EPRI

2023 TECHNICAL UPDATE

Energy Storage Cost Metrics

Exploring the Usefulness of "Levelized Cost of Storage" and Other Metrics

Energy Storage Cost Metrics

Exploring the Usefulness of "Levelized Cost of Storage" and Other Metrics

3002028562

Technical Update, November 2023

EPRI Project Manager
M. Evans

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

EPRI PREPARED THIS REPORT.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Together…Shaping the Future of Energy®

ACKNOWLEDGMENTS

EPRI prepared this report.

Principal Investigator
M. Evans

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner: *Energy Storage Cost Metrics: Exploring the Usefulness of "Levelized Cost of Storage" and Other Metrics.* EPRI, Palo Alto, CA: 2023. 3002028562.

ABSTRACT

The Levelized Cost of Storage (LCOS) metric can be a useful basis for comparing energy storage system costs, meaningfully capturing roundtrip efficiency, upfront and ongoing costs, and lifetime in a single number. But capturing so many characteristics in a single number can mask differing attributes that would normally invalidate comparison, especially when the metric is presented to a lay audience or used in broad-reaching analysis. The LCOS metric does not include an indication of the value of a storage system's services or its duration, so its applicability for comparison is often limited to cases where the value, measured by duration and services, of the storage systems are similar. Because LCOS levelizes the total cost of owning and operating a storage system over energy discharged from the storage system, it is best suited for services that are based on energy discharged from the storage system rather than services that are based on readiness (reserves, backup power) or power contributions (regulation). Every calculation of LCOS depends heavily on background, inclusions or exclusions, methods, and assumptions, which require careful consideration.

Keywords

LCOS
LCOC
Energy Storage
Cost Metrics

CONTENTS

1 BACKGROUND AND PURPOSE

The Levelized Cost of Storage (LCOS) metric can be a useful basis for comparing energy storage system costs, meaningfully capturing roundtrip efficiency, upfront and ongoing costs, and lifetime in a single number. But capturing so many characteristics in a single number can mask differing attributes that would normally invalidate comparison, especially when the metric is presented to a lay audience or used in broad-reaching analysis. The LCOS metric does not include an indication of the value of a storage system's services or its duration, so its applicability for comparison is often limited to cases where the value, measured by duration and services, of the storage systems are similar. Because LCOS levelizes the total cost of owning and operating a storage system over energy discharged from the storage system, it is best suited for services that are based on energy discharged from the storage system rather than services that are based on readiness (reserves, backup power) or power contributions (regulation). Every calculation of LCOS depends heavily on background, inclusions or exclusions, methods, and assumptions, which require careful consideration.

In a perfect world, a metric serves as an indicator of what it intends to measure, directly informs decisions, and performs consistently across its domain of applicability. Nuance and complexity can shrink a metric's applicability beyond the bounds of usefulness but neglecting nuance when constructing a metric can render its decision-making power weakened by uncertainty. This balance is struck with every metric, including those that attempt to measure energy storage cost and value. This report will examine the levelized cost of storage (LCOS) metric, how it has been used, where its applicability ends, and potential alternatives.

What is "Levelized Cost of Storage"?

LCOS is an adaptation of the levelized cost of energy (LCOE) metric, which has been used broadly to compare the cost to generate each kWh of electricity with a generator. LCOE has been used to compare storage systems and solar plus storage systems in the past, to criticism mostly coming from the fact that energy storage is not a primary source of electricity. LCOE also does not indicate the value of the energy produced. When comparing between similar dispatchable generation or between two instances of the same kind of technology, this can be useful.

Whereas LCOE includes the present value of costs associated with owning and operating a generator and levelizes these costs over every kWh it is expected to generate over its lifetime, LCOS is adapted to include a similar set of costs (instead of variable costs like fuel, LCOS will typically include a charging electricity cost in $/kWh) and levelizes them over every kWh of electricity discharged from the storage system.

Energy storage systems do not return as much energy when they discharge as they consumed when charging thanks to a set of inefficiencies that are collectively called roundtrip efficiency. Two energy storage systems that cost the same amount of money to own and operate and charge from the same source of electricity may differ in LCOS thanks to differences in roundtrip efficiency. This is similar to the use of efficiency metrics for a fueled generator (e.g., heat rate) and a cost for fuel in the LCOE metric. That the energy source for storage is generally the same as the product (energy storage charges from and discharges electric power) is not important for the LCOS metric, but it can be very important when the value of the storage is considered (storage can generate value when charging as well as when discharging) or when case-specific considerations apply (recharging storage may be limited when there is a broader electricity shortfall).

