How To

# Calculate & Measure Round-trip Efficiency of an Energy Storage System


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# How to Calculate & Measure Round-trip Efficiency of an Energy Storage System

**Efficiency** is defined as the ratio of how much work is being produced by a "system" for a given energy that is put into it. One example of a system is an automobile, being a collection of moving parts designed to convert stored energy (e.g. carbon fuel) into mechanical energy (forward motion). An automobile's efficiency is defined as the delivered horsepower over a period of time divided by the chemical energy contained within the fuel it consumed over that time. The vehicle's efficiency is not just a single number. It varies depending on driving conditions (temperature, terrain) and style (speed, acceleration, variability).

**efficiency = output / input**

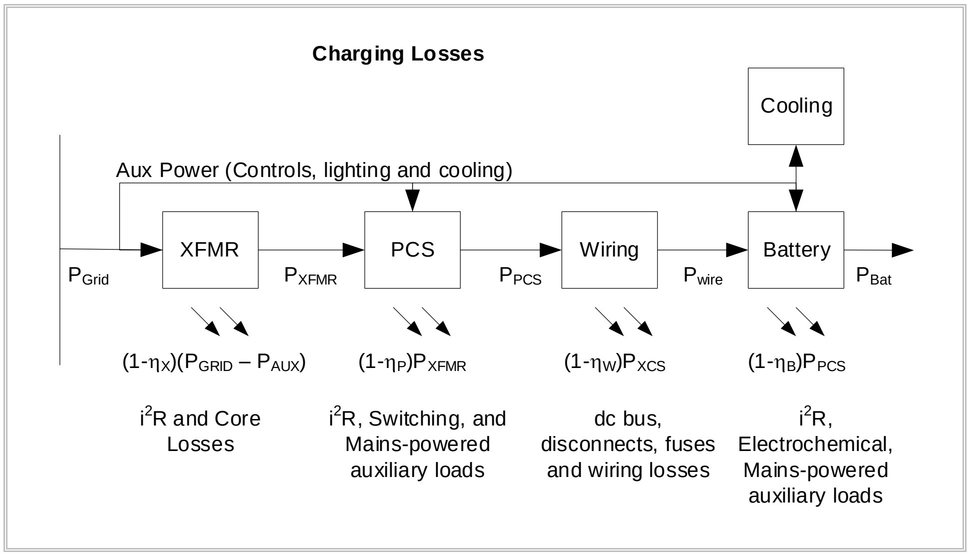
Efficiency is a means to compare and rank power and energy conversion systems by their ability to save their customers' money and resources. Power plants that convert fuel to electricity, power supplies that convert alternating current (ac) to direct current (dc) and battery chargers that deliver dc power into a battery are all examples systems that can be judged by their efficiency.

An energy storage system is a collection of subsystems that convert power or energy from one form to another in a multi-staged process. Calculating the efficiency of an energy storage system requires taking all of those processes into account and understanding the effects of the operating conditions on each of them.

For example, a battery-based energy storage system contains an ac to dc (ac/dc) power conversion, an ac/ac transformer, auxiliary power systems, controls, wiring, disconnects, fuses, circuit-breakers, a battery, and temperature management systems. The flow of energy starts at the grid from where high-voltage ac power is transformed into a locally compatible ac voltage (determined by the ac/dc converter), then converted to an appropriate dc level (determined by the battery) by a bidirectional ac/dc power conversion system (PCS), wherein it is converted to chemical energy inside the battery. When needed, the chemical energy is converted back to dc power which flows through the dc busses, wiring and fuses to the PCS, through the ac wiring and into the transformer which converts the low-voltage ac to the grid's higher ac voltage. In parallel to this power flow, smaller, but not negligible amounts of power are used to keep the battery and conversion equipment at their optimal operating temperatures.

The round-trip efficiency of the energy storage system is defined as the energy discharged at its terminals over the energy that was used to charge it at a specified rate. This assumes that the battery started and ended at the same state over the course of the full cycle. Additionally, the charging energy shall include all energy required to maintain the system while charging, including heating, cooling and controls, while the discharged energy needs to discount the temperature management and controls power required during the discharge cycle. Every system is different, so the pathways and conversion factors are different, and the equations to quantify their efficiencies can get messy very quickly. However, the following method demonstrates an easy way to generalize the total system efficiency knowing the individual subsystem efficiencies and the relative auxiliary power loads.

