An Investigation of How Electrical Energy Storage Roundtrip Efficiency Impacts Grid-Level Infrastructure Sizing

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18 February 2025 | Berlin, Germany

Abstract

Roundtrip efficiency is an important performance parameter for an energy storage system. Based on an energy balance, a simple model is developed to analyze the impact of roundtrip efficiency on the required size of the overall energy infrastructure beyond the storage system itself, represented by a capacity overbuild factor. It is derived from a basic sensitivity analysis that roundtrip efficiency is the most influential parameter to control capacity overbuild. A brief quantitative study is conducted for the edge case of a solar PV-only energy system, revealing that overbuild sensitivity diminishes above 50% storage roundtrip efficiency. Typical performance values of selected storage technologies reveal that sufficiently designed thermal batteries may be practical alternatives to lithium-ion batteries in large-scale installations, without their lower roundtrip efficiencies causing significant secondary drawbacks.

1. Introduction

Reliably storing intermittent electricity supply from wind and solar generation on largest scales at low cost is one of the biggest challenges in the energy sector today. Beyond lithium-ion battery energy storage systems (BESS), a wide range of alternatives is under development and commercialization [1].

Levelized costs of storage (LCOS) are typically used as metric to compare different storage technologies. They quantify the discounted costs per unit of discharged electricity under the consideration of all technical and economic parameters affecting lifetime costs. In this sense, they are directly related to the levelized costs of electricity (LCOE) used to compare different power generation technologies. However, a commonly agreed definition of LCOS and its main parameters has not been established yet and some publications exclude relevant parameters or lack methodological clarity. [1]

This is critical if a parameter describes the system-level influence of a storage technology. As already noted by the U.S. National Renewable Energy Laboratory (NREL) in 1995: "to fully evaluate the economies of storage for an electricity-generating technology, storage must be examined within the utility system as a whole, not simply as a component of the generating system" [2, p. 76].

Roundtrip efficiency (RTE) is an important parameter to determine LCOS and typically defined as the ratio of the amount of energy that can be discharged from a storage to the amount of energy that it has been charged with. It is obvious that, for low RTE, more energy is wasted in a charging-discharging cycle and therefore LCOS will be higher due to higher charging costs for the same output. Additionally, requiring a larger amount of energy input for a defined output also means that the whole upstream energy and utility infrastructure must be sized, procured, installed, commissioned, and maintained to according to this increased charging energy need. RTE is therefore a key metric for the utility-level impact of a storage technology, which motivated the further examination of their dependency conducted in this paper.

This paper is structured into three main parts: First, an energy balance for a simplified energy system will be used to derive an equation that models the impact of RTE on the utility-level. Second, a basic sensitivity analysis based on partial derivatives of the main parameters will be provided, combined with a brief discussion about why utility-level impact matters and how it may manifest in energy projects. And third, a simplified edge-case study will be conducted to quantify and compare the RTE-based impact of a limited set of energy storage technologies.

2. Energy Balance

In the simplest form, an energy system containing a storage with utility-level boundaries can be described as shown in Figure 1.

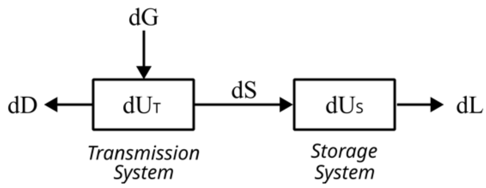

Figure 1: Model of a Simple Energy System

Here, an amount of energy dG is generated by a solar or wind powerplant and distributed by an energy transmission system; either to satisfy an energy demand dD or to be stored in an energy storage system as amount dS. Transmission and storage system can both experience a change in internal energy, dU_T and dU_S. Losses during charging/discharging of the storage are accounted as dL. For simplicity, it shall be assumed that all internal capacitances and inductances of the transmission system are sufficiently small and therefore changes in internal energy can be neglected, $dU_T = 0$. Further, all losses during distribution like transformer and cable losses shall be ignored. They can be modeled as loss term to the demand dD if different grid configurations were to be analyzed.

The energy balance for the transmission system according to the first law of thermodynamics can now be derived as:

$$dU_T = 0 = dG - dD - dS \tag{1}$$

$$\Rightarrow \; dG = dD + dS \tag{1a}$$

For the storage system, the energy balance yields:

$$dU_S = dS - dL \tag{2}$$

It must now be considered that there are two scenarios for the operation of an energy storage.