Definitions for LCOS vary and the details of the definition do impact the applicability of the metric. Instead of providing an explicit calculation for LCOS, this report will generally use a qualitative description of the metric that comes from the Energy Information Administration (EIA), "the average revenue per unit of electricity … discharged that would be required to recover the costs of building and operating… a battery storage facility… during an assumed financial life and duty cycle". [1]

This report will exclusively cover definitions of LCOS that levelize costs over kWh of energy discharged, though some metrics called "LCOS" exist that levelize over kW of discharging power capacity. Here, these metrics are called "levelized cost of capacity" (LCOC) instead.

Why is LCOS an Appealing Metric for Comparing Energy Storage Systems?

If you are tasked setting a society-wide target for energy storage system costs, as the United States Department of Energy did [2] for "long duration stationary applications", how could you construct a useful metric? Energy storage systems differ from each other in enough ways that this would be a daunting task. Storage systems may have different roundtrip efficiencies $\left(\frac{Energy\ Discharged\ (kWh)}{Energy\ Charged\ (kWh)}\right)$, duration $\left(\frac{Energy\ Capacity\ (kWh)}{Discharging\ Power\ Capacity\ (kW)}\right)$, self-discharge rate (% of stored energy lost per hour), auxiliary loads (kW of power used for cooling, etc.), upfront costs, fixed ongoing costs, variable ongoing costs, the ability to independently size charging and discharging power capacities, startup time, maximum ramp rate, minimum power level and many more.

LCOS can meaningfully include many of these. It considers the costs of electricity for charging and other uses, which internalizes roundtrip efficiency losses because the metric levelizes over energy discharged. It also includes both upfront and ongoing costs over the expected lifetime of a system. This lends the metric well to engage with tradeoffs many storage systems face, like tradeoffs between upfront cost and roundtrip efficiency.

Is it Worthwhile to Consider Costs Without Considering Value?

Storage systems, in particular Lithium ion batteries, have been touted for their flexibility. But this means they are designed to serve a huge range of, sometimes very specific, use cases. Some storage systems are installed exclusively as backup power systems. Others serve short duration ancillary service needs. Others shift large quantities of energy based on wholesale electricity market prices. In each case, the storage system is designed to maximize the rate of return on the investment, be the least-cost/best-fit solution, or similar. This can mean choosing a solution that does not minimize overall costs or levelized costs – instead choosing a solution based on both cost and value.

The problem can arise when considering value in a metric. Unlike traditional generation, storage has a limited energy capacity, can run out of stored energy, and needs to recharge periodically. This creates a complicated value calculation that often relies on time series modeling to ensure the calculated value does not depend on the storage system over-committing itself.

Cost metrics like LCOS have been used to fill the gap left by difficult value calculations. When comparing two similar storage systems performing the same set of services, the value of the storage systems should be similar, leaving only the cost side to differentiate the two. LCOS is useful because it provides a platform for meaningfully comparing the costs of systems that differ in ways that defy direct comparison. LCOS can provide answers to questions like, "How much capital cost is a 1% improvement in roundtrip efficiency worth?", assuming the two systems provide the same value. LCOS reporting usually separates storage systems by use case and technology type to support meaningful comparisons.

The US EIA writes in their Annual Energy Outlook 2022, "Although LCOE [Levelized Cost of Electricity], LCOS, and LACE [Levelized Avoided Cost of Electricity] do not fully capture all the factors considered in NEMS [National Energy Modeling System], when used together as a value-cost ratio (the ratio of LACE-to-LCOE or LACE-to-LCOS), they provide a reasonable comparison of first-order economic competitiveness among a wider variety of technologies than is possible using LCOE, LCOS, or LACE individually." [3]

Caution should be applied, as will be discussed in Chapters 3 and 4, to avoid an all-too-easy scenario where the LCOS metric is used to compare across storage systems that are dissimilar in the wrong ways.

How has LCOS Been Used?

The United States Department of Energy (DOE) publicized an industry-wide target of $0.05/kWh LCOS, along with their own calculator and has included a selection criteria in funding opportunity announcements that evaluates "The degree to which the proposed project provides a reasonable pathway to achieving DOE's aggressive levelized cost of storage (LCOS) goal of $0.05/kWh". [4]

LCOS is sometimes used is for screening energy storage technology types as a step to reduce computational intensity before a capacity planning modeling exercise or similar. Metrics like LCOS present a convenient and straightforward basis for ranking energy storage systems or types of energy storage, but care should be taken to avoid misrepresentation.

In some publications, LCOS has been used to try to identify what storage technology types will be most viable in the future for specific services based on cost projections.