**The diagram to the right shows the power flow and losses throughout a typical energy storage system during a charge half-cycle.**




This diagram shows the auxiliary power coming directly from the grid, as it usually is. Sometimes the auxiliary power is derived from other sources, but when considering the system as a whole, the auxiliary power and grid power can be combined into one as the "input" power to the system. Therefore, the energy going into the battery is the power coming from the grid minus the auxiliary power multiplied by the product of one-ways efficiencies between the input and including the battery and the time it takes to charge the battery.

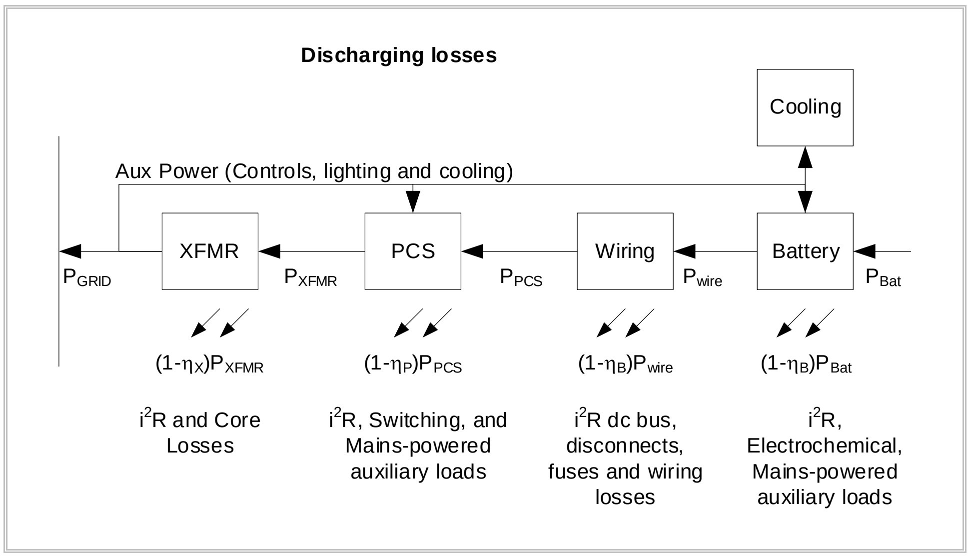
$$E_{Bat} = (P_{grid_{in}} - P_{aux}) \cdot \eta_X \cdot \eta_P \cdot \eta_W \cdot \eta_B \cdot t_{chg} \tag{1}$$

(technically, this should be an integral, but (1) is true if the power flows are constant over the charge period)

$E_{Bat}$ is a term which represents the ideal energy stored inside the battery which is hidden behind the losses between the electrochemistry and the outside terminals of the system. $t_{chg}$ is the time that it takes to charge the battery at the rate of $P_{grid_{in}}$, which is the power coming from the grid during a charge half-cycle. Finally, $\eta_X$, $\eta_P$, $\eta_W$, and $\eta_B$, are the one-way efficiencies of the transformer, PCS, wiring, and battery, respectively.

Going in the other direction during a discharge half-cycle, the ideal energy coming from the inside of the battery, $E_{Bat}$, is converted to electrical power, passed through the wiring and fuses, then converted to ac power and transformed into the grid's ac voltage, exiting into the grid as $P_{grid_{out}}$.

**Auxiliary power, $P_{aux}$, is shown here being taken from the terminals of the energy storage system and sent to the cooling system and other ancillary loads.**




The equation for the discharging power flow is shown below, assuming constant power flows:

$$(P_{grid_{out}} + P_{aux}) \cdot t_{Dis} = E_{Bat} \cdot \eta_X \cdot \eta_P \cdot \eta_W \cdot \eta_B \tag{2}$$

Where $t_{Dis}$ is the time it takes to discharge this energy at constant power rates.

Ultimately, we want to solve for a ratio energy out over energy in to get the round-trip efficiency:

$$\eta_{RTE} = \frac{E_{grid_{out}}}{E_{grid_{in}}} \tag{3}$$

However, the format of (1) and (2) would make this ratio difficult to solve for while eliminating $E_{Bat}$. So, the terms $P_{grid_{in}} - P_{aux}$ and $P_{grid_{out}} + P_{aux}$ are converted to factors that resemble efficiency terms:

$$E_{Bat} = \left[E_{grid_{in}}(1 - \frac{P_{aux}}{P_{grid_{in}}})\right] \cdot \eta_X \cdot \eta_P \cdot \eta_W \cdot \eta_B \quad (4)$$

