Energy Storage Cost and Performance Assessment LCOS Workbook v.2024 Documentation

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1 Introduction

The methodology in this documentation uses many calculations found in Short, et al. [1], with modifications made to account for specific storage aspects (e.g., costs due to round trip efficiency [RTE] losses). The LCOS is determined as the average $/kWh value that energy discharged from the storage system must be sold at to recover total project revenue requirements over the analysis period.

The analysis period (number of years over which costs are recovered) of the storage system may be different than the project life (the number of years for which the storage system is in operation). To account for this difference, residual value is estimated based on the additional revenue generated after the analysis period until the end of the system's project life. This energy is assumed to be sold at a $/kWh price equal to the LCOS. The residual value formula derivation is provided in Appendix A.

This page documents the formulas and equations used within the LCOS workbook directly as well as formulas used to develop various inputs into the calculator (e.g., storage augmentations and replacements). Note that, for simplification, the LCOS calculator assumes that storage systems are operational in year 1.

2 LCOS

2.1 LCOS Formulation

The LCOS is determined as the average $/kWh value that energy discharged from the storage system must be sold at to recover total project revenue requirements over the analysis period. Therefore, the total present value of all storage project revenue requirements across the analysis period (inclusive of taxes, depreciation, and other components) less the present value of any residual value (RV) at the end of the analysis period (N) must equal the total present value of the LCOS ($/kWh) multiplied by the energy output (kWh) in each given year of the analysis period (Equation 1).

$$\sum_{n=0}^{N} \frac{Revenue\ Requirement_n(\$)}{(1+WACC)^n} - \frac{RV_N(\$)}{(1+WACC)^N} = \sum_{n=0}^{N} \frac{Annual\ Energy\ Output_n\,(kWh) \times LCOS\ (\$/kWh)}{(1+WACC)^n} \quad (1)$$

From Equation 1, we can solve for LCOS (Equation 2).

$$LCOS\ (\$/kWh) = \left[\sum_{n=0}^{N} \frac{Revenue\ Requirement_n\ (\$)}{(1+WACC)^n} - \frac{RV_N(\$)}{(1+WACC)^N}\right] \times \left[\sum_{n=0}^{N} \frac{Annual\ Energy\ Output_n(kWh)}{(1+WACC)^n}\right]^{-1} \quad (2)$$

Where,

Term	**Definition**	**Formula**
N	Analysis period (years)	
n	Year of analysis period	
WACC	Weighted average cost of capital	$[DebtFraction \times i \times (1-t)] + [(1-DebtFraction) \times Cost\ of\ Equity]$
RV_N	Residual value at N ($)	See residual value section
i	Interest rate (%)	
t	Combined federal and state tax rate (%)	

2.2 Revenue Requirements

Revenue requirements include the total revenue that must be realized to recover all costs associated with the project. This includes all overnight capital costs (OCC), project financing (e.g., interest paid on debt used to finance capital), operations & maintenance (O&M) costs, tax depreciation, investment tax credits (ITC), costs to charge the storage system inclusive of round-trip efficiency (RTE) losses, and any augmentation, replacement, or major overhaul (ARMO) costs incurred to maintain operation. Equation 3 shows the net present value of revenue requirements.

$$Net\ Present\ Value\ of\ Revenue\ Requirements = \sum_{n=0}^{N} \frac{Revenue\ Requirement_n}{(1+WACC)^n} \quad (3)$$

The net present value of each cost component (note that OCC is already in present value since it is incurred in time 0) is calculated and then annualized to give the annualized revenue requirement (ARR) which determines the constant annual payment that much be made each year the analysis period to cover all costs (Equation 4)

$$Revenue\ Requirement_n = ARR =$$

$$(FCR \times OCC) + \left(CRF \times \sum_{n=0}^{N} \frac{O\&M_n + Warranty_n + ECC_n + ARMO_n + Decommissioning_n}{(1+WACC)^n}\right) \quad (4)$$