Scenario 1: Oversupply

During a time interval τ_1, an oversupply of generated energy compared to the demand occurs, $dG > dD$. This oversupply is used to charge the storage, $dS > 0$. Equations (2) and (3) can now be integrated over τ_1 to yield the total amounts of energy handled during this time interval:

$$\int_{\tau_1} dG = \int_{\tau_1} dD + \int_{\tau_1} dS \tag{3}$$

$$\Rightarrow \; G_1 = D_1 + S_1 \tag{4}$$

$$\int_{\tau_1} dU_S = \int_{\tau_1} dS - \int_{\tau_1} dL \tag{5}$$

$$\Rightarrow\ U_{S,1} = S_1 - L_1 \tag{6}$$

Combining (4) and (6) leads to

$$G_1 = D_1 + U_{S,1} + L_1 \tag{7}$$

which makes sense as it says that all generated energy G_1 is either satisfying demand D_1, converted to internal energy of the storage system $U_{S,1}$ for later discharge, or dissipated as charging loss L_1.

Scenario 2: Overdemand
During time interval τ_2 there is an overdemand of energy compared to the generation, $dG < dD$. This is compensated by discharging the storage. Considering that this is equivalent to $dS < 0$, the direction of energy flow between transmission and storage system dS reverses and the energy balances for both transmission and storage now yield:

$$dG = dD - dS \tag{8}$$

$$dU_S = -dS - dL \tag{9}$$

Equivalent to case *(1) Oversupply*, integration of equations (8) and (9) over time interval τ_2 gives:

$$G_2 = D_2 - S_2 \tag{10}$$

$$U_{S,2} = -S_2 - L_2 \tag{11}$$

Both combined and reordered lead to:

$$G_2 = D_2 + U_{S,2} + L_2 \tag{12}$$

This is equivalent to equation (7) and may look nonsensical at first, as the term $+\,U_{S,2}$ on the right seems to suggest another charging process of the storage that decreases the generated amount of energy G_2. However, rearranging equation (12) to

$$(G_2 - U_{S,2}) = (D_2 + L_2) \tag{12a}$$

and remembering that $U_{S,2} < 0$ based on equation (11) it is obvious that $\left(G_2 - U_{S,2}\right) > 0$. Ergo, equation (12) is correctly interpreted as generation during overdemand G_2 being supplemented by discharged internal energy $U_{S,2}$ from the storage system, to meet momentary demand D_2 and discharging losses.

Coupling both Scenarios
Energy conservation requires that all the internal energy dU_S discharged from the storage during τ_2 must equal all the internal energy charged during τ_1:

$$\int_{\tau_1} dU_S = \int_{\tau_2} dU_S \tag{13}$$

$$\Rightarrow\ U_{S,1} = U_{S,2} \tag{14}$$

Substituting (14) with (6) and (11), it follows:

$$S_1 - L_1 = -S_2 - L_2 \tag{15}$$

$$\Rightarrow\ L_2 - L_1 = -S_1 - S_2 \tag{15a}$$

Introducing the Roundtrip Efficiency η_{RTE}
As discussed already, RTE is defined as the ratio of the amount of energy that can be discharged from a storage to the amount of energy that it has been charged with. Considering this in the context of roundtrip energy flows to and from the storage, the useful output is equivalent to the total discharge energy S_2, and the input to the total charging energy S_1:

$$\eta_{\mathrm{RTE}} = \frac{S_2}{S_1} \tag{16}$$

$$\Rightarrow\ S_2 = S_1\,\eta_{\mathrm{RTE}} \tag{16a}$$

Substituting S_2 in (15a) with (16a) we get:

$$L_2 - L_1 = -S_1 - S_1\,\eta_{\mathrm{RTE}} \tag{17}$$

Deriving a Combined Equation
We can now derive an equation that expresses the total generated energy during oversupply as a function of roundtrip efficiency, $G_1 = f(\,\eta_{\mathrm{RTE}})$. By substituting S_2 in equation (10) with (15) we get

$$G_2 = D_2 + S_1 + L_2 - L_1 \tag{18}$$

and further considering equation (17)

