Levelized Cost of Storage

Gravity Storage

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This report is the independent expert opinion of the author.

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Summary

Levelized cost of storage (LCOS) quantify the discounted cost per unit of discharged electricity for a specific storage technology and application. The metric accounts for all technical and economic parameters affecting the lifetime cost of discharging stored electricity and represents an appropriate tool for cost comparison of electricity storage technologies.

Figure 1 shows the LCOS for Heindl Energy's Gravity Storage and the four most common deployed technologies for bulk electricity storage and compares the values to LCOS ranges identified by the financial advisory Lazard.

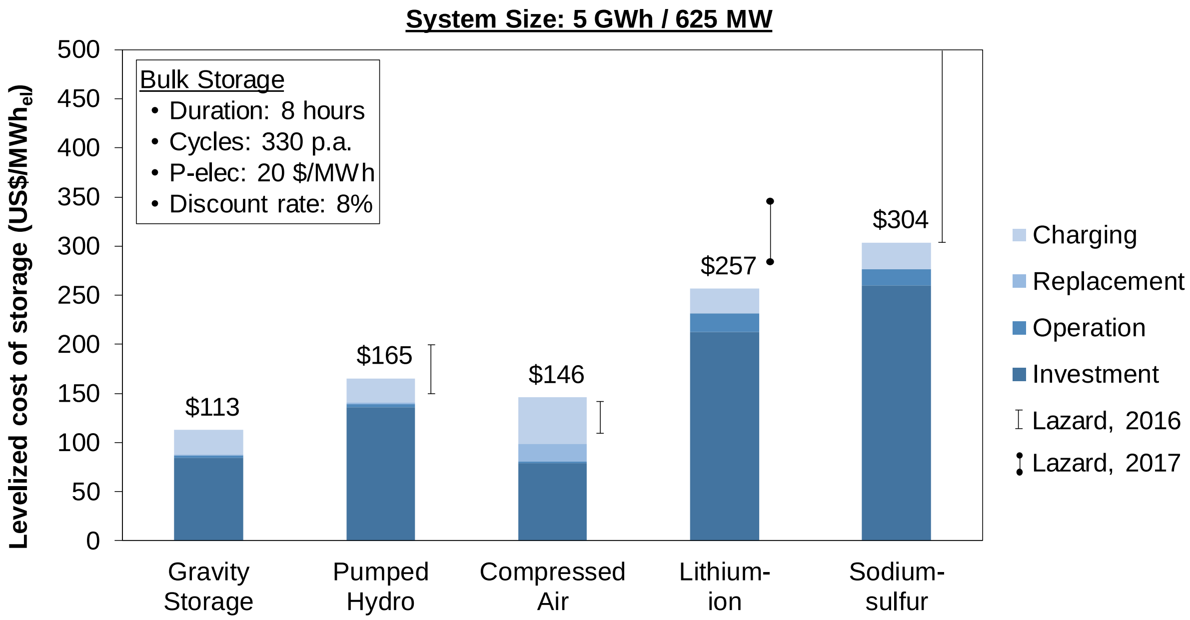


Figure 1 – LCOS in US$/MWh$_{el}$ for investigated bulk storage technologies of 5 GWh system size, 8 hours discharge duration, 330 full equivalent charge cycles per year, electricity price of 20 US$/MWh and 8% discount rate. Values are compared to results from studies by Lazard. Only lithium-ion among technologies considered in 2017 study.

Based on the given data, Gravity Storage is the most cost-effective bulk electricity storage technology for systems larger than 1 GWh, followed by compressed air (CAES) and pumped hydro (PHS). Low specific energy investment costs represent the key advantage for these technologies at the required discharge duration of 8 hours. Gravity Storage further benefits from moderate specific power investment costs and more significant scale effects with increasing system size.

Introduction – Role of bulk storage

This analysis for bulk electricity storage considers Heindl Energy's Gravity Storage, conventional pumped hydro, compressed air, lithium-ion and sodium-sulfur battery storage. The latter four are the most widely deployed stationary storage technologies.

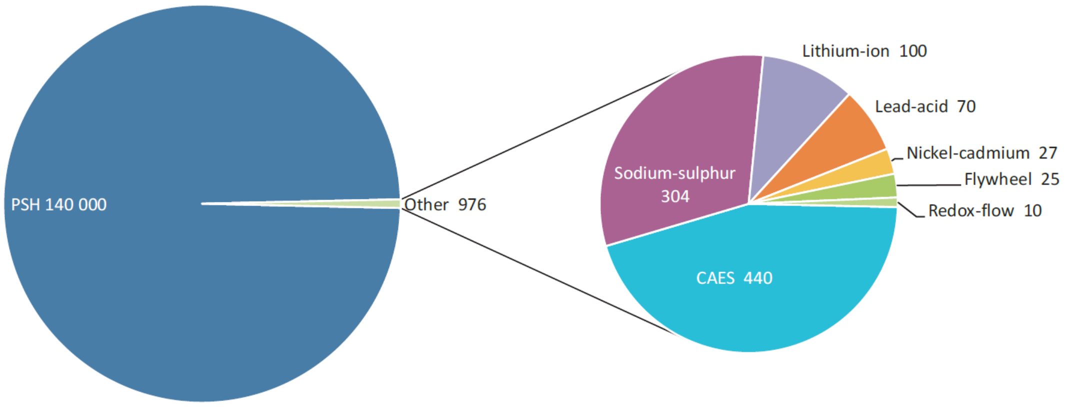


Figure 2 – Global installed electricity storage capacity in 2010 in MW [1]*; PSH – Pumped Hydro Storage, CAES - Compressed Air Energy Storage*

While positive market and policy trends support year-on-year growth of over 50% for battery storage, near-term storage needs will largely be answered by bulk storage technologies like pumped hydro or similar in absolute terms (blue column).