And

$$E_{grid_{out}}\left(1 + \frac{P_{aux}}{P_{grid_{out}}}\right) = E_{Bat} \cdot \eta_X \cdot \eta_P \cdot \eta_W \cdot \eta_B \quad (5)$$

Where

$$E_{grid_{in(out)}} = P_{grid_{in(out)}} \cdot t_{Chg(Dis)} \quad (6)$$

Substituting (4) for $E_{Bat}$ in (5), and solving for $\frac{E_{grid_{out}}}{E_{grid_{in}}}$, results in a convenient format shown in (7):

$$\eta_{RTE} = \frac{E_{grid_{out}}}{E_{grid_{in}}} = \frac{1-\frac{P_{aux}}{P_{grid_{in}}}}{1+\frac{P_{aux}}{P_{grid_{out}}}} \cdot (\eta_X \cdot \eta_P \cdot \eta_W \cdot \eta_B)^2 \quad (7)$$

Furthermore, if $\frac{P_{aux}}{P_{grid_{in}}}$ is less than 10%, and $P_{grid_{in}} = P_{grid_{out}} = P_{grid}$, then it can be shown that:

$$\frac{1-\frac{P_{aux}}{P_{grid_{in}}}}{1+\frac{P_{aux}}{P_{grid_{out}}}} \approx \left(1 - \frac{P_{aux}}{P_{grid}}\right)^2 \quad (8)$$

A fictitious "efficiency" variable, $\eta_{Aux}$ is assigned to the parenthetical term, and substituted it back into (6), resulting in:

$$\eta_{RTE} = (\eta_{Aux} \cdot \eta_X \cdot \eta_P \cdot \eta_W \cdot \eta_B)^2 \quad (9)$$

Where:

$$\eta_{Aux} = 1 - \frac{P_{aux}}{P_{grid}} \quad (10)$$

Finally, although each of the efficiency terms in (9) is a one-way efficiency, the battery's efficiency is often given in terms of round-trip efficiency, $\eta_{B_{RTE}}$, in a typical manufacturer's specification sheet. Thus, (10) could be written as:

$$\eta_{RTE} = (\eta_{Aux} \cdot \eta_X \cdot \eta_P \cdot \eta_W)^2 \cdot \eta_{B_{RTE}} \quad (11)$$

Using (11), the RTE can be calculated of a typical lithium-ion based energy storage system having the following typical performance characteristics:

- $P_{grid_{in(out)}} = 1800\text{kW}$
- $P_{Aux} = 15\text{kW}$
- $\eta_X = 99.3\%$
- $\eta_P = 98.5\%$
- $\eta_W = 99.5\%$
- $\eta_{B_{RTE}} = 96\%$

$$\eta_{RTE} = (\eta_{Aux} \cdot \eta_X \cdot \eta_P \cdot \eta_W)^2 \cdot \eta_{B_{RTE}} = (0.992 \cdot 0.993 \cdot 0.985 \cdot 0.995)^2 \cdot 0.96 = 89.5\% \qquad (12)$$

**How does that affect the bottom line of an operating energy storage system?**

| | |
|---|---|
| Using a 400 MWh site as an example, where the cost of bulk electrical power is $35 per MWh, the total cost of cycling the system every day for a year is roughly calculated as: | $\text{Cost}_{charging} = 365\frac{\text{cyc}}{\text{yr}} \cdot (1 - \eta_{RTE}) \cdot 400\text{MWh} \cdot \frac{\$35}{\text{MWh}}$ <br> $= \$536{,}550$ |

**Improving the round-trip efficiency of this site by just 1% would save an additional $51,000 in yearly electricity costs.**

## More details about the subsystem efficiencies

Again, an energy storage system (ESS) includes many components, each with its own efficiency, and those subsystems (and how well they work together) have a cumulative effect on the efficiency of the overall system. Given the number of parts to a typical grid-scale ESS, small losses throughout can add up to a much bigger overall total.

In this section, we will take a closer look at the following subsystems: battery cell, wiring, PCS (inverter), transformer, temperature management and aux power – as well as the effects of cycle profile on efficiency.

### Battery cell efficiency

When current is forced into a battery cell, most of the energy is stored in a chemical form while some of the energy is lost in heat. Lithium-ion cells are some of the most efficient of all chemistries, with round-trip efficiencies in the 90 to 98% range. The losses are generally caused by electron and ion transfer inefficiencies. In general, cells built for high rates of discharge will be more efficient at a given rate than cells built for higher energy at lower rates. At low rates, such as four-hour discharge and charge half-cycles, it is not unusual to see 97 to 98% round-trip efficiencies from a typical NMC cell.