Where,

Term	Definition	Formula
N	Analysis period	
n	Year of analysis period	
OCC	Overnight capital cost ($)	
$WACC$	Weighted average cost of capital	
FCR	Fixed charge rate	$\frac{CRF\left[1-(t\times PVD_{MACRS})\times\left(1-\frac{ITC}{2}\right)-ITC\right]+p_1+p_2}{(1-t)}$
t	Combined federal and state tax rate (%)	
PVD_MACRS	Present value of depreciation following appropriate MACRS schedule	
ITC	Investment tax credit (%)	
$p1$	Property tax (as a % of capital)	
$p2$	Insurance (as a % of capital)	
CRF	Capital recovery factor	$\frac{WACC}{1-(1+WACC)^{-N}}$
$O\&M_n$	Total operations & maintenance costs incurred in year n ($)	$[FOM_n \times Rated\ Power\ (kW)] + [VOM_n \times AEO_n]$
ECC	Electricity charging cost inclusive of costs due to RTE losses	$\frac{Electricity\ Cost}{RTE} \times AEO_n$
RTE	Round trip efficiency (%)	
$ARMO_n$	Augmentation, replacement, and major overhaul costs incurred in year n ($)	
$Warranty_n$	Warranty costs in year n ($)	
$Decommissioning_n$	Costs for any disconnection, disassembly, removal, and site remediation in year n ($)	
FOM_n	Fixed O&M ($/kW-year)	
VOM_n	Variable O&M ($/kWh discharged)	

Term	Definition	Formula
AEO_n	Annual energy output (kWh) at specified depth of discharge	$Cycles\_per\_day_{DOD} \times 365 \times Storage\ Rated\ Energy \times DOD$
DOD	Depth of discharge (%)	
$Cycles\_per\_day_{DOD}$	Maximum cycles per day at specified DOD	$min\left(\frac{24}{CT + Rest_c + DT + Rest_d}, \frac{1}{DOD} * \frac{Annual\_cycle\_limit}{365}\right)$
$Annual\_cycle\_limit$	Maximum allowed cycles at 100% DOD per year based on warranty or other restrictions.	
CT	Charge time (hrs)	$CT = \frac{DT}{RTE}$
DT	Discharge time (hrs)	$DOD \times Storage\ Duration$
$Rest_c$	Rest time after charge (hrs)	
$Rest_d$	Rest time after discharge (hrs)	

The present value of depreciation uses the Modified Accelerated Cost Recovery Schedule (MACRS). Batteries not charged with solar resources >75% of the time qualify for a 7-year MACRS depreciation schedule [2]. For non-batteries, projects with initial "clearing and grading land improvements with respect to any electric utility transmission and distribution plant" [3] are assumed to be 20-year properties.

When the ITC is claimed, the accelerated depreciation rules allow for the full tax basis less half the ITC to be depreciated [4]. Energy storage is eligible for the ITC so long as it is >5 kWh and applies whether projects are paired with solar or standalone [5]. The amount of the ITC is variable depending on several factors. If the project is either < 1 MW or ≥ 1 MW but also meets the prevailing wage and apprenticeship requirements, the base ITC is 30%. Otherwise, if the project is ≥ 1 MW but does not meet the prevailing wage and apprenticeship requirements, the base ITC is 6%. Additional adders (Energy Community Adder and Domestic Content Adder) are included in the base ITC for projects that qualify. If the project qualifies, each adder offers an additional 10% credit if the project is either < 1 MW or ≥ 1 MW but also meets the prevailing wage and apprenticeship requirements. If the project is ≥ 1 MW and does not meet the prevailing wage and apprenticeship requirements, the adder is 2%. For full details on the requirements and specifications, refer to the Inflation Reduction Act [6] and the tax code.

2.3 Augmentations, Replacements, and Major Overhauls

Augmentations, replacements, and major overhauls (ARMO) are significant capital expenditures necessary to continue operation of the storage system at the specified depth of discharge across its project life. What type of ARMO and at what frequency they occur will depend on multiple factors including the storage technology type, the cycle life (if it is a battery storage system), and others. The subsections that follow describe some of the types that can occur and how they might be calculated.