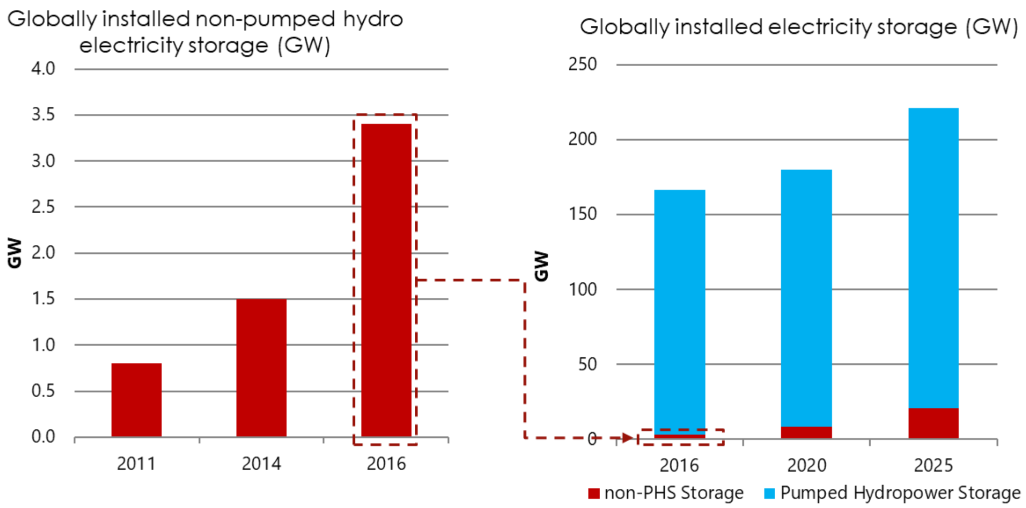


Figure 3 - Left: Increase in global installed non-pumped hydro electricity storage (GW) from 2011 to 2016. Right: Projected increase in total global installed electricity storage (GW) for 2020 and 2025. [2]

This highlights the market potential for comparable alternatives to conventional pumped hydro.

Introduction – Levelized cost of storage

The levelized cost of storage (LCOS) quantifies the discounted cost per unit of discharged electricity for a specific storage technology and application. The metric accounts for all technical and economic parameters affecting the lifetime cost of discharging stored electricity and therefore represents an appropriate tool for cost comparison of electricity storage technologies.

$$LCOS\left[\frac{\$}{MWh}\right]=\frac{Investment\ +\ Operation\ +Charging\ +\ End\_of\_life}{Electricity\ discharged}$$

LCOS reflect the internal average price at which electricity can be sold for the investment's net present value to be zero, i.e. its revenue requirement, and is therefore analogous to the concept of levelized cost of electricity (LCOE) for generation technologies. An increasing number of academic and industry studies look at LCOS of storage technologies and applications [3–8].

The equation below depicts the cost and performance parameters included in this analysis in more detail. These are:

- **Investment cost (Capex):** The model considers specific energy and power investment costs. These are multiplied with nominal energy and power capacity respectively and summed to yield total investment cost.
- **Replacement cost ($Capex_R$):** Technology components need replacement at specified intervals. In the model, these costs are represented as power specific replacement costs and multiplied with power capacity.
- **Operation cost:** Fixed operating cost per year and variable operating cost are combined and displayed as a percentage of the total investment cost.
- **Power cost (P_{elec}):** This is the cost per unit electricity for charging the storage device. It refers to the wholesale power price and excludes taxes, fees or subsidies.

- **End-of-life cost:** The cost or value of the technology at its end-of-life.
- **Discount rate (r):** This is used to discount future replacement, operating and end-of-life cost, as well as electricity generation, because it represents future revenues.
- **Depth-of-discharge (DoD)**: Amount of usable energy storage capacity.
- **Round-trip efficiency (η_{RT}):** This metric indicates how much of the electricity that is used to charge the storage system can be discharged later.
- **Lifetime (N):** The operating lifetime of a technology is defined by the minimum between cycle life divided by full cycles per year and shelf life.
- **Full cycles per year (#cycles):** Number referring to equivalent full charge and discharge cycles per year. It indicates energy throughput of the storage device rather than actual number of full and part cycles.
- **Construction time (years)**: Time during which a technology is built. It inflates investment costs and deflates future cost and revenues.
- **Annual degradation (Deg):** Annual percentage representing the reduction of nominal energy storage capacity if applicable.
- **Period (n):** A particular year under consideration.

