction

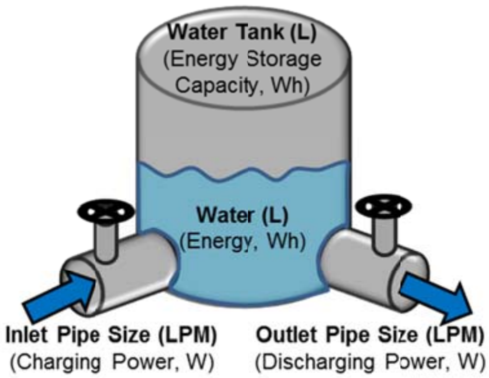
Energy storage is being considered as a new and important component in the utility grid to perform services like frequency regulation or primary reserve which help to balance the supply and demand of electricity on the grid, or help prepare the grid for the eventual integration of large amounts of renewable but variable intermittent generation like wind and PV. There are also a number of applications and services for behind-the-meter (customer side of the meter) locations that can help electricity users manage and control consumption, ultimately helping them reduce their cost of electricity by peak shaving or demand charge reduction. All of these applications have a certain amount of economic value for the user, but to understand whether this economic value is enough to justify the procurement and use of energy storage, one must understand the cost of the energy storage in context of its capabilities, and effectively compare among the various types of energy storage available.

Power vs Energy

An important basic electrical concept which has an impact on energy storage cost comparisons is the difference between power and energy. Energy is required to perform work, while power is the rate at which energy is either provided or consumed. Energy can be measured in watt-hours (Wh), while power can be measured in watts (W).

For instance, assume a 10W power-efficient LED lamp – over the course of 1 hour it will consume 10Wh. If it is on for 2 hours it will use 20Wh, if on for 3 hours it will use 30Wh, and so on. Let's now assume we have an energy storage device that can hold 30Wh of energy (Wh). This energy storage device will be able to power the lamp for 3 hours (10W lamp for 3 hours = 30 Wh), *but only if its power capability is 10W or greater*. If its power capability is 5W, the lamp will not function properly – even though it has enough energy storage capability to run it for 3 hours. The energy storage device will not be able to perform the job of powering the lamp because it does not have enough **Power** capability, despite having the required **Energy** storage capability.





A useful analogy here is that energy can be thought of as water. Imagine a water tank – one could measure the water tank capacity in liters (L). As the water flows into and out of the tank, one could describe the flowrate in liters per minute (LPM). Likewise, imagine now an energy storage tank – perhaps a battery – whose energy storage capacity can be measured in watt-hours. As energy is flowing into and out of the battery, we would then describe the flowrate instead of in liters per minute but in Wh per minute (or simplified, watts).

Typical Upfront Cost Metrics

The normalized cost metric of "$/Wh-storage-capacity", or simply "$/Wh" in shorthand is very frequently used and one of the most common metrics to measure the normalized cost of energy storage devices. It should be noted that this metric can be confused with the cost of electricity, which is measured in a similar metric of "$/kWh" (or in wholesale electricity markets "$/MWh"). Thus it can be clearer to specify "$/Wh-storage" instead of simply "$/Wh". Either way, this metric describes the cost of the energy storage capability. By way of the water analogy, the $/Wh metric would be most similar to the cost of the water *tank* (*not* the cost of the water inside, which would itself be more similar to the cost of electricity).

However, the other useful cost metric is based on power capability, or the rate at which energy can be put in or taken out of the storage device, and measured in watts. This other metric of "$/W" is also frequently used to measure cost and performance along with the "$/Wh" metric. They are very different from each other and must be understood. Together they are the two primary metrics when looking at the upfront costs of energy storage.

What's Included?

In addition to performance metrics like power capability and energy storage capacity, cost itself can be multi-faceted. In the case of battery-based energy storage systems there are several different major categories beyond just the battery cells themselves that add cost to an energy storage installation. These cost categories, sometimes called 'balance-of-plant' or 'balance-of-system', are required to enable energy storage systems to interconnect to the utility grid or to the customer's power system. Thus it is important when faced with a cost discussion to make clear that all parties are discussing the same costs. As almost all energy storage systems installed for grid services or for behind-the-meter applications require alternating current (AC) power, and most energy storage systems (especially electrochemical battery-based ones) are direct current (DC) power, it is useful to look at costs at the DC level and then at AC system level. Common cost levels of DC energy storage systems discussed in the industry are:

- Cells
- Modules
- Energy storage racks
- Battery system/zone
- Fully containerized DC system

Some common component levels in a DC energy storage system

The graphic to the right shows the build-up of components in a DC energy storage system from most basic (cells) to most complex (containerized). Cells are assembled into modules, which are assembled into racks, then into groups of battery racks, also called zones, then finally packaged in an outdoor weatherproof and thermally managed enclosure, oftentimes a modified ISO shipping container that can range from 20' in length up to 53' in length.