2 METHODOLOGY-BASED LIMITS ON USEFULNESS

As alluded to earlier in this paper, there are potential pitfalls when trying to use a metric like LCOS to compare between storage systems or storage types. Many definitions of LCOS have been published by organizations and individuals. Lazard, who introduced the metric in 2015, describes it as, “solving for the $/MWh value that results in a levered IRR [internal rate of return] equal to the assumed cost of equity”. [5]

In practice, this calculation depends on assumptions beyond the storage system itself, including financing assumptions like debt-to-equity ratio, cost of debt, cost of equity, tax rates, etc. In addition, the definition of LCOS necessarily makes decisions about what calculations to include and how to perform those calculations. Examples include how much the storage system is operated (kWh discharged per year), fixed and variable O&M costs, auxiliary load, degradation, residual value/cost at end of life, etc.

Others have published definitions in varying degrees of complexity. This section will examine common methodological considerations for calculating LCOS to establish a framework for understanding the applicable domain of the LCOS metric.

Fixed Cycling Assumptions

LCOS is a metric that levelizes system costs over kWh of energy discharged from the storage system and every definition of LCOS needs to establish how much the storage system will be used each year (kWh discharged/year). Real energy storage systems operate in response to a variety of stimuli and do not tend to operate the same amount every year, but a fixed assumption is required for the LCOS metric.

The amount a storage system is operated can depend strongly on the services it is engaged in during any given year. A storage system that spends most of the time either charging or discharging to perform a bulk energy shifting application may be operated much more than a system that is operated only for backup power or transmission/distribution asset upgrade deferral.

There are fundamental limits on how much a storage system can be operated in a year based on the hours available in the year and the roundtrip efficiency of the storage system. A hypothetical, 100% efficient storage system could spend up to half of the year charging and the other half discharging. Real storage systems have roundtrip efficiencies less than 100%, though, and need to spend longer charging than discharging (assuming charging power capacity equals discharging power capacity). A Lithium ion system with a roundtrip efficiency of 85% could spend up to 4,735 hours[1] in a typical year with 8,760 hours charging and the remaining 4,025 hours discharging. A thermal energy storage system with a roundtrip efficiency of 35% would need to spend a much longer time charging for each hour of discharging and could spend up to

[1] $8760\ hrs = Charging\ Time + Discharging\ Time$ $Discharging\ Time = RTE * Charging\ Time$

6,489 hours charging and 2,271 hours discharging. Clearly, these two systems have different bounds on the amount of energy they can discharge in a year given their different roundtrip efficiencies.

Methods like the DOE's calculator assume that the storage system cycles continuously without rest (as in the calculations above) and can adapt to systems with different roundtrip efficiencies, but this results in unrealistic cycling (it is unlikely that a storage system would spend all year charging and discharging in most cases – a much lower capacity factor is more likely). This approach also has the effect of decoupling LCOS from the services the storage system will provide, making LCOS an attribute of the storage system itself (with associated finance assumptions, etc.) instead of an attribute of the storage system in a particular use case. This is not reflected in most LCOS publications, which publish results separately for different use cases. Other LCOS definitions treat the annual energy discharged from the storage system as an input and it is left to the user of the metric to ensure their assumptions are feasible.

One final approach is to assume a fixed number of cycles per day. This is similar to the fixed energy throughput assumption but is modified by the duration of the storage system. This could cause confusion if the LCOS metric is used to compare between storage systems that have a different duration (see Storage Duration) because longer-duration systems with the same power capacity will discharge more energy per cycle.

If the calculation assumes a set amount of energy discharged per year or a fixed number of cycles per day, this quantity should be based on the services the storage system is providing and care should be taken to **avoid using the LCOS metric to compare between storage systems that will be operated significantly differently. Otherwise, the LCOS metric will seemingly favor the system that is operated more (which would result in a lower LCOS, everything else being equal).**

Note: LCOS calculations levelize costs over kWh of energy discharged from the storage system and this energy throughput is independent from the charging power capacity of the storage system. Some types of energy storage use different equipment to charge and discharge the system, so can have different charge and discharge power capacities. This can result in cases where the storage can charge much more quickly than it can discharge, for example, breaking the limit on energy throughput described above. Optimizing charge and discharge power capacities independently can improve the benefit to cost ratio of a storage system, but since value is not considered in LCOS, only changes in cost will impact most LCOS calculations.