$$LCOS\left[\frac{\$}{MWh}\right] = \frac{Capex + Capex_R + \sum_{n=1}^{N}\frac{Operation}{(1+r)^n} + \frac{End\_of\_life}{(1+r)^{N+1}}}{\#cycles * DoD * C_{nom\_e} * \eta_{RT} * \sum_{n=1}^{N}\frac{(1+Deg)^n}{(1+r)^n}} + \frac{P_{elec}}{\eta_{RT}}$$

Capex:	Investment cost ($)	C_{nom_e}:	Nominal capacity (MWh)
$Capex_r$:	Replacement cost ($)	DoD:	Depth-of-discharge (%)
O&M:	Operating cost ($)	N:	Lifetime (years)
End-of-life:	End-of-life cost / value ($)	#cycles:	Full cycles per year (#)
P_{elec}:	Power cost ($/$kWh_{el}$)	Deg:	Annual degradation (%)
r:	Discount rate (%)	n:	Period (year)

Note: Equation excludes explicit expressions for construction time, replacement intervals and specific investment and replacement cost. See “Levelized Cost of Storage - The Case of Gravity Storage”[6] for a more detail account of the approach.

Assumptions – Cost and performance data

Input data are at the core of application-specific LCOS analyses. Table 1 and 2 display the economic and technical input parameters for application and technologies considered in this report.

Table 1 – Economic and technical application requirements for bulk storage assumed in this study

Bulk storage	
Nominal energy capacity	1 – 10 GWh
Discharge duration	8 hours
Power cost	20 $/MWh_{el}$
Full cycles per year	330
Discount rate	8%

Nominal energy capacity and **discharge duration** define equally sized electricity storage systems to ensure a fair comparison.

Power cost represent an illustrative wholesale power price representative for large-scale solar plants in geographies with high solar irradiation, where co-location of bulk storage is a likely application example for Gravity Storage. In this study, the power price is the same for all technologies.

Full cycles per year are representative of the typical daily cycle schedule a bulk storage technology co-located with a solar plant could perform.

The **discount rate** of 8% is assumed representative for energy and infrastructure projects in recent years and applied accordingly to all technologies. The scenario analyses for 6% and 4% reflect low current interest rates and the potential satisfaction of investors with these returns in low risk and regular, stable revenue investments.

This report compares the cost-effectiveness of five technologies providing bulk storage: Heindl Energy Gravity Storage, conventional pumped hydro, compressed air, lithium-ion and sodium-sulfur battery systems. Data for the Heindl Energy Gravity Storage system is provided by Heindl Energy GmbH. The data for the remaining technologies is based on literature sources that use manufacturer quotes.

Table 2 – Cost and performance parameters for considered bulk electricity storage technologies

Input Data		**Gravity Storage**	**Pumped hydro**	**Compr. air**	**Lithium-ion**	**Sodium-sulfur**
System size: 1 GWh / 0.125 GW						
Capex - energy	$/kWh	337	220	15	278	298
Capex - power	$/kW	692	1,349	896	282	454
System size: 2 GWh / 0.250 GW						
Capex - energy	$/kWh	229	178	14	263	298
Capex - power	$/kW	609	1,267	729	250	426
System size: 5 GWh / 0.625 GW						
Capex - energy	$/kWh	139	134	12	245	298
Capex - power	$/kW	547	1,166	554	213	392
System size: 10 GWh / 1.250 GW						
Capex - energy	$/kWh	96	109	11	232	298
Capex - power	$/kW	523	1,094	451	189	368
O&M cost	%	0.30%	0.31%	0.36%	1.38%	0.88%
Replacement cost	$/kW	25	112	90	-	-
EoL cost	$/kWh	-	-	-	-	-
Discharge duration	hours	8	8	8	8	8
Depth of discharge	%	100%	100%	100%	80%	80%
Cycle life	#	19,800	21,900	14,600	3,500	5,500
Shelf life	years	60	60	40	10	15
Round-trip efficiency	%	80%	80%	42%	81%	75%
Degradation	% pa	0%	0%	0%	-3%	-2%
Construction time	years	3.5	5	5	1	2
Replacement interval	years	10	20	4	-	-

Note: *Capex* represents specific energy and power cost, not total cost in energy / power terms.

Size-dependent **specific energy / power investment cost** for Gravity Storage are provided by Heindl Energy GmbH. The values for other technologies are derived based on a regression of manufacturer quotes for systems of different size from 2011 [9]. For lithium-ion the resulting cost curve is adjusted to represent 2017 data [4]. No cost reduction was assumed for other technologies.

Table 3 compares the investment cost assumptions of this study for a 1 GWh / 125 MW system to alternative values from industry studies.

Table 3 - Comparison of investment cost assumptions of 1 GWh / 125 MW systems in this study to other studies

	Comment	**Pumped hydro**	**Compressed air**	**Lithium-ion**	**Sodium-sulfur**
Total Cost in $/kWh	This study	389 [9]	127 [9]	349 [4,9]	361 [9]
	Lazard	213 - 313 [3]	130 - 188 [3]	335 - 425 [4]	410-1200 [3]
	IEA, DNV, Yan	261 - 597 [10]	127 [11]	703 - 810 [12]	1110-1449 [12]

Results – LCOS values for Gravity Storage

Levelized cost of storage for Gravity Storage systems decrease as a function of system size. While systems of 1 GWh energy storage capacity and 125 MW power capacity discharge electricity at 204 US$/MWh, systems of 5 GWh and 625 MW discharge electricity at 113 US$/MWh, and systems of 10 GWh and 1,250 MW at 94 US$/MWh, based on the given cost and performance data in Table 2.