However, in addition to the DC energy storage system there are additional components and costs to bring a complete AC energy storage system to a site, install it, and ensure proper interconnection. These costs can include:

- Power conversion system
- Transformer(s)
- Switchgear
- Cabling or other conductors
- Installation costs

Thus when faced with a value for energy storage cost in $/Wh, it is important to distinguish from the various levels of cost. At the most basic level is the cost of just the cells, which at best is an indicator of total cost, but ultimately one will need the cost at the most complete solution level, the "all-in" cost of an installed and commissioned energy storage system. Depending on the type of energy storage technology used, the energy storage itself may NOT be the majority of the cost of the system.

Example of a complete AC energy storage solution installed and in commercial operation

Comparing Costs

Once the cost of the energy storage has been established, how can both the cost per power and the cost per energy storage be evaluated simultaneously to decide what makes the most economic sense for any given application? One way to do that is to look at the power cost - $/W or $/kW, as the case may be for most energy storage applications being discussed for the purposes of this paper – and then compare it to energy storage capability directly. How does this work?

First, one can consider cost per rated power ($/kW) on one axis, and simple energy storage capability on the other. To simplify the way energy storage capability is displayed, one can consider energy storage as the amount of time, or **duration**, that the energy storage system is capable of delivering the rated power.

For instance, a peak shaving application requires a 1kW/2kWh energy storage system to be able to deliver 1kW for 2 hours, or 120 minutes:

- Assume the total cost of the system $1000
- The cost per kW is $1000/1kW = $1000/kW
- The cost per kWh is $1000/2kWh = $500/kWh

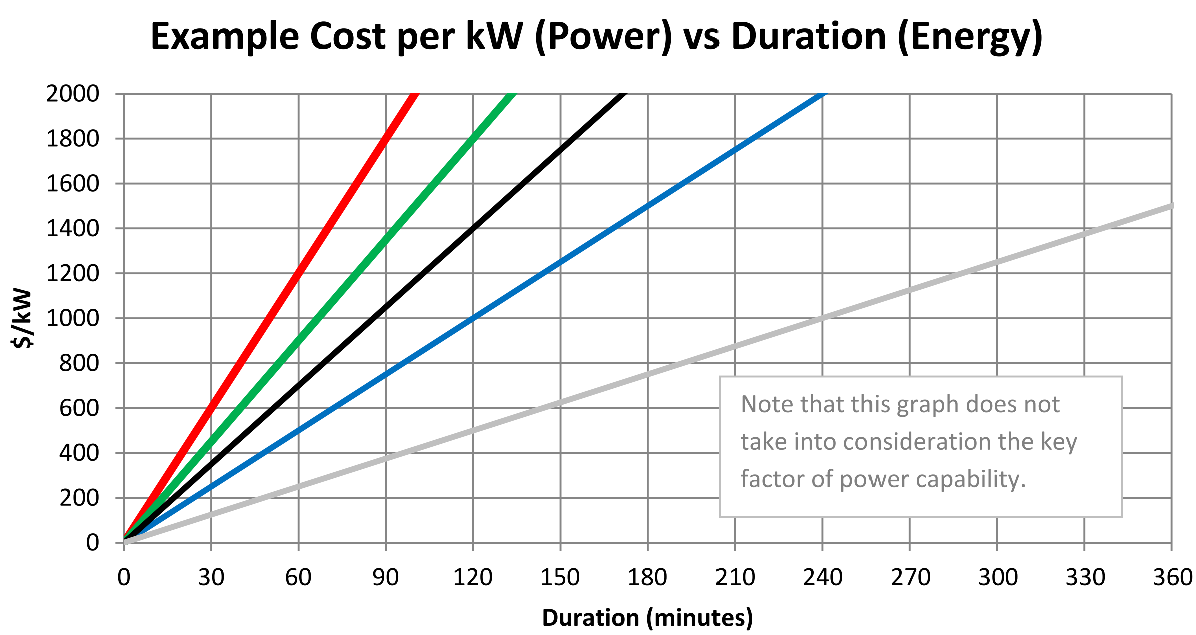
However, let's assume the application changes and the same energy storage system must now be enlarged for longer duration –perhaps another 60 minutes, or 50% more energy storage – but holding the power requirement constant at 1kW:

- System cost would increase to $1500
- The cost per kW is $1500/1kW = $1500/kW

- The cost per kWh is $1500/3kWh = $500/kWh
- Duration is now 180 minutes and a plot can be created showing this particular energy storage system's capability and cost over a range of durations.

Next, there are a **variety of different energy storage technologies** with various power costs at different durations. It is helpful to create an example graph to show how this works. Note that the values on this graph are not based on real systems, but instead are a blend of various types of energy storage technologies and example costs, for helping to understand how the cost comparison works. Each line on the graph represents a different energy storage technology.

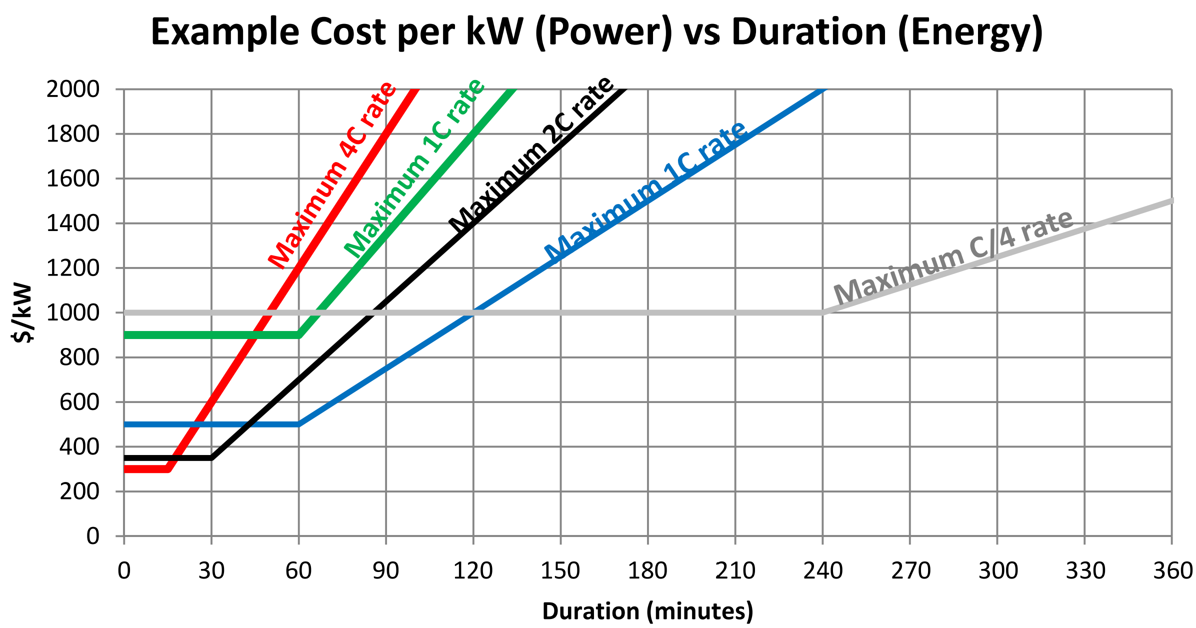
The following graph shows (in blue) the sample energy storage technology discussed earlier; at a two hour duration (i.e. 120 minutes), the power capability cost is $1000/kW and the energy storage capability cost is $500/kWh. Thus at different inherent normalized costs, the **slopes of these lines are equivalent to the energy storage capability cost**, and can vary with different technologies as shown below:



For instance while the blue line is $1000/kW and 120 minutes, the black curve is more expensive at $1400/kW at the same duration of 120 minutes – and one can follow the y-axis up or down at the 120 minute duration to see where it intersects the other colored plots. Similar comparisons can be made with the other example curves on this graph and one can easily deduce that the lowest cost energy storage device on this graph is the gray line, which is the least expensive at all durations, and is in actuality $250/kWh. However, **one key factor has not been considered** in the above graph.