Storage Duration

The duration of a storage system is not typically a direct input to a LCOS calculation, though it can be included in things like the DOE calculator for estimating energy throughput. Many LCOS reports separate storage systems by technology and by the set of services it provides, which can also naturally group storage systems by duration. **Using LCOS to compare across storage systems that differ significantly in duration can result in faulty conclusions because storage**

energy capacity contributes to overall cost and functionality but is not necessarily associated with the energy throughput. This can lead to conclusions that erroneously favor shorter-duration storage systems with a lower LCOS because the value of additional duration is not considered in the LCOS metric.

Degradation

Many kinds of storage degrade over their useful life. Most notably, the usable energy capacity of Lithium ion battery energy storage systems can decrease with use and with time. Some definitions of LCOS include this effect by reducing the kWh of energy discharged each year over the life of the system. Other definitions assume the usable energy capacity of the system is constant over the life of the system. Still others will include augmentation and replacement costs in the ongoing costs of the system while keeping the usable kWh of energy capacity constant.

For Lithium ion batteries, use and lifetime are not independent. Care should be taken to **ensure that the assumed lifetime of the storage system, with augmentation or replacement where appropriate, matches the assumed operational profile**. If a Lithium ion battery system is continuously cycled, as is used to generate the kWh of energy discharged per year in the DOE calculator, it will likely degrade and reach its end of life quickly. Alignment between the annual energy discharged and the lifetime is important for the LCOS metric to retain its meaning, but some comparisons may still be drawn between storage systems using a LCOS metric that does not align use with lifetime.

Charging Cost Assumptions

Whereas LCOE metrics include fuel costs where applicable, LCOS metrics usually include a charging cost ($/kWh of energy charged). Including this is important to retain the meaning of the metric as the sale price of electricity needed to break even because the electricity used to charge storage systems is generally not valueless. This is usually included in LCOS as a single number or a single number in real terms, though it may be escalated through the life of the storage in other cases.

Unless a storage system charges from electricity based on a retail tariff, power purchase agreement, or similar arrangement that fixes the value of electricity, it will likely charge from electricity that takes a range of values depending on the wholesale value of electricity. It is usually left to the user of the metric to determine the appropriate assumption for the charging cost, which could be an energy-weighted average of the value of electricity expected over the system's life.

But this raises questions when comparing storage systems with different durations or that are performing different services. A high-efficiency storage system may be able to charge for an hour or two each day during the least-cost times for electricity. But a low-efficiency system may need to charge for much longer to achieve the same amount of discharge energy and may need to do so when the cost of electricity is higher. Additionally, a storage system that is performing services requiring operation at times not aligned with electricity cost fluctuations may charge from higher cost electricity than one whose primary service is to shift energy from low-cost times to high-cost times.

A potential misrepresentation can also occur when the storage is assumed to charge from energy with zero or negative cost. In cases where the charging cost of electricity is negative, a lower efficiency storage system has a more desirable LCOS than a higher efficiency system. This potential conclusion neglects the value component of decision making, which still may favor the higher efficiency system.

Escalation and Discounting

LCOS calculations can differ in their approach to escalating costs over the life of the system and discounting costs or energy throughput to present. The simplest approaches involve no escalation or discounting at all. These calculations simply divide the total upfront costs of the system by the total number of kWh expected to be delivered by the storage over its life and add any variable and charging costs to this number. Most calculations do include some form of escalation and discounting, like they do for LCOE.

Definition of Variable Operation and Maintenance Costs

Several approaches are used to bring variable operation and maintenance costs into LCOS. In simpler calculations, this is excluded entirely, or it is left to the user to include variable costs into the charging cost assumption. Variable operation and maintenance costs are usually expressed in $/kWh of energy discharged and can be directly added to the charging cost assumption when adjusted for roundtrip efficiency. Other calculations include an explicit representation of variable operation and maintenance costs, which usually appears alongside charging costs as another cost that scales with kWh of energy discharged.

Some LCOS definitions include repowering or replacement costs into the variable operation and maintenance cost, which is a way to levelize these costs over discharged energy. Others rely on good estimations of the life of the system and upfront costs, so do not need to include repowering or replacement in variable operation and maintenance costs or anywhere else. Either method can appropriately capture the impact of repowering and replacement on LCOS.

Finally, some methods include operations costs in LCOS but leave out repowering and replacement costs, as above.

If comparisons being drawn between storage systems using LCOS include variable operation and maintenance, repowering, and replacement costs consistently and that these fully represent the total cost of owning and operating the storage, variable operation and maintenance cost methods should not restrict the applicability of LCOS.