$$G_2 = D_2 - S_1\,\eta_{\mathrm{RTE}} \tag{18a}$$

$$\Rightarrow\ S_1 = \frac{D_2 - G_2}{\eta_{\mathrm{RTE}}} \tag{18b}$$

This can now be combined with equation (4) to yield the desired expression:

$$G_1 = D_1 + \frac{D_2 - G_2}{\eta_{\mathrm{RTE}}} \tag{19}$$

As one would intuitively expect, the total energy generated during times of oversupply G_1 must be sufficiently large to 1) satisfy the momentary energy demand D_1 and 2) charge the energy storage system in such a way that any overdemand of energy $D_2 - G_2$ can be met by discharging the storage, including energetic compensation for any losses from storage operation, $1/\eta_{\mathrm{RTE}}$.

3. Overbuild and its Impact on Assets and Infrastructure

It is useful to develop equation (19) into a dimensionless form to enable a more generalized analysis. Hence, a new parameter can be introduced, the *Overbuild Factor* Φ, quantifying how much more energy generation capacity must be installed during times of oversupply than momentarily demanded to accommodate the charging/discharging characteristics of the energy storage system:

$$\Phi = \frac{G_1}{D_1} \tag{20}$$

Using equation (19), this can be reformulated as

$$\Phi = \frac{G_1}{D_1} = \left(1 + \frac{D_2 - G_2}{D_1\,\eta_{\mathrm{RTE}}}\right) \tag{20a}$$

Overbuild Sensitivity to Scenario-Dependent Parameters
As equation (20a) shows, additional parameters besides the RTE remain which depend on the scenario of each storage project, no matter if for an islanded microgrid or a utility-scale energy system. Evaluating equation (20a) quantitatively therefore requires certain assumptions, which shall be approached after a basic sensitivity analysis of the overbuild factor based on partial derivatives has been conducted. In the following, all parameters are assumed to be completely independent from each other.

η_{RTE} – Overbuild is negatively correlated to the inverse square of the roundtrip efficiency:

$$\frac{\partial \Phi}{\partial \eta_{RTE}} = \left(-\frac{D_2 - G_2}{D_1\, \eta_{RTE}^2}\right) \Rightarrow \frac{\partial \Phi}{\partial \eta_{RTE}} \sim \left(-\frac{1}{\eta_{RTE}^2}\right) \quad (21)$$

This quadratic influence highlights the importance of achieving high storage roundtrip efficiencies for energy storage technologies and should therefore be one of the main development priorities.

D_1 – Overbuild is also negatively correlated to the inverse square of the energy demand during times of oversupply:

$$\frac{\partial \Phi}{\partial D_1} = \left(-\frac{D_2 - G_2}{D_1^2\, \eta_{RTE}}\right) \Rightarrow \frac{\partial \Phi}{\partial D_1} \sim \left(-\frac{1}{D_1^2}\right) \quad (22)$$

The opportunities to influence this parameter are limited as it is directly correlated to primary energy consumption. For an individual energy project, improving the efficiency of electricity-consuming processes may provide a certain remedy, however, on a societal level, the feasibility and desirability of a significantly decreased primary energy consumption is highly controversial and beyond the scope of this paper.

D_2 - Energy demand during times of overdemand has a linear-positive correlation to overbuild capacity:

$$\frac{\partial \Phi}{\partial D_2} = \frac{1}{D_1\, \eta_{RTE}} = const. \; > 0 \quad (23)$$

Reducing D_2 is beneficial because less energy has to be stored for such time intervals. This can be achieved by load-shifting and operational flexibilization which is, however, not indefinitely possible for certain industrial assets with significant energy offtake. Limitations arise from process economics or basic thermodynamics. Increases in D_2 increase overbuild, and they may potentially even rise beyond the levels of D_1. This may occur in scenarios with significant levels of electric vehicle adoption and home-charging overnight, as well as further electrification of building heating and cooling during the morning and evening demand peaks.

G_2 - Energy generation during times of overdemand has a linear-negative correlation to overbuild capacity:

$$\frac{\partial \Phi}{\partial G_2} = \frac{-1}{D_1\, \eta_{RTE}} = const. \; < 0 \quad (24)$$

Increasing G_2 may be achieved by combined solar PV – wind projects due to their rather anti-cyclical power generation or adding flexible peaker plants. Reducing G_2 and accepting a higher overbuild is only desirable if adding G_2 generation capacity would be, from an overall project economic point of view, more costly than adding additional capacity for oversupply and energy storage.