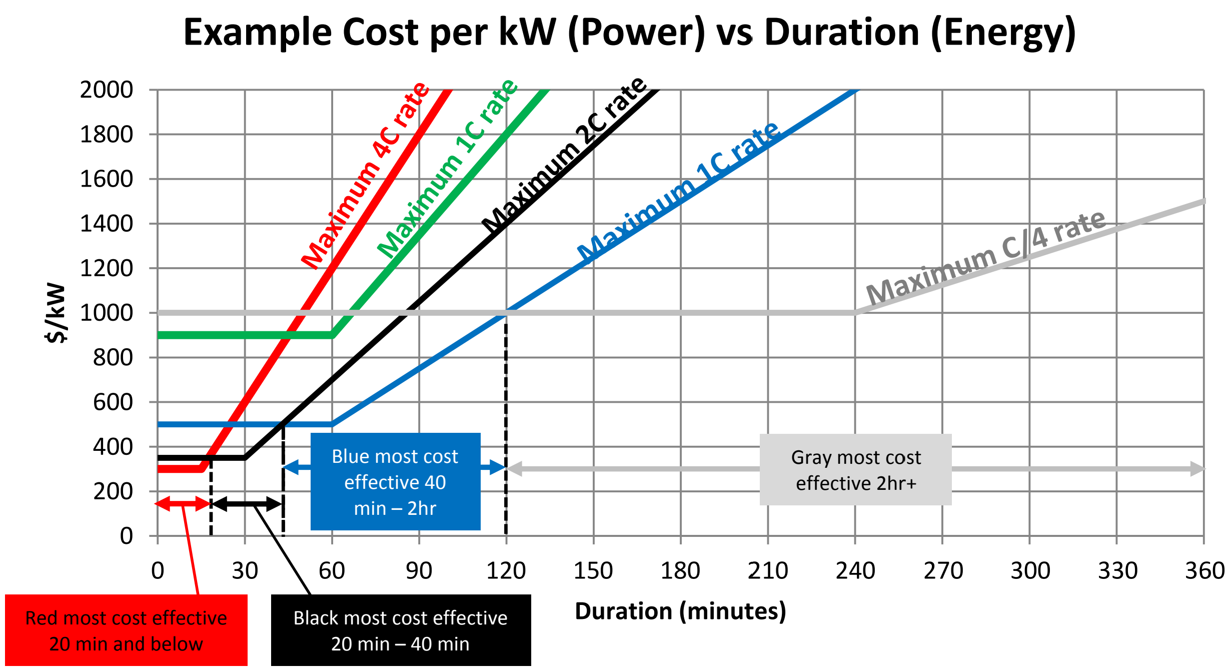
To realistically extend these cost curves down to shorter durations, the underlying energy storage technology must have a higher *power* capability – and not all energy storage technologies are capable of the high power capability necessary to get down to short duration like 30 minutes or 15 minutes. For instance, to achieve 1kW output power, some technologies may need to be sized at 1kWh (a 1:1: power:energy ratio), but others may need to be much larger – perhaps sized at 4kWh to be able to output 1kW and still deliver all the energy stored within (a 4:1 power:energy ratio). Yet other technologies that have a high power to energy ratio may only need 0.25 kWh to achieve that 1kW power output. Each technology has a certain power capability, also known as rate capability (defined by a metric called "C-rate"), which it typically cannot exceed without compromising the delivery of the energy stored, causing overheating, or abusing the storage technology in some way. This maximum C-rate capability will be different for various storage technologies.

After evaluating lots of different technologies within lithium ion battery chemistries and beyond into metal-air or flow batteries, one will find the following impact on the cost curves: a truncating of capabilities as certain energy storage technologies get into the high power range (which is essentially the left side of the graph).



Now, one can notice that after adjusting the plots for their power to energy capabilities, the interpretation of 'what is low cost' changes dramatically. For example, the gray plot (previously our lowest cost champion) is now modified by its maximum power to energy ratio or C rate of ¼ (0.25). This essentially means that for every kWh of energy storage, the maximum power output is one quarter of that, or 0.25 kW. Saying it another way: to achieve one kW of power output, the energy storage system must be 4 kWh in size. The effect this has on the cost curve is that now, to achieve a kW of power output, one must have 4 kWh, or basically 1kW for 4 hrs (240 minutes) of discharge duration. In other words, even if one only needed 60 minutes (1 kWh) of energy storage, but still need 1 kW of power output, one needs to 'oversize' the energy storage system to 4 kWh to achieve the 1 kW power capability. Thus the gray cost plot now goes flat and levels off at 240 minutes, since for it to achieve a 1kW power output capability, it must have 4kWh of energy storage capacity.