Storage Services

Most reports involving LCOS distinguish sets of services or use cases and do not use LCOS to compare across use cases. **Because the services a storage system provide can dramatically influence how much energy throughput the storage system experiences in a year and can influence design decisions like the duration of the storage system, it is usually not possible to use LCOS to compare between storage systems providing different sets of services.**

Some services lend themselves better to comparison with LCOS than others. In the simplest energy time shifting applications, LCOS may be useful to draw comparisons between storage systems with similar durations. Frequency regulation, on the other hand, might present a bigger hurdle for comparison using LCOS. In cases like this, the energy throughput assumptions used to calculate LCOS can be harder to generate and since energy throughput is not the primary source of value for the storage system, it is less relevant as a basis for levelizing costs.

3 ALTERNATIVES

Energy storage system costs are often represented by a set of metrics, including upfront capital cost (often normalized to $/kW or $/kWh), fixed ongoing costs, variable ongoing costs, and end of life costs rather than a single metric. Charging costs may be left to the value analysis later. Representing costs this way can be useful, but this presents some challenges for comparing storage systems that are not technically similar. Determining if it is better to explore high-cost, high-efficiency systems or low-cost, low-efficiency systems might be a challenge here, or navigating tradeoffs, like those between lifetime and upfront capital cost.

LCOS fills some of the gaps left by these approaches. By combining all components of the total cost of ownership into a single number with charging cost (and therefore roundtrip efficiency), meaningful comparisons can be made, but the metric is not applicable to all types of comparisons.

Storage systems can provide value through a broad range of services, only some of which are based on the quantity of energy discharged by the system. Storage systems that are designed and built for other purposes may not be well-served by a metric based around the quantity of energy delivered from the system. Some storage systems generate a large portion of their value through ancillary services. For these systems, measuring costs against the quantity of an ancillary service they provide ($/kW-hr instead of $/kWh) or Levelized Cost of Capacity ($/kW-yr) may be more useful. Similarly, resource adequacy capacity contributions could indicate the use of a Cost of New Entry ($/kW-yr adjusted for resource adequacy capacity contribution) metric instead of LCOS.

Other storage systems may be installed for the purposes of deferring investment in additional transmission or distribution infrastructure. In these cases, an economic carrying cost metric might be more useful as a more direct point of comparison to traditional infrastructure, assuming all systems being compared have been sized to meet the same need. In other utility planning scenarios, where the solution selected will be the least-cost solution that solves a very particular need, the best cost metric to use may simply be the present value cost.

4 CONCLUSIONS

The LCOS metric is appealing as a simple, one-dimensional metric for comparing energy storage systems and stands out among other cost metrics in its ability to capture important characteristics of storage cost and performance. But the underlying complexity of the calculation can mean that an audience digesting LCOS results may reach unintended conclusions without good study design and documentation. A full analysis that captures the costs and value of each system is the most relied-on option, but requires detailed modeling, good forecasts for the services the systems will provide, and a lot of work. Excluding the value side from this analysis and looking at costs alone can reduce the barriers to producing a comparison significantly.

LCOS results should only be used as a basis for comparison between storage systems that are similar in duration and in the services they will provide. Adding energy capacity adds both value and cost, but only the cost is considered in the LCOS metric.

Despite being a metric that expresses costs, not value, LCOS is generally inseparable from the services a storage system will provide because of the impact the services have on design and operation. Different services will dictate different amounts of annual energy throughput over which costs are levelized.

The field of battery energy storage has grown broad enough that there are naturally many ways of accounting for the costs of battery degradation – an important implicit component of LCOS. Whether the LCOS method mimics oversizing (increased upfront costs with a realistic lifetime), augmentation (increased fixed or variable ongoing costs), replacement (discounted future payments to replace system components), or other, the cost of degradation should not be double counted and should fully capture the expected life cycle costs of the system.

Energy storage systems can have technical attributes like a fuel or waste heat input or the ability to independently size charging and discharging power capacity that are not fully captured by the LCOS metric.

5 REFERENCES

1. https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf
2. https://www.energy.gov/energy-storage-grand-challenge/articles/energy-storage-grand-challenge-roadmap
3. https://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf
4. https://www.energy.gov/oced/funding-notice-long-duration-energy-storage-demonstrations
5. https://www.lazard.com/media/nltb551p/lazards-lcoeplus-april-2023.pdf

Export Control Restrictions

Access to and use of this EPRI product is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or U.S. permanent resident is permitted access under applicable U.S. and foreign export laws and regulations.

In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI product, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI products, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes.

Your obligations regarding U.S. export control requirements apply during and after you and your company's engagement with EPRI. To be clear, the obligations continue after your retirement or other departure from your company, and include any knowledge retained after gaining access to EPRI products.

You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of this EPRI product hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

Program:

Energy Storage & Distributed Generation

3002028562

EPRI
3420 Hillview Avenue, Palo Alto, California 94304-1338 USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com