Levelised Cost of Storage

The Case of Gravity Storage

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Contents

Summary

The complexity of electricity storage technologies and different requirements in applications represent a challenge for adequate cost assessment of electricity storage solutions.

Therefore, cost assessments of electricity storage solutions must be based on their levelised cost of storage (LCOS), an application-specific quantification of a technology's discounted cost of electricity per unit of discharged electricity.

Figure 1 shows the LCOS for Gravity Storage and the four most common deployed storage technologies for bulk electricity storage, and compares the values to LCOS figures identified by Lazard [1].

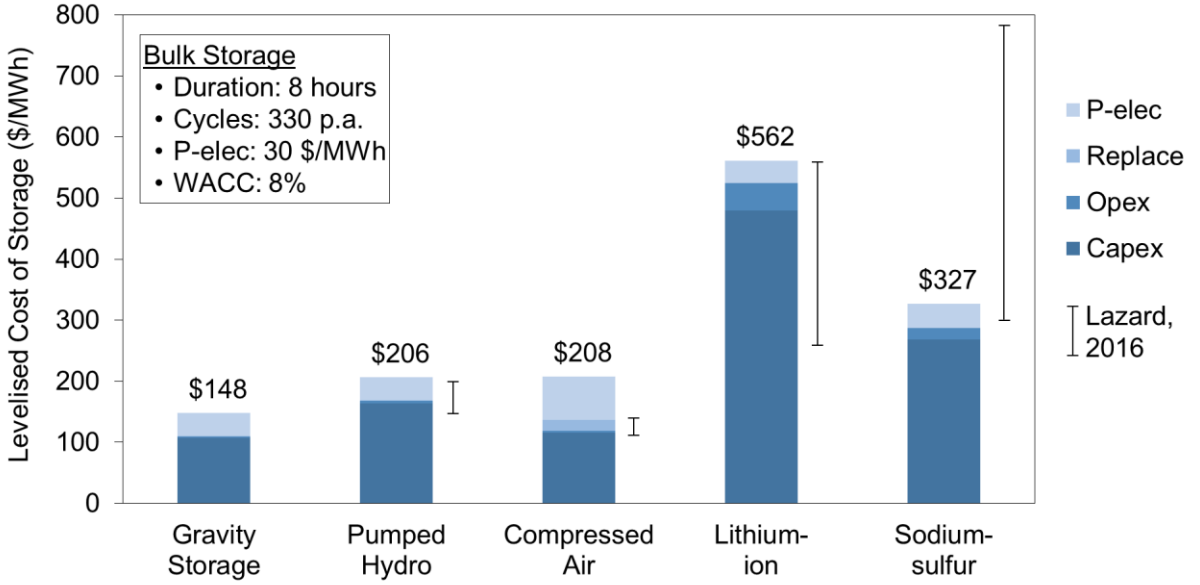

Figure 1 - Levelised cost of storage for Gravity Storage and the four comparison technologies for bulk electricity storage. Error bars indicate results for LCOS in similar study [1].

Based on the given data, Gravity Storage is most cost efficient for bulk electricity storage, followed by pumped hydro (PHS) and compressed air energy storage (CAES). Low specific energy capital costs represent the key advantage for these technologies at the required discharge duration of 8 hours. Gravity Storage further benefits from moderate specific power capital costs compared to PHS and CAES.

Differences to the figures identified by Lazard are due to the missing accounts of construction time and replacement cost for PHS and CAES as well as degradation for battery storage, and diverging assumptions for efficiency and lifetime for CAES and battery storage technologies.

The discount rate has a significant impact on LCOS, in particular for Gravity Storage, PHS and CAES due to their long construction time (inflation of capital cost & deflation of future revenues) and long lifetime (deflation of future revenues). A reduction from 8% to 6% or 4% leads to reduced LCOS of up to 25% or 45% respectively.

Levelised Cost of Storage – Definition and Method

The complexity of electricity storage technologies and fundamentally different requirements in applications represent a challenge for adequate cost assessment of electricity storage solutions. In addition, capital costs can be reported for varying technology scopes (e.g. cells, packs, systems), while other technical or economic parameters that are key to overall lifetime cost are neglected. Therefore, an appropriate cost assessment of electricity storage solutions must be based on the metric: levelised cost of storage, for a specific application at comparable technology scopes.