The LFP (lithium iron phosphate) variant of lithium ion has some additional losses which are not as prevalent in the oxide variants (lithium cobalt oxide - LCO, nickel manganese cobalt - NMC, lithium manganese oxide - LMO, etc). One unique aspect of LFP is the hysteresis between charge and discharge voltage curves. This additional voltage difference quantifies the additional round-trip losses seen in this chemistry. Even at extremely low rates, this difference can amount to about 1.5% round-trip losses. Thus, the round-trip efficiency of an LFP cell will always be at least 1.5% lower than an equivalently rated oxide-based cell. LFP cells designed for 1-to-4-hour cycles can expect to see just 95 to 96.5% round-trip efficiencies.

As the rate of discharge-charge increases, the losses will increase, and the efficiency will decrease. It's not unusual for a cell to see 85% round-trip efficiency when discharging at rates of an hour or less.

### Wiring efficiency

Wires, busbars and connectors are prevalent throughout an energy storage system. Anywhere electrons flow through metallic conductors, the inefficiencies will manifest as dissipated heat proportional to the square of the current. It's possible to design a system in which the total losses are negligible, but the cost and volume of metallic content would be prohibitive in a practical real-world application. Generally, a good rule of thumb is to limit the total conductive wiring losses in a system to less than 1%. This not only makes good economic sense but is practical as well. Consider for example a 4 MWh battery discharging at a 4-hour rate. That's 1 MW worth of power flowing through the large number of dc wires, buses and connectors. If they generated 1% losses at this rate, there would be 10 kW of heat being dissipated into the enclosure during an entire cycle!

The power-flow diagrams above show the "wiring losses" between the battery and the PCS. Although wiring losses occur at every junction and even within subcomponents because the battery consists of many cells over a geometrically dispersed volume, most of the wiring-losses will occur at the dc level.

## PCS efficiency

Losses in a power conversion system occur in the wiring, filter components, cooling apparatus and switching devices. In general, most of the PCS losses are proportional to the current and voltage being converted, but there are some losses which occur even as the PCS is idle. To represent the PCS fully in all modes of operation, a curve showing efficiency vs. power output is useful to have. Often, manufacturers provide a "full load" efficiency and a "CES" efficiency. The former is self-explanatory, but the latter is representative of a "Typical" load profile. For the purposes of defining the full-power round-trip efficiency or an energy storage system, it is more appropriate to the use "full-load" efficiency for the PCS subcomponent.

Modern PCS are extremely efficient, most of which tout around 98.5% one-way efficiency. Next generation PCS that use silicon-carbide transistors and diodes will exhibit 99% or higher efficiencies, some as high as 99.3%!

## Transformer efficiency

Transformers lose energy through conductive losses of current flowing through their metallic winding as well the power required to maintain an energized magnetic field in the iron core. The former losses are naturally proportional to the load they carry, while the latter is lost whether the transformer is supporting a load or not.

Modern transformers, and in particular, transformers larger than 1 MW, are required to conform to NEMA and IEC regulations for efficiency. A table of those requirements is shown below.

| | Constant Core Losses (% of Pmax) | Mains Power Losses (% of power rating) |
|---|---|---|
| LV-MV 60Hz - NEMA Premium | 0.070% | 0.72% |
| LV-MV 50Hz - IEC | 0.070% | 0.81% |
| MV-HV 60Hz - NEMA Premium | 0.070% | 0.23% |
| MV-HV 50Hz - IEC | 0.070% | 0.24% |

As a result, medium voltage transformers will typically see a one-way power efficiency greater than 99.2%. High voltage transformers will see efficiencies over 99.7%!

## Temperature management and auxiliary power losses

This category of losses is a catch-all for all other hard-to-quantify losses, some of which are constant and some of which are proportional to the power flowing through the system. The largest loss in this category is that which is used to control the temperature of the batteries and power equipment. Consider the cooling system in a typical battery energy storage system. There are many different designs in the industry, but fundamentally the cooling system needs to remove the losses incurred in the batteries during a cycle, otherwise the accumulated heat will inevitably cause the cell to overheat and be damaged. Considering a 4 MWh battery, if it is 96% round-trip efficient, 4% of that energy will be dissipated in the battery during a full charge-discharge cycle, or 160 kWh. If the cooling system is designed for only one cycle per day, it would have to remove that amount of heat in 24 hours at a rate of at least 6.7 kWh per hour. To account for aging factors, and to support more than one cycle per day, HVAC systems are typically oversized by 3X or more. Practically, this may amount to an electrical load of between 5 and 10 kW for this sized battery.