2.3.1 Fixed Replacements

For some technologies, various components of the storage system are replaced at fixed intervals, typically equal to the component's calendar life. The replacement schedule for these components is equal to as many replacements required prior to the end of the project life. For example, if the project life (years for which it is operational) of a storage system is 60 years and the power equipment has a life of 30 years, then there is one replacement cost incurred in year 30 equal to the cost of the power equipment.

2.3.2 Storage Block Replacements Corresponding to Cycle Life

For some batteries, such as Lead Acid and Zinc energy storage systems, it is assumed that the DC storage block (DC SB) must be replaced when available energy reaches 80% of rated energy or at the end of its calendar life, whichever occurs first. Equation 5 below shows how this timestep is calculated.

$$\text{DC SB Replacement Timestep} = \min\left(\frac{Cycle\ Life\ at\ Specified\ DOD}{Cycles\ per\ year\ at\ DOD},\ calendar\ life\right) \quad (5)$$

Note that, for simplification purposes in the LCOS calculator, these timesteps are rounded to the nearest integer year value.

As an example, for a system with a replacement timestep of 7 years and a calendar life of 12 years, the storage block would be replaced every 7 years of operation.

2.3.3 Storage Block Augmentation

For some systems, augmentation rather than replacement is assumed when available energy reaches the discharge energy corresponding to DOD. For lithium ion, for example, it is assumed that the DC SB is operated at an average DOD of 80% at the beginning of the project and 60% once the first augmentation occurs to capture remaining available energy. Additional augmentations are done each time the available energy of a DC SB reaches 60% of rated energy. The amount of augmentation required for each augmentation considers available energy of the DC SB and the additional energy needed to ensure the required discharge energy at 80% DOD based on rated energy of the non-augmented battery is available at 60% DOD based on rated energy of the augmented battery. For lithium-ion systems it is assumed that the DC SB used for the last augmentation will have some useful energy remaining or available at the end of the project life that remains unused. Note that if the calendar life of the storage system is reached before the first augmentation is required, then the storage block is replaced at the calendar life and no augmentation occurs. If the calendar life of the storage system occurs after the augmentation but before the remaining cycle life of the first storage block operated at 60% DOD occurs, then the storage block is replaced at the calendar life and its replacement is assumed to operate at 60% DOD.

Equation 6 through 9 show various components required to determine when augmentation occurs and when subsequent replacements occur using an example of an 80% primary DOD, a 60% secondary DOD, and an assumed end of life of 60% of rated energy.

$$\text{Primary DC SB augmentation year} = \frac{Cycle\ Life\ at\ 80\%\ DOD}{Cycles\ per\ year\ at\ 80\%\ DOD} \quad (6)$$

$$\text{Cycles remaining in primary DC SB} = \left(1 - \left(\frac{1-0.80}{1-0.60}\right)\right) \times Cycle\ Life\ at\ 60\%\ DOD \quad (7)$$

$$\text{Years remaining in primary DC SB at augmentation} = \frac{Cycles\ remaining\ in\ primary\ SB}{Cycles\ per\ year\ at\ 60\%\ DOD} \quad (8)$$

$$\text{Cycle years of secondary DC SB} = \min\left(\frac{Cycle\ Life\ at\ 60\%\ DOD}{Cycles\ per\ year\ at\ 60\%\ DOD},\ calendar\ life\right) \quad (9)$$

$$\text{Augmentation fraction} = \frac{primary\ DOD\ (\%) - secondary\ DOD\ (\%)}{secondary\ DOD\ (\%)} \quad (10)$$

Following the above, the primary storage block will be augmented starting at the *Primary DC SB augmentation year* and again every *Cycle years of secondary DC SB*. The amount that is augmented corresponds to the *Augmentation fraction* where the cost of augmentation corresponds to the augmentation fraction multiplied by the DC SB cost. Storage blocks will get replaced starting when the primary DC SB is offline or at the calendar life, whichever occurs first, and repeated every *Cycle years of secondary DC SB* throughout the remainder of the project life.

For a diagram of these augmentation and replacement timesteps, see Figure 6.1 in the 2022 Grid Energy Storage Technology Cost and Performance Assessment report.