It should be noted that, besides the hard to influence D_1, RTE is the determining factor of how impactful measures based on D_2 and G_2 are. The lower RTE is, the more impactful both parameters become:

$$\lim_{\eta_{RTE} \to 0} \left(\frac{\partial \Phi}{\partial D_2}\right) = \infty \quad (25)$$

$$\lim_{\eta_{RTE} \to 0} \left(\frac{\partial \Phi}{\partial G_2}\right) = -\infty \quad (26)$$

It can be similarly shown that measures to improve D_2 and G_2 become less impactful if RTE is high.

Additionally, comparing equations (21), (23), and (24) shows that, even at low RTE, it seems to be more beneficial to aim for RTE improvements because of the overbuild's much higher sensitivity. Let $0 < \eta_{RTE} < 1$, then for all η_{RTE}:

$$\left|\frac{\partial \Phi}{\partial \eta_{RTE}}\right| > \left|\frac{\partial \Phi}{\partial D_2}\right| = \left|\frac{\partial \Phi}{\partial G_2}\right| \quad (27)$$

The analysis which quantitative ranges of improvement are actually realistic in practice is beyond the scope of this paper.

Why Overbuild Matters beyond LCOE

Significant infrastructure is required to generate, manage, and distribute electrical power; and this infrastructure must increase in size depending on the required level of primary energy production and therefore overbuild. Ergo, for a project or whole energy system with identical energy demand, larger overbuild leads to:

- Significantly more installed generation capacity (solar panels, wind turbines, etc.).
- More and/or larger auxiliary assets to distribute the electrical power (transformers, power electronic converters, cables, concrete foundations, buildings and other on-site infrastructure to maintain the generation and auxiliary capacity. For example, to clean solar panels from dust or sand in desert areas).
- More land and/or sea area for asset installation.

This is problematic for a couple of reasons:

- Supply of auxiliary assets like transformers and key materials like copper is limited and impacts feasibility and timelines.
- Land availability is constrained by natural conservation efforts, geographical limitations, or local residents' acceptance issues.
- Project execution risks and timelines increase for more and larger assets, as do investment and financing costs.
- More assets subject to degradation also means more infrastructure and energy consumption for recycling, secondary materials, and supply chains. Finally, overall more waste will be generated unless economically viable recycling processes with sufficient recovery rates are available for every single material involved.

These factors will drive up the LCOE and thereby negatively impact charging cost and LCOS. But it should also be clear that they go beyond pure commercial considerations and, as in the case of resource supplies or available land, are physically constraint and therefore set hard limits to the feasibility of a project or the switch of a complete national grid to clean energy. Given its high sensitivity, minimizing overbuild by maximizing energy storage RTE is therefore a general imperative.

4. Quantification for a Simple Solar PV-only Edge Case

Discussions about the relationship between RTE and overbuild were qualitative so far and shall now be briefly quantified.

Model Simplification

As a simple model, an energy system solely relying on solar PV and storage shall be used, leading to the infamous "*Duck Curve*" with significant storage need to capture the large solar PV overproduction during the day for discharge during the morning and evening consumption peaks. This is motivated by the fact that solar PV is by far the fastest growing form of renewable power production globally [3], with enormous remaining potential. Accordingly, equation (20a) is simplified with the following assumptions:

$D_1 = D_2$	The total energy demand during times of overproduction shall be equal to the demand during oversupply. This correctly represents industrial off-takers operating 24/7 or ideal baseload energy systems.

$G_2 = 0$ Generation during times of overdemand shall be zero, which is the case for nighttime or very unfavorable weather conditions in a pure solar PV scenario.

Equation (20a) can now be written as

$$\Phi = \frac{G_1}{D_1} = \left(1 + \frac{1}{\eta_{\mathrm{RTE}}}\right) \tag{28}$$

and is visualized in Figure 2. Table 1 provides an overview of practical values and their resulting overbuild requirements.