An interesting thing happens now as one looks at the other plots and their respective C-rate capabilities. Regarding the power cost, we find there are now different regions of best cost alternatives, depending on capabilities of the underlying energy storage technologies. As an example, if we again need the 1kW/1kWh energy storage for our application, we can now look at the 1 hr (60 minute) duration point, follow it upwards, and find that it first intersects with the blue curve, which is the lowest cost alternative on this graph at $500/kW. However expanding our vision to the entire range where the blue curve is the low cost alternative, we find if a storage device anywhere between about 40 minutes and 120 minutes is needed, the blue curve is the lowest cost. Only until energy storage at 2 hours is needed does the crossover point occur between blue and gray.



Why is this important? Considering a 1kW peak shaving application for instance, one might simply take the cost of energy storage ($250/kWh for gray and $500/kWh for blue) and conclude that gray is always better than blue. However this is only the case when the energy storage requirement is for *greater than two hours of storage.* If the requirement is just for one hour of peak shaving (and recalling that we need to shave 1kW of peak demand) – a blue system would cost less than a gray system since the blue system would be one quarter the size of the gray (blue being 1kWh, gray being 4kWh), even though the gray is half the cost from an energy storage capability perspective. Thus it is **always better to understand both of these metrics simultaneously** before trying to decide what is best for the energy storage application.

Lastly, one will notice that there is a green curve on the graph. This green curve is **never** the lowest cost alternative at **any** discharge duration along the x-axis. What could possibly be the use for this green energy storage technology? This has to do with yet another metric – related to cost – that has not been touched upon in this paper: cost over time. More details on this more thorough treatment of total cost of ownership of energy storage, also known as levelized cost of storage, can be found in a separate white paper, "Development and Practical Use of a Levelized Cost of Storage (LCOS) Metric".

Conclusions

Although the costs of energy storage technologies can be complex, there are methods that can help one understand them and effectively compare them against other available alternatives. First, it is imperative that we understand the application for which the energy storage will be used. In energy-based applications, we need to understand the costs with respect to how much energy the storage can contain; this is like buying a water tank based on its cost per unit volume. In applications such as peak shaving and load-shifting, the amount of **energy** that can be stored and redeployed at another time is the most valuable metric. In power-based applications, it is important to understand the costs with respect to how much power the energy storage can deliver at any given time; this is like buying a water hose and pump based on a cost per flow-rate metric. In applications such as frequency regulation and demand charge reduction, the rate of energy delivery and absorption (**power**) is the most valuable metric.

Graphing the costs per size of energy storage on a $/kW vs duration plot for a variety of different prospective energy storage technologies and products can help clarify just which option is suited for different applications. In such a plot, it is abundantly clear which product is lower cost for some applications, but not others, and how there may be no energy storage technology that is better than all others for all applications.

Finally, in any comparison regarding energy storage it is vital that we comprehend all the costs associated with the storage product not just upfront, but also over time. The costs include not just the energy storage, the balance of equipment around the storage, but the containment, installation, and ongoing maintenance and management, among other things, must be considered. A complete levelized-cost-of-storage tool can help insure that all factors are considered, from start to finish.

About the Authors

Roger Lin is Senior Director of Product Marketing at NEC Energy Solutions, where he leads the product management and global marketing group.

With over nine years of experience in energy storage technologies and applications, he has held a variety of roles and was responsible for several successful product development efforts including hybrid electric vehicle batteries, lithium ion cells, and grid energy storage systems.

Prior to that, he has held roles in venture capital, business development, and research and development. Roger received his Master of Engineering degree in Materials Science from MIT, his Bachelor of Science in Ceramic Engineering from Rutgers University, and is an inventor on nine United States patents.

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Before NEC Energy Solutions, Mr. Hoff served 18 years in various roles developing UPS products for American Power Conversion. This experience gave him broad exposure in energy storage technologies, power control, electronic controls and communications, manufacturing processes and the power market. Mr. Hoff holds a BS in Electrical Engineering and Power from Drexel University, and a MS in Electrical Engineering and Power from Northeastern University.