2.3.4 Replacements Based on System Charge or Discharge Hours

For some energy storage systems, components are replaced based on the number of hours they are operated for as either a charging or discharging component. For hydrogen systems, for example, the fuel cell stack is assumed to be replaced every 40,000 operating hours. Since the fuel cell stack is associated with the discharging of the hydrogen energy storage system. It is replaced every 40,000 discharge hours. For the electrolyzer, it is assumed to be replaced every 60,000 operating hours, corresponding to charging hours.

2.4 Residual Value

RV is defined as the discounted sum of the required revenue generation from the end of the analysis period to the end of the project life. The equation below is used to calculate the RV at time N. N denotes the years for the analysis period, L denotes the number of years of project life, and PCI is the capital costs inclusive of any ITC and depreciation deductions. For more detail and the derivation of the RV formula shown below, see Appendix A.

$$RV = (1+WACC)^N \left[\left(1 - \frac{\sum_{n=0}^{N} \frac{AEO_n}{(1+WACC)^n}}{\sum_{l=1}^{L} \frac{AEO_l}{(1+WACC)^l}} \right) PCI + \sum_{n=0}^{N} \frac{C_{on}}{(1+WACC)^n} - \left(\frac{\sum_{n=0}^{N} \frac{AEO_n}{(1+WACC)^n}}{\sum_{l=0}^{L} \frac{AEO_l}{(1+WACC)^l}} \right) \left(\sum_{l=0}^{L} \frac{C_{ol}}{(1+WACC)^l} \right) \right] \tag{10}$$

2.5 Assumptions and Financial Parameters

Various financial parameters are used in the LCOS calculator and are listed below along with their references.

Parameter	Value	Reference
Inflation rate	2.80%	[7]
Interest rate – nominal	8.00%	[8]
COE - nominal	13.00%	
Debt fraction	50.0%	
Tax rate (Federal and State)	25.7%	[9]
Property tax rate	0.84%	[10]

Parameter	Value	Reference
Insurance rate	0.4%	[11]
Fixed O&M cost escalation rate - real	2%	

The property tax rate refers to the population weighted average industrial personal property tax rate for the largest city in each US state [10].

2.5.1 Technological Parameters

For battery energy storage systems that are providing DC RTE values, the inverter and transformer are each assumed to have a one-way RTE of 98% ($.98^2$ bidirectional), following estimates outlined in Viswanathan, et al. [12]. For hydrogen energy storage systems that provide DC RTE values, the unidirectional inverter is assumed to have a one-way efficiency of 98% and the rectifier is assumed to have a one-way efficiency of 98%.

3 References

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Appendix A – Derivation of Residual Value Formula

Let L = Project lifetime (e.g., 40 years)
Let N = Analysis period (e.g., 15 years)
AEO_t = Annual energy output
Let d = Discount rate
Let C_c = Capital costs
Let C_{ot} = Operating costs at time t. Operating costs include operations, maintenance, ARMO, charging, and anything else not included in the initial construction.

For the full lifetime, L, of a project, the LCOS can be defined as:

$$LCOS = \frac{\sum_{l=0}^{L} \frac{C_c}{(1+d)^l} + \sum_{l=0}^{L} \frac{C_{ol}}{(1+d)^l}}{\sum_{l=0}^{L} \frac{AEO_l}{(1+d)^l}}$$

This can also be expressed with a residual value at the end of the analysis period, t=N. For this equation, the project will have completed payoff of financing, but will still have lifetime N-L years of operation to generate revenue and incur operating costs.

$$LCOS = \frac{\sum_{n=0}^{N} \frac{C_c}{(1+d)^l} + \sum_{n=0}^{N} \frac{C_{on}}{(1+d)^n} - \frac{RV}{(1+d)^N}}{\sum_{n=0}^{N} \frac{AEO_n}{(1+d)^n}}$$