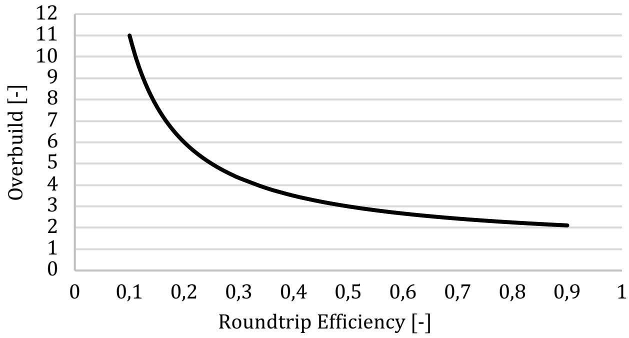

Figure 2: Impact of roundtrip efficiency on overbuild for a solar-PV only scenario.

Table 1: Practical values for roundtrip efficiency and overbuild.

Roundtrip Efficiency	*Overbuild*	*Scenario*
1	2	Ideal storage
0.80	2.25	Battery storage, US monthly average 2018/19 [4] (lithium-ion)
0.80	2.25	Pumped hydro storage, US monthly average 2018/19 [4]
0.64*	2.56	Minimum efficiency of a state-of-the-art gas GTCC power plant [5].
0.44	3.27	Hydrogen storage, assuming only electrolysis efficiency of 70% (mature alkaline, maximum [6]) and 64% GTCC reconversion efficiency.
0.32	4.12	Hydrogen storage, assuming only electrolysis efficiency of 50% (mature alkaline, minimum [6]) and 64% GTCC reconversion efficiency.

*Used as an estimate for large-scale thermal energy storage with similar heat-to-electricity conversion technology. Does not account for charging or self-discharge due to heat dissipation (sensible heat storage) or incomplete chemical reactions (thermochemical storage).

Discussion

It can be seen that, within a wide range of RTE between 0.5 – 1, the overbuild increases only slightly from 2 to 3. Given the edge case character of this curve this increase may be smaller in many real world scenarios. The major requirements for capacity overbuild occur for RTE < 0.5, which is far below typical battery and pumped hydro energy storage systems (RTE ≈ 0.8) with only slightly increased overbuild ($\Phi = 2.25$) compared to the ideal storage with $\Phi = 2$. State-of-the-art gas turbine combined cycle plants (GTCC), used in Table 1 to estimate the RTE of large-scale thermal energy storage, requires only slightly higher overbuild ($\Phi = 2.56$) and therefore highlights the theoretical potential of thermal batteries as alternative to lithium-ion technology at large scale. It should be considered though that the conversion efficiency of turbines usually strongly depends on power rating, so this comparative similarity in overbuild likely holds for large-scale storage projects only. Looking at estimates for hydrogen, it becomes evident that this technology is not an ideal contender for short-term day-night solar-PV shifting due to the low RTE = 0.32 - 0.44. However, the overbuild requirements with roughly 1.5 - 2x of the ideal storage are not overly excessive, so it could still have value as seasonal storage to capture the significant energy overproduction during summer months if the overall project economics for electrolyzer plant and hydrogen storage permit. Advanced fuel cells in smaller scale installations may improve RTE although achieving the level of established battery and pumped hydro storage is rather unlikely.

5. Conclusion and Outlook

This paper investigated the impact of electrical energy storage RTE on the utility-level infrastructure. From derivation and analysis of an equation describing this impact it was concluded that RTE has a dominating impact on utility-level sizing, although this impact seems to quickly diminish in solar PV-only scenarios at RTE > 0.5.

Further research should extend the overbuild sensitivity analysis and especially consider which absolute parameter variations are realistic in practical application. Another direction could be the quantitative investigation of a wider range of storage technologies and scenarios, potentially going beyond the integral "lump sum" energetic models of oversupply and overdemand towards a time-resolved model based on real-world data and scenarios. Finally, the approach is similarly applicable to power systems in space applications, either on spacecraft or stations on planetary surfaces without access to fossil or nuclear power sources. Further research could focus on the requirements of such missions and how this impacts the suitability of different storage technologies.

6. Abbreviations

GTCC Gas Turbine Combined Cycle
LCOE Levelized Costs of Energy
LCOS Levelized Costs of Storage
NREL U.S. National Renewable Energy Laboratory
PV Photovoltaic
RTE Roundtrip Efficiency

7. References

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