Definition

The levelised cost of storage (LCOS) quantifies the discounted cost of electricity per unit of discharged electricity [2]. This refers to electrical energy ($/MWh) or electric power ($/MW) [3]. It thereby accounts for all technical and economic parameters influencing the lifetime cost of storing and discharging electricity and is comparable to the levelised cost of electricity (LCOE) for energy generation technologies. Current literature also refers to this metric as: levelised cost of stored energy [4], life cycle cost [5] or levelised cost of electricity [6]. Some studies differentiate between net internal costs of storing electricity, excluding power price and storage efficiency, and cost per unit of discharged electricity, including both. This report uses the latter, in line with the above definition and the most impactful LCOS studies to date [1–3].

The different requirements of electricity storage applications in terms of size, discharge duration, i.e. inverse of C-rate, or annual cycles affect capital costs or operational life. In addition, some applications require electric energy, others electric power. Thus, an LCOS comparison for electricity storage technologies must use the appropriate basis ($/MWh or $/MW) and must be performed for each application separately. This analysis explores LCOS for bulk electricity storage using the $/MWh basis.

The considered technology scope includes all technology components required to charge, store and discharge electricity up to and including the transformer at the intersection with the transmission grid.

Method

A comprehensive LCOS comparison should include all relevant components that affect lifetime cost of a technology. Table 1 reviews the LCOS components included in recent studies. Regarding economic parameters, replacement cost, residual value and taxes are not always included. While the former two should be considered, taxes are relevant in a location-specific context, which is not the case in this analysis. Regarding technical parameters, cycle life, shelf life, construction time, degradation and self-discharge are not always considered, although they should be. This analysis only excludes self-discharge as it is irrelevant at daily cycling for the technologies considered.

Table 1 – LCOS components included in recent LCOS studies.

	LCOS components	**Apricum** [3]	**Jülch** [2]	**Lazard** [1]	**This report**
Economic	Capital cost	x	x	x	x
	Replacement cost		x	x	x
	Operating cost	x	x	x	x
	Power cost	x	x	x	x
	Residual value	x	x		x
	Discount rate / WACC	x	x	x	x
	Taxes			x	
Technical	Nominal capacity	x	x	x	x
	Depth of discharge	x	x	x	x
	Round-trip efficiency	x	x	x	x
	Cycle life	x	x		x
	Shelf life		x		x
	Construction time				x
	Degradation rate	x			x
	Self-discharge		x		

Below formula depicts the LCOS components included in this analysis. These are:

- **Capital cost (Capex):** The model considers specific energy and power capital costs. Multiplying these with nominal energy and power capacity respectively yields total capital cost.

- **Replacement cost ($Capex_r$):** Technology components need replacement at specified replacement intervals. In the model, these costs are represented as energy and power specific replacement costs and multiplied with energy or power capacity respectively.

- **Operating cost (Opex):** Fixed operating cost per year and variable operating cost per unit electricity charged or discharged are combined and displayed as a percentage of the total capital cost of the given technology.

- **Power cost (P_{el}):** 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.

- **Residual value (Residual):** The technology's end-of-life value is included as residual value. It is applied in the year subsequent to the final operation year.

- **Discount rate (r):** Weighted average cost of capital (WACC) at which future expenses or revenues are discounted. In the model, it is used to discount capital cost during construction time, replacement cost, operating cost and residual value. Also, electricity generation is discounted as it represents future revenues.

- **Nominal capacity (C_{nom}):** The model considers nominal energy storage capacity, nominal power capacity and discharge duration to relate the two.

- **Depth-of-discharge (DoD)**: Amount of usable energy storage capacity. Some technologies experience severe degradation when fully charged or discharged. Depth-of-discharge indicates charge and discharge levels that can be sustained without significant degradation.

- **Round-trip efficiency (η_{RT}):** This metric indicates how much of the electricity that is used to charge the battery can be discharged later on. It covers the whole technology scope from charging to discharging at the transformer.

- **Lifetime (N):** The operating life of a technology. It is defined by the minimum value of shelf life or cycle life divided by full cycles per year.

- **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 capital costs and deflates future revenues. It is assumed that capital costs are made available in the first year and spent at half the construction time, a valid simplification in the absence of detailed financing plans (similar result to spending equal fractions each year).
- **Annual degradation (Deg):** Nominal energy storage capacity of certain technologies reduces with the number of cycles (relative to DoD) and time. This is represented as an annual percentage of nominal energy storage capacity.
- **Period (n):** A particular year under consideration.
- **Replacement intervals:** Regular intervals at which replacement occurs.
- **Replacement number:** Number of replacement events during operating life.

$$LCOS\left[\frac{\$}{MWh}\right] =$$

$$\frac{\frac{CAPEX}{(1+r)^{\frac{T_c-1}{2}}} + \sum_{R=1}^{\frac{N}{T_r}} \frac{CAPEX_R}{(1+r)^{T_c+R*T_r}}}{\#cycles * DoD * C_{nom} * \eta_{RT} * \sum_{n=1}^{N} \frac{(1+DEG)^n}{(1+r)^{n+T_c}}}$$

$$+\frac{\sum_{n=1}^{N} \frac{OPEX}{(1+r)^{n+T}}}{\#cycles * DoD * C_{nom} * \eta_{RT} * \sum_{n=1}^{N} \frac{(1+DEG)^n}{(1+r)^{n+T_c}}}$$

$$-\frac{\frac{Residual}{(1+r)^{N+T_c+1}}}{\#cycles * DoD * C_{nom} * \eta_{RT} * \sum_{n=1}^{N} \frac{(1+Deg)^n}{(1+r)^{n+T_c}}}$$

$$+\frac{P_{el}}{\eta_{RT}}$$

Capex:	Capital cost ($)
Capex$_r$:	Replacement cost ($)
Opex:	Operating cost ($)
Residual:	Residual value ($)
P_{el}:	Power cost ($/kWh$_{el}$)
r:	Discount rate / WACC (%)
C_{nom}:	Nominal capacity (MWh)
DoD:	Depth-of-discharge (%)
η_{RT}:	Round-trip efficiency (%)
N:	Lifetime (years)
#cycles:	Full cycles per year (#)
T_c:	Construction time (years)
Deg:	Annual degradation (%)
n:	Period (year)
T_r:	Replacement interval (years)
R:	Replacement number (#)

Input Data – Storage Technologies and Characteristics

This analysis for bulk electricity storage considers Gravity Storage, pumped hydro, compressed air, lithium-ion and sodium-sulfur battery storage. In 2010, the latter four were the most common deployed electricity storage technologies (Fig. 2).

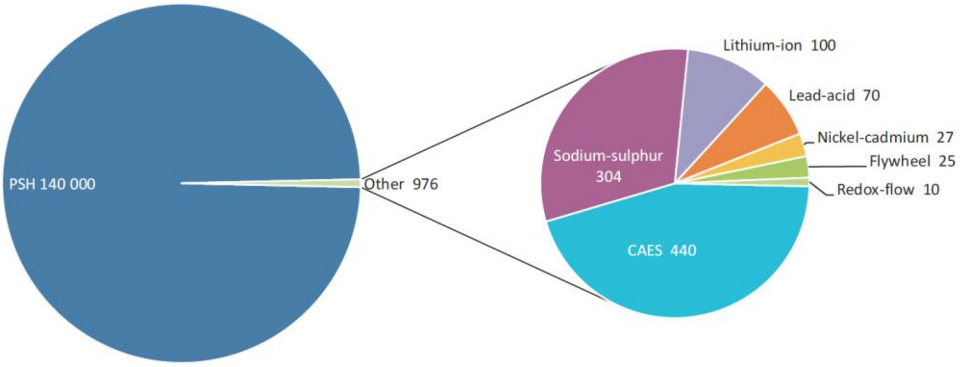

Figure 2 – Global installed electricity storage capacity in 2010 in MW [7]*; PSH – Pumped Hydro Storage, CAES - Compressed Air Energy Storage*

By 2017, their installed capacity has changed to

- Pumped hydro storage: 169,000 MW [8]
- Compressed air energy storage: 410 MW [8]
- Lithium-ion battery storage: 2,600 MW [9]
- Sodium-sulfur battery storage: 530 MW [10]

Table 2 depicts the economic and technical characteristics of these technologies. These values are used as input parameters for the LCOS model.

Nominal capacities reflect realistic system sizes for each technology in bulk electricity storage application for which industry data were available. Changes in nominal capacity may affect energy and power specific capital costs. These are represented explicitly to minimise the impact of different system sizes on total capital cost.

The **discharge duration** of 8 hours is applied across all technologies to reflect bulk electricity storage and ensure comparability between the technologies.

Table 2 – Technology parameters for bulk electricity storage.

Input Data		**Gravity Storage**	**Pumped Hydro**[11]	**Compr. Air**[11]	**Lithium-ion**[12]	**Sodium-sulfur**[11]
Nominal capacity	kWh	8,000,000	9,600,000	1,088,000	35,000	720,000
Discharge duration	hours	8	8	8	8	8
Capex - energy	$/kWh	148	93	17	538	298
Capex - power	$/kW	579	1,950	825	615	490
Replacement - energy	$/kWh	-	-	-	538	298
Replacement - power	$/kW	25	112	90	615	490
Opex	%	0.30%	0.31%	0.36%	1.38%	0.88%
Residual value	$/kWh	-	-	-	-	-
Depth of discharge	%	100%	100%	100%	80%	80%
Round-trip efficiency	%	80%	80%	42%	81%	75%
Degradation	% pa	0%	0%	0%	-3%	-2%
Construction time	years	5	5	5	1	2
Cycle life	#	19,800	21,900	14,600	3,500	5,500
Shelf life	years	60	60	40	10	15
Replacement interval	years	10	20	4	10	15
Power cost	$/kWh$_{el}$	0.03	0.03	0.03	0.03	0.03
Annual cycles	#	330	330	330	330	330
Discount rate / WACC	%	8%	8%	8%	8%	8%

Specific energy / power capital cost represent the marginal cost of building or adding a unit energy or power capacity to the storage technology. Table 3 compares resulting **total capital cost** per energy capacity to data inputs used in Lazard's LCOS study for 8 hour storage duration applications. The values for compressed air and sodium-sulfur battery storage are lower in this analysis. For pumped hydro and lithium-ion, they are within the range identified by Lazard.

Table 3 – Comparison of total capital cost per nominal energy storage capacity data to Lazard data.

Capital cost	**Comment**	**Pumped Hydro**	**Compressed Air**	**Lithium-ion**	**Sodium-sulfur**
$/kWh *(total/energy)*	This model	337 [11]	120 [11]	1,713 [12]	366 [11]
	Lazard	238-350 [1]	146-210 [1]	1,633-1,876 [1]	468-1,369 [1]

Replacement costs for battery technologies reflect their capital costs. This is based on the assumption that no replacement takes place during the operational life and the complete battery and balance-of-plant would have to be replaced at its end.

Operational costs for pumped hydro and compressed air energy storage are ~0.3% of total capital costs. Replacement costs are accounted for separately, while other studies often combine replacement and operational costs.

For this analysis, no **residual value** for any technology is assumed. This is based on the uncertainty whether technology components have a distinct value or incur disposal costs at their end-of-life.

Round-trip efficiency for compressed air energy storage (CAES) is assumed 42%, lower than in other LCOS studies (e.g. [1,5]). Those studies consider adiabatic instead of conventional CAES or do not account for the natural gas required during discharge in conventional CAES plants. Their complete exergetic efficiency of charging, storage and discharging is between 25-45% [13]. Data provided for battery storage technologies are for the complete system, including losses from power conversion, HVAC equipment loads, control system and self-consumption [12]. It is common to state efficiency values without these components. However, they add 5-10% losses [12].

Construction time is assumed equal for mechanical (~5 years [14]) and significantly lower for battery storage technologies (1 – 2 years).

Power costs and **annual cycles** are equal for all technologies. These inputs are determined by the storage application.

A **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.

Results – LCOS Values and Differences to Lazard's Analysis

Based on the given input data, Gravity Storage is the most cost-effective technology for bulk electricity storage at 148 $/MWh, followed by pumped hydro and compressed air energy storage at ~200 $/MWh (see Fig. 3). Sodium-sulfur and lithium-ion battery storage is significantly more expensive at 327 and 562 $/MWh respectively.

The superiority of mechanical storage technologies is based on their low specific energy capital cost, which is significant at a discharge duration of 8 hours. In addition, these technologies benefit from long lifetime (40-60 years) and high discharge capability (100%). LCOS for Gravity Storage is another 25% cheaper than for pumped hydro or compressed air due to its lower power cost, albeit marginally higher energy cost.

The relatively high energy cost for battery technologies translate into a significant capital cost disadvantage per nominal energy storage capacity in this application, in particular for lithium-ion (see Table 3). This effect is increased by the limited depth-of-discharge (~80%). Capacity degradation and the short operational life have a further detrimental effect on LCOS in this application.

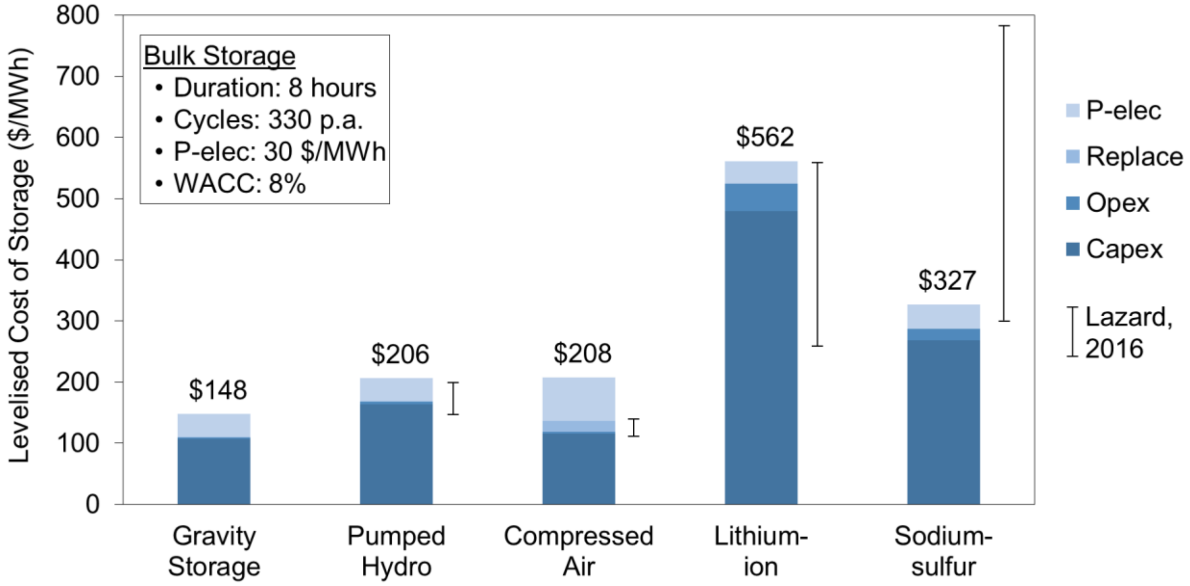

Figure 3 – Levelised cost of storage for Gravity Storage and the four comparison technologies for bulk electricity storage. Error bars indicate results for LCOS in similar study [1].

The results differ from the values obtained by Lazard in the application "Transmission system" with similar performance requirements [1]. This is due to the missing account of construction time and replacement cost for mechanical technologies and battery degradation, and different efficiency and lifetime assumptions for compressed air and battery storage.

Reducing construction time from 5 to 1 year for mechanical storage technologies reduces their LCOS by 20-30% in this analysis and leaves pumped hydro and compressed air at the lower end or slightly above the range found by Lazard. Construction time inflates capital costs and deflates future revenue, a significant impact at a discount rate of 8%.

When omitting replacement costs and assuming an efficiency of 77% for compressed air (same as Lazard), LCOS is at 80 $/MWh, below the range given by Lazard. This is intuitive given the lower capital cost assumption in this present analysis (see Table 3). However, such replacement and efficiency assumptions are unrealistic for conventional, diabatic compressed air plants [11].

When omitting degradation and assuming a 20 year lifetime without replacement costs, the LCOS for lithium-ion battery storage drop to 370 $/kWh, within Lazard's range. The same adjustments for sodium-sulfur battery storage returns 260 $/MWh, which is slightly below Lazard's range. Again, this is intuitive given the lower capital cost assumption in this present analysis.

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 and Project Duration

Discount Rate

The discount rate is a parameter of uncertainty and potential dispute. Figure 4 depicts the impact of a reduced discount rate on the LCOS of the investigated technologies.

A reduced discount rate of 6% translates into an LCOS reduction of 7-25% and a discount rate of 4% to 14-45%. Pumped hydro is most affected, closely followed by Gravity Storage and compressed air. Sodium-sulfur and lithium-ion battery storage is affected to a lesser extent. This is based on the two technology characteristics:

- Construction time: inflation of capital costs & deflation of future revenue
- Lifetime: deflation of future revenue

The long construction time (5 years) and lifetime (40-60 years) for mechanical storage technologies renders these technologies much more sensitive to the discount rate. Conversely, 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).