Setting the LCOS at the end of the analysis period inclusive of residual value to the LCOS over the project life equal to each other yields:

$$\frac{\sum_{l=0}^{L} \frac{C_c}{(1+d)^l} + \sum_{l=0}^{L} \frac{C_{ol}}{(1+d)^l}}{\sum_{l=0}^{L} \frac{AEO_l}{(1+d)^l}} = \frac{\sum_{n=0}^{N} \frac{C_c}{(1+d)^n} + \sum_{n=0}^{N} \frac{C_{on}}{(1+d)^n} - \frac{RV}{(1+d)^N}}{\sum_{n=0}^{N} \frac{AEO_n}{(1+d)^n}}$$

The capital costs (OCC) are only paid in year 0, so we can remove the summation on both sides and denote them as PCI, the capital costs inclusive of any ITC and depreciation deductions [1]. $\mathrm{PCI} = \mathrm{OCC} \times (1 - (\mathrm{t} \times \mathrm{PVD\_MACRS})(1 - \mathrm{ITC}/2) - \mathrm{ITC})$. This gives:

$$\frac{PCI + \sum_{l=0}^{L} \frac{C_{ol}}{(1+d)^l}}{\sum_{l=0}^{L} \frac{AEO_l}{(1+d)^l}} = \frac{PCI + \sum_{n=0}^{N} \frac{C_{on}}{(1+d)^n} - \frac{RV}{(1+d)^N}}{\sum_{n=0}^{N} \frac{AEO_n}{(1+d)^n}}$$

We need to solve for the residual value, RV. Multiply both sides by the denominator of the right hand side (RHS), $\sum_{n=0}^{N} \frac{AEO_n}{(1+d)^n}$, and group it with the denominator of the left hand side (LHS).

$$\left(\frac{\sum_{n=0}^{N} \frac{AEO_n}{(1+d)^n}}{\sum_{l=0}^{L} \frac{AEO_l}{(1+d)^l}}\right)\left(PCI + \sum_{l=0}^{L} \frac{C_{ol}}{(1+d)^l}\right) = PCI + \sum_{n=0}^{N} \frac{C_{on}}{(1+d)^n} - \frac{RV}{(1+d)^N}$$

Next, bring the term containing RV to the LHS and all other terms to the RHS:

$$\frac{RV}{(1+d)^N} = PCI + \sum_{n=0}^{N} \frac{C_{on}}{(1+d)^n} - \left(\frac{\sum_{n=0}^{N} \frac{AEO_n}{(1+d)^n}}{\sum_{l=0}^{L} \frac{AEO_l}{(1+d)^l}}\right)\left(PCI + \sum_{l=0}^{L} \frac{C_{ol}}{(1+d)^l}\right)$$

Next, solve for RV by multiplying both sides by $(1+d)^N$

$$RV = (1+d)^N\left[PCI + \sum_{n=0}^{N} \frac{C_{on}}{(1+d)^n} - \left(\frac{\sum_{n=0}^{N} \frac{AEO_n}{(1+d)^n}}{\sum_{l=0}^{L} \frac{AEO_l}{(1+d)^l}}\right)\left(PCI + \sum_{l=0}^{L} \frac{C_{ol}}{(1+d)^l}\right)\right]$$

Finally, simplify the expression by combining the two terms with PCI:

$$RV = (1+d)^N\left[\left(1 - \frac{\sum_{n=0}^{N} \frac{AEO_n}{(1+d)^n}}{\sum_{l=0}^{L} \frac{AEO_l}{(1+d)^l}}\right)PCI + \sum_{n=0}^{N} \frac{C_{on}}{(1+d)^n} - \left(\frac{\sum_{n=0}^{N} \frac{AEO_n}{(1+d)^n}}{\sum_{l=0}^{L} \frac{AEO_l}{(1+d)^l}}\right)\left(\sum_{l=0}^{L} \frac{C_{ol}}{(1+d)^l}\right)\right]$$

With this formulation, RV can be computed based on the cost and quantity parameters that are entered into the model. Some interpretation and intuition for the terms is:

- The first term represents the weight of the initial capital costs. If the energy output is constant and there is no discounting this would reduce to the fraction of the lifetime that the capital has been used (e.g., 15/40 = 0.375). As discounting is usually applied for levelized costs analysis, this term weighs the capital by the appropriately discounted energy output and the fraction of the capital's lifetime that has been used up.
- The second term includes value from the operating costs incurred during the analysis time.
- The third term subtracts value from operating incurred during the full lifetime of the project. This term serves two roles. First it applies a similar weight to the operating costs during the analysis time as what is applied to the capital costs. Second, it subtracts the costs that will be incurred after the analysis time, discounted appropriately.