While the battery is cycling, the cooling systems may be drawing full power, and after the cycle is finished and during the idle period between cycles, the cooling systems may draw intermittent power depending on how much it has to cool the batteries after the last cycle and how hot the environment is outside the enclosure. For single-cycle focused round-trip specifications, the general practice is to use the full-load cooling power plus all the other constant-power loads as the basis for calculating the "auxiliary" efficiency $\eta_{\mathrm{Aux}}$ in (9), (10), and (11). The next section discusses the effect of idle-time auxiliary power on the effective round-trip efficiency.

## The effects of cycle profile on efficiency

The general form of efficiency, $\eta_{\mathrm{RTE}} = \frac{\mathrm{E}_{\mathrm{grid}_{\mathrm{out}}}}{\mathrm{E}_{\mathrm{grid}_{\mathrm{in}}}}$ (3), defines the total round trip efficiency as the energy that leaves the system over ALL the energy that enters the system. During a single-cycle analysis derived above, these terms are fairly straightforward to quantify, as shown in (9) - (11). However, there are periods between cycles, during which power is coming into the system to power auxiliary loads such as controls, monitoring, communications, cooling, heating, and transformer core excitation. Although they may be small in comparison to the main losses accounted for during cycling, they can amount to a lot of energy when integrated over long idle times (sometimes up to 20 hours per day) between cycles. Most storage solution providers do not include this aspect of round-trip efficiency because the assumptions can vary considerably in different applications. Some applications will cycle more than once a day, some even continuously. Some ESS are located in cold environments, others in hot and humid areas. Each of these factors will affect the actual "effective" round-trip efficiency by a few percent and are excluded from the specified RTE because they are "customer-specific" considerations. That doesn't mean they should be ignored in the financial assessment of the ESS solution though. Educated customers should ask their providers for all the loads, whether they run continuously, or variably through a daily cycle. To calculate the effective round-trip efficiency, use the following equation:

$$\eta_{RTE} = \frac{E_{grid_{out}}}{E_{grid_{in}}} = \frac{1-\frac{P_{aux}}{P_{grid}}}{1+\left(\frac{P_{aux}+P_{idle}\cdot t_R}{P_{grid}}\right)} \cdot (\eta_X \cdot \eta_P \cdot \eta_W)^2 \cdot \eta_{B_{RTE}} \qquad (12)$$

Where $P_{aux}$ is the average auxiliary power drawn during a charge half-cycle, $P_{idle}$ is the average power consumed during the idle period between cycles and $t_R$ is the ratio of the idle time to the discharge time. Invariably, the instantaneous values of $P_{aux}$ and $P_{idle}$ will vary considerably during their respective periods, so it is important to characterize their average values to use in (12).

To see how idle time could affect the effective round-trip efficiency, consider the example of a representative system below:

- $P_{grid_{in(out)}} = 1800\text{kW}$
- $P_{Aux} = 15\text{kW}$
- $P_{idle} = 5\text{kW}$
- $\eta_X = 99.3\%$
- $\eta_P = 98.5\%$
- $\eta_W = 99.5\%$
- $\eta_{B_{RTE}} = 96\%$
- $t_{Dis} = 4\ \text{hr}$
- $t_{idle} = 15\ \text{hr}$

$$\eta_{\text{RTE}} = \frac{1 - 0.0083}{1 + \left(\frac{15 + 5 \cdot 3.75}{1800}\right)} \cdot (0.993 \cdot 0.985 \cdot 0.995)^2 \cdot 0.96 = 88.5\%$$

**This is a percent lower than the single-cycle only analysis done in (12) above, representing an almost 10% increase in total system losses.**

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## Summary

Losses from battery cells, wiring, PCS, transformers, temperature management, and controls all detract from the efficiency of an energy storage system. Although the losses in each subsystem are relatively low, they all add up to a considerable amount: in the range of around 10% (round-trip), depending on a number of factors, but especially the rate at which they are charged and discharged. Other factors such as wiring losses, and battery chemistry, although small, should not be ignored.

Finally, the actual site conditions and application profile will change the effective round-trip efficiency seen in a given application. Although small, they should not be ignored when doing a full financial analysis of an ESS project. In one typical example detailed above, a 400 MWh site cycled once a day would cost $565 thousand dollars in electricity charges per year. Saving just one percent of RTE would save about $50 thousand operating costs per year for this one site.