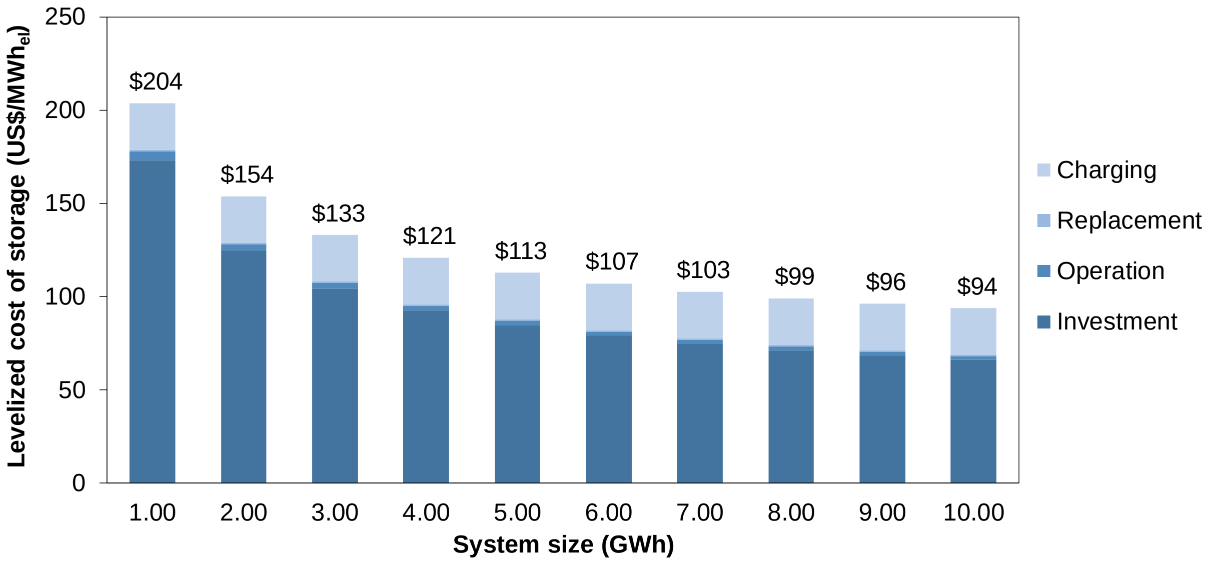


Figure 4 – Levelized cost of storage for Heindl Energy Gravity Storage systems for different system sizes. Energy storage capacity ranges from 1 to 10 GWh. Discharge duration is kept constant at 8 hours, so respective power capacity ranges from 125 to 1,250 MW. Different shading of blue indicates LCOS components, namely power, replacement, operation and investment cost.

The reduction in levelized cost as a function of increased system size is driven by the reduction in energy and power specific investment cost. The reason for this relative cost reduction is that any increase in piston diameter will increase storage capacity to the forth power while construction costs increase only to the second power.

A new construction technology, alternative designs and an update for input assumptions reduce the levelized cost of storage for Heindl Energy Gravity Storage compared to the previous report from November 2017 [6].

Figure 5 details the drivers of the LCOS reduction from 148 to 99 US$/MWh$_{el}$ for the 8 GWh / 1,000 MW Gravity Storage system investigated in the previous report [6]. The most significant reduction of 23 US$/MWh$_{el}$ is in investment cost, a direct result of the reduction in specific energy (148 to 108 US$/kWh$_{cap}$) and power cost (579 to 529 US$/kW$_{cap}$). These lower specific investment costs are achieved due to a new construction technology, namely the excavation of the piston by diamond wire saws. In addition, more detailed engineering studies enable the development of alternative, more affordable designs. As a result, construction time can be reduced by 20-30%, reducing LCOS by a further 13 US$/MWh, because the systems can start operating earlier and future revenues are discounted less. Finally, the updated power cost assumption from 30 to 20 US$/MWh$_{el}$ reduces LCOS by another 13 US$/MWh$_{el}$. This power cost assumption reflects the cost level of power purchase agreements for solar power in regions with high solar irradiation in the near future [13]. Wind power is also projected to reach this price level for high quality sites, although later than solar power [13].

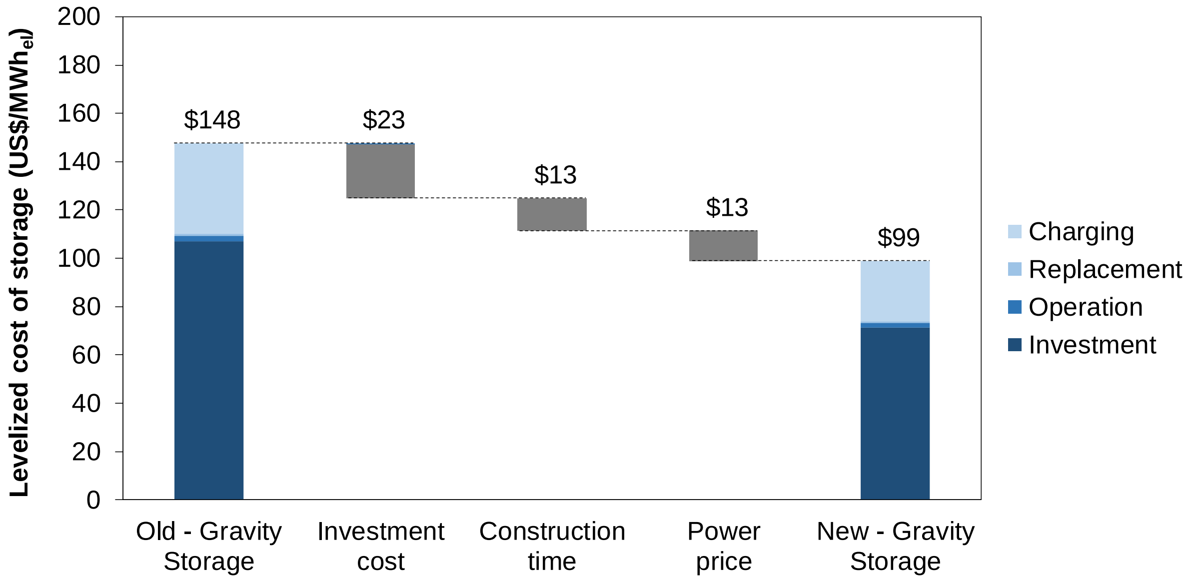


Figure 5 – LCOS reduction due to new construction technology, alternative design and updated power cost assumption for a 8 GWh / 1,000 MW Gravity Storage system compared to report from November 2017 [6].

Results – LCOS comparison to alternative technologies

Based on the given input data in Table 2, Heindl Energy Gravity Storage systems are the most cost-effective bulk electricity storage technology for storage capacities larger than 1 GWh. Compressed air energy storage is most cost-effective for 1 GWh systems (Fig. 6).

While LCOS for Gravity Storage systems reduce by 54% when increasing system size from 1 GWh (204 US$/MWh$_{el}$) to 10 GWh (94 US$/MWh$_{el}$), pumped hydro and compressed air only reduce by ~30%, lithium-ion by 17% and sodium-sulfur battery systems by only 3%. The limited LCOS reduction of sodium-sulfur is due to the lack of scaling effects for energy related investment cost [9].

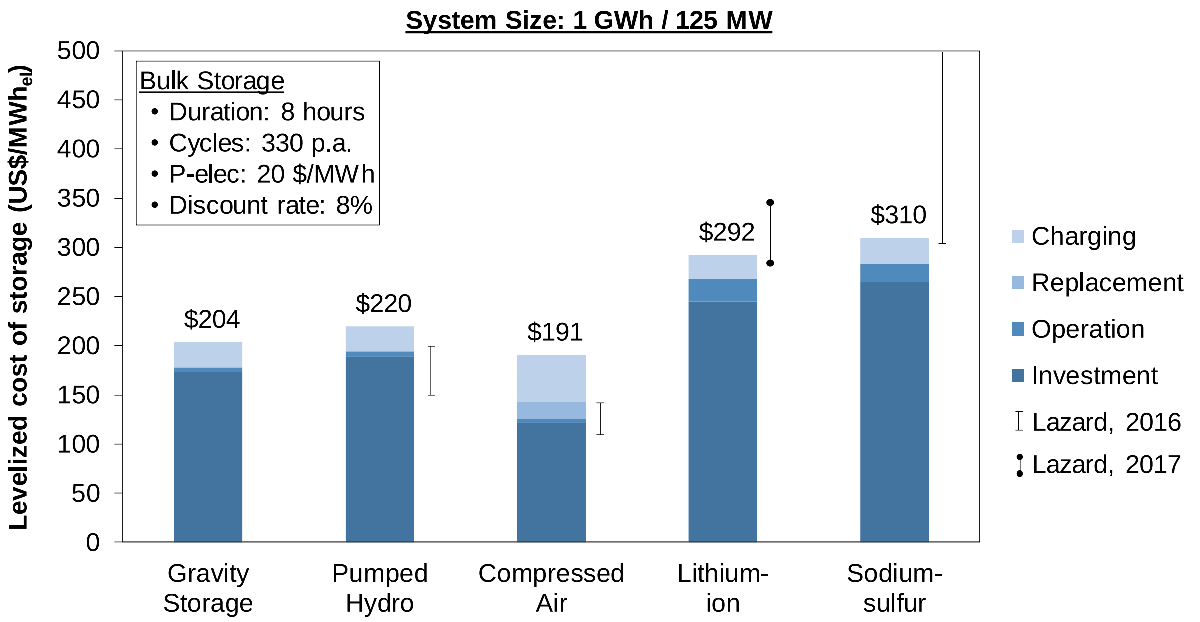
For a system size of 5 GWh energy storage capacity and 625 MW power capacity, LCOS for Gravity Storage are 113 US$/MWh$_{el}$, followed by compressed air at 146 US$/MWh$_{el}$, pumped hydro at 165 US$/MWh$_{el}$ and lithium-ion and sodium-sulfur battery storage at 257 US$/MWh$_{el}$ and 304 US$/MWh$_{el}$ respectively. Investment cost constitute more than 75% of LCOS for all technologies, apart from compressed air where the low round-trip efficiency and high replacement cost mean that charging and replacement cost constitute half of total LCOS.

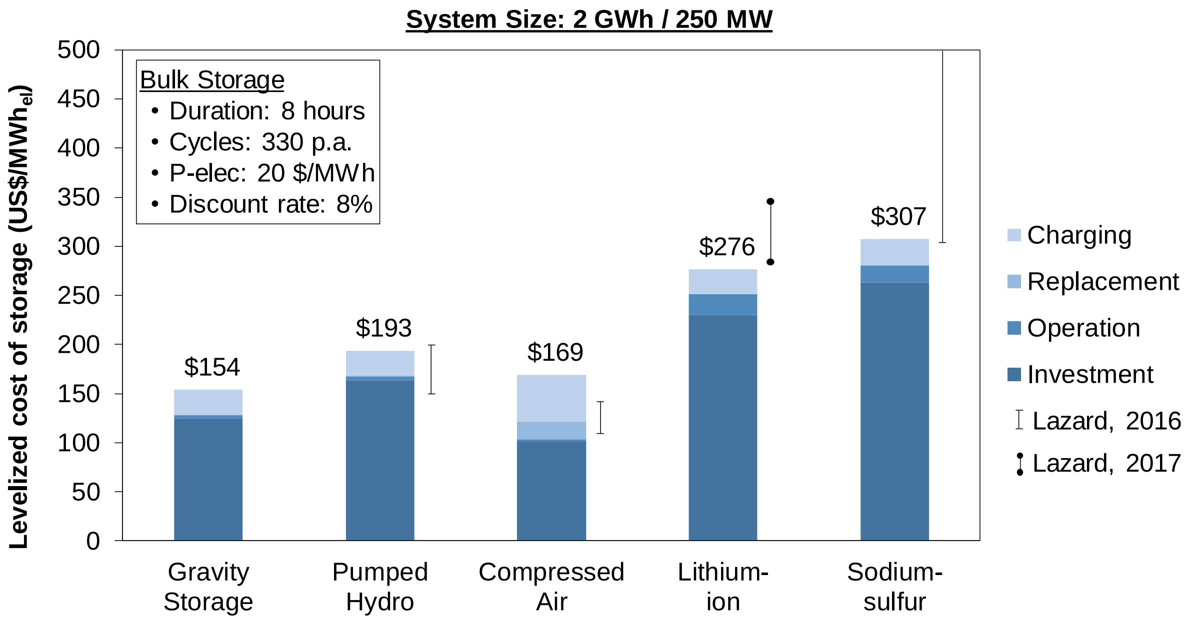
Mechanical are more cost-effective than electrochemical storage technologies due to low specific energy cost, which is significant at a discharge duration or energy-to-power ratio of 8 hours. In addition, these technologies benefit from long lifetime (40-60 years) and high discharge capability (100%), both increasing the amount of electricity discharged during technology lifetime.

LCOS for Gravity Storage is 30% lower than for pumped hydro due to its lower power cost, albeit similar specific energy cost. This is because conventional pumped hydro storage would need larger water reservoirs and longer tunnels and pipes for the same energy and power capacity.

Compared to compressed air, LCOS are 20% lower for Gravity Storage due to the higher round-trip efficiency and lower replacement cost that outweigh the significantly lower specific energy cost of compressed air.

Gravity Storage is more than 50% more cost-effective than lithium-ion and sodium-sulfur battery storage, because of significantly longer lifetime and lack of depth-of-discharge limitation and energy storage capacity degradation.





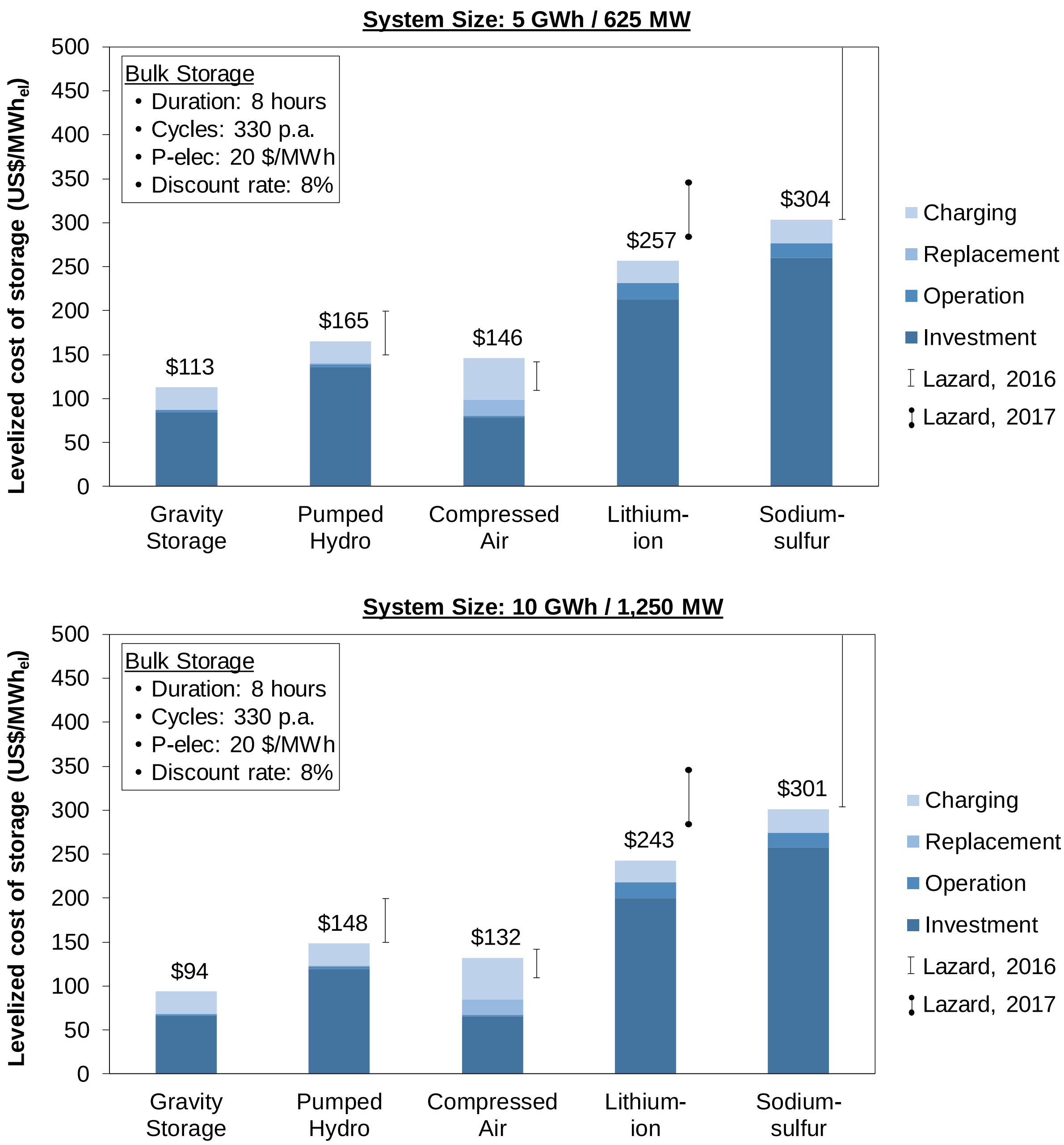


Figure 6 – LCOS in US$/MWh$_{el}$ for investigated bulk storage technologies of different sizes, 8 hours discharge duration, 330 full equivalent charge cycles per year, electricity price of 20 US$/MWh and 8% discount rate. Values are compared to results from studies by Lazard in the application "Transmission system" (System size: 0.8 GWh, 100 MW) [3] *and "Peaker replacement" (System size: 0.4 GWh, 100 MW)* [4]*. These applications were chosen for two reasons: 1. Highest similarity with application requirements investigated in this study; 2. Largest system sizes investigated by Lazard. Only lithium-ion is among technologies considered in 2017 Lazard study.*

The results are compared to LCOS studies by the financial advisory Lazard. While the 2017 report contains detailed analyses on lithium-ion as "peaker replacement" [4], the 2016 study also includes pumped hydro, compressed air and sodium-sulfur for the application "transmission system" [3], with similar application requirements to this study.

For the 5 GWh system, pumped hydro LCOS are within the range identified by Lazard. The higher investment cost assumptions used in this study (see Table 3) are countered by the lower power cost (20 US$/$MWh_{el}$ vs 35 US$/$MWh_{el}$).

Compressed air energy storage is at the upper end of the range. Here, the lower investment cost assumptions (see Table 3) are countered by the significantly lower round-trip efficiency (42 vs 77%) and the presence of replacement cost in this study. However, the lack of replacement cost and efficiency values above 50% are unrealistic for conventional, diabatic compressed air energy storage plants [9,11].

For lithium-ion, this study suggests lower LCOS than identified by Lazard. This is because of the scale impact for a 5 GWh system identified in this study. The values by Lazard are identified for a 0.4 GWh system.

Finally, the LCOS values for sodium-sulphur are still within the range identified by Lazard, despite the lower investment cost assumptions in this study (see Table 3). This is a result of the inclusion of capacity degradation and a shorter lifetime (15 vs 20 years) in this study, which have a converse impact.

In addition, the discount rate used by Lazard is not given. The impact of different discount rate assumptions is explored in the next section.

Impact Analysis – Effect of Discount Rate

The discount rate is a parameter of uncertainty and potential dispute. Figure 7 depicts the impact of a reduced discount rate on the LCOS of the investigated bulk electricity storage technologies.

A discount rate reduction from 8% to 6% translates into an LCOS reduction of 7-26%, and a discount rate reduction from 8% to 4% returns an LCOS reduction of 14-46%. In absolute terms, the LCOS for Gravity Storage at 5 GWh / 625 MW, for example, would reduce from 113 US$/MWh$_{el}$ to 89 and 68 US$/MWh$_{el}$ respectively.

Conventional pumped hydro is most affected by a change in discount rate, closely followed by Gravity Storage and then compressed air. Sodium-sulfur and lithium-ion battery systems are affected to a lesser extent. This is based on the two technology characteristics:

- Construction time: inflation of investment cost & deflation of future revenue
- Lifetime: deflation of future revenue

The long construction time (~5 years) and lifetime (40-60 years) for mechanical storage technologies render these technologies much more sensitive to the discount rate. In contrast, discount rate assumptions have a less pronounced effect on battery storage technologies due to their relatively short construction time (1-2 years) and lifetime (10-15 years).

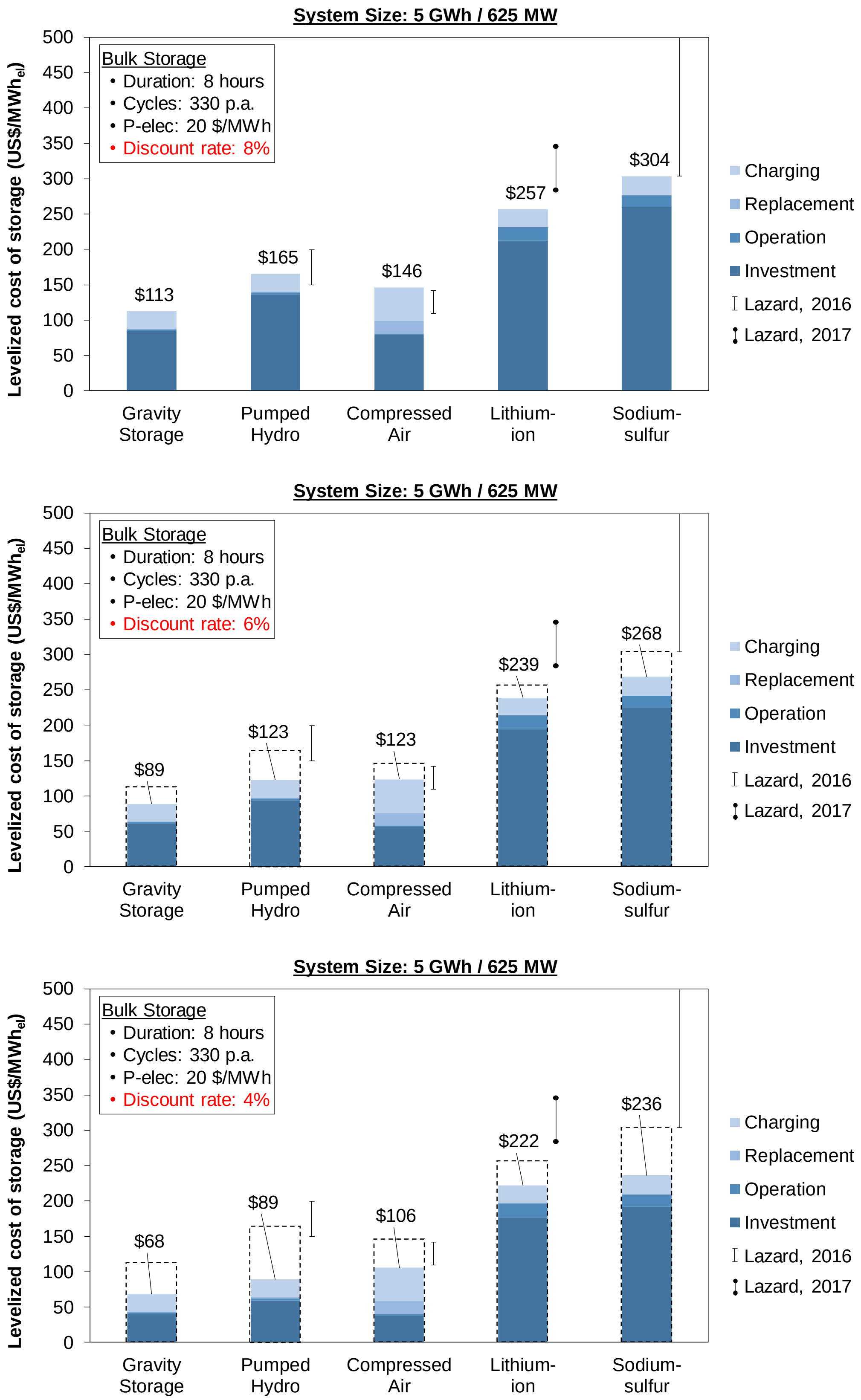


Figure 7 – Impact of different discount rate assumption (8%, 6%, 4%) on LCOS for 5 GWh / 625 MW systems. Discount rates reflect energy and infrastructure projects in recent years (8%), low current interest rates (6%) and the potential satisfaction with returns in low risk and regular, stable revenue investments (4%). Values compared to results from studies by Lazard [3,4]. *Dashed rectangles reflect respective LCOS at 8% discount rate and are included as visual guidance.*

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