The formula for RV can be simplified if AEO and operating costs are assumed to be zero in year 0 and constant across all other years. When this is the case, time subscripts can be removed from AEO and C_o as they are constant, and the summations begin in year 1. A constant can be factored outside the summation, so $\sum_{n=0}^{N} \frac{AEO}{(1+d)^n}\ AEO = AEO \times \sum_{n=0}^{N} \frac{1}{(1+d)^n}$, and similarly for the summation containing C_o. RV can be written as:

$$RV = (1+d)^N [\left(1 - \frac{AEO \times \sum_{n=1}^{N} \frac{1}{(1+d)^n}}{AEO \times \sum_{l=1}^{L} \frac{1}{(1+d)^l}}\right) PCI + C_o \times \sum_{n=1}^{N} \frac{1}{(1+d)^n} - \left(\frac{AEO \times \sum_{n=1}^{N} \frac{1}{(1+d)^n}}{AEO \times \sum_{l=1}^{L} \frac{1}{(1+d)^l}}\right)\left(C_o \times \sum_{l=1}^{L} \frac{1}{(1+d)^l}\right)]$$

This can then be simplified by cancelling AEO in both terms where it is in the numerator and denominator. Similarly, in the third term, the summation of $\sum_{l=0}^{L} \frac{1}{(1+d)^l}$ appears in the numerator and the denominator and can be cancelled.

$$RV = (1+d)^N[\left(1 - \frac{\sum_{n=1}^{N} \frac{1}{(1+d)^n}}{\sum_{l=1}^{L} \frac{1}{(1+d)^l}}\right) PCI + C_o \sum_{n=1}^{N} \frac{1}{(1+d)^n} - (\sum_{n=1}^{N} \frac{1}{(1+d)^n})(C_o)]$$

The second and third terms are now the same, so taking their difference yields 0, so when output and operating costs are constant, RV simplifies to:

$$RV = (1+d)^N[\left(1 - \frac{\sum_{n=1}^{N} \frac{1}{(1+d)^n}}{\sum_{l=1}^{L} \frac{1}{(1+d)^l}}\right) PCI]$$

The remaining summations are both a geometric series with a common ratio of $\frac{1}{(1+d)}$. The formula for the finite sum of the geometric series $\sum_{n=1}^{N} \frac{1}{(1+d)^n}$ is $\frac{1-(1+d)^{-N}}{d}$. Substituting this in gives:

$$RV = (1+d)^N[\left(1 - \frac{\frac{1-(1+d)^{-N}}{d}}{\frac{1-(1+d)^{-L}}{d}}\right) PCI]$$

Finally, the fraction can be simplified by canceling the d in both denominators to give:

$$RV = (1+d)^N[\left(1 - \frac{1-(1+d)^{-N}}{1-(1+d)^{-L}}\right) PCI]$$

For the LCOS calculator, the WACC is used as the discount rate. In the calculator, most operating costs are constant across all years, including ECC and insurance and property tax costs. The categories of costs that are not constant for all years is the FOM and ARMO costs. Using the result that RV does not include constant operating costs but does include time-specific costs, the RV value as applied in the calculator is:

$$RV = (1+WACC)^N[\left(1 - \frac{1-(1+WACC)^{-N}}{1-(1+WACC)^{-L}}\right) PCI] + \sum_{n=1}^{N} \frac{ARMO_n + FOM_n}{(1+WACC)^n} - \left(\frac{1-(1+WACC)^{-N}}{1-(1+WACC)^{-L}}\right)\left(\sum_{l=1}^{L} \frac{ARMO_l + FOM_l}{(1+d)^l}\right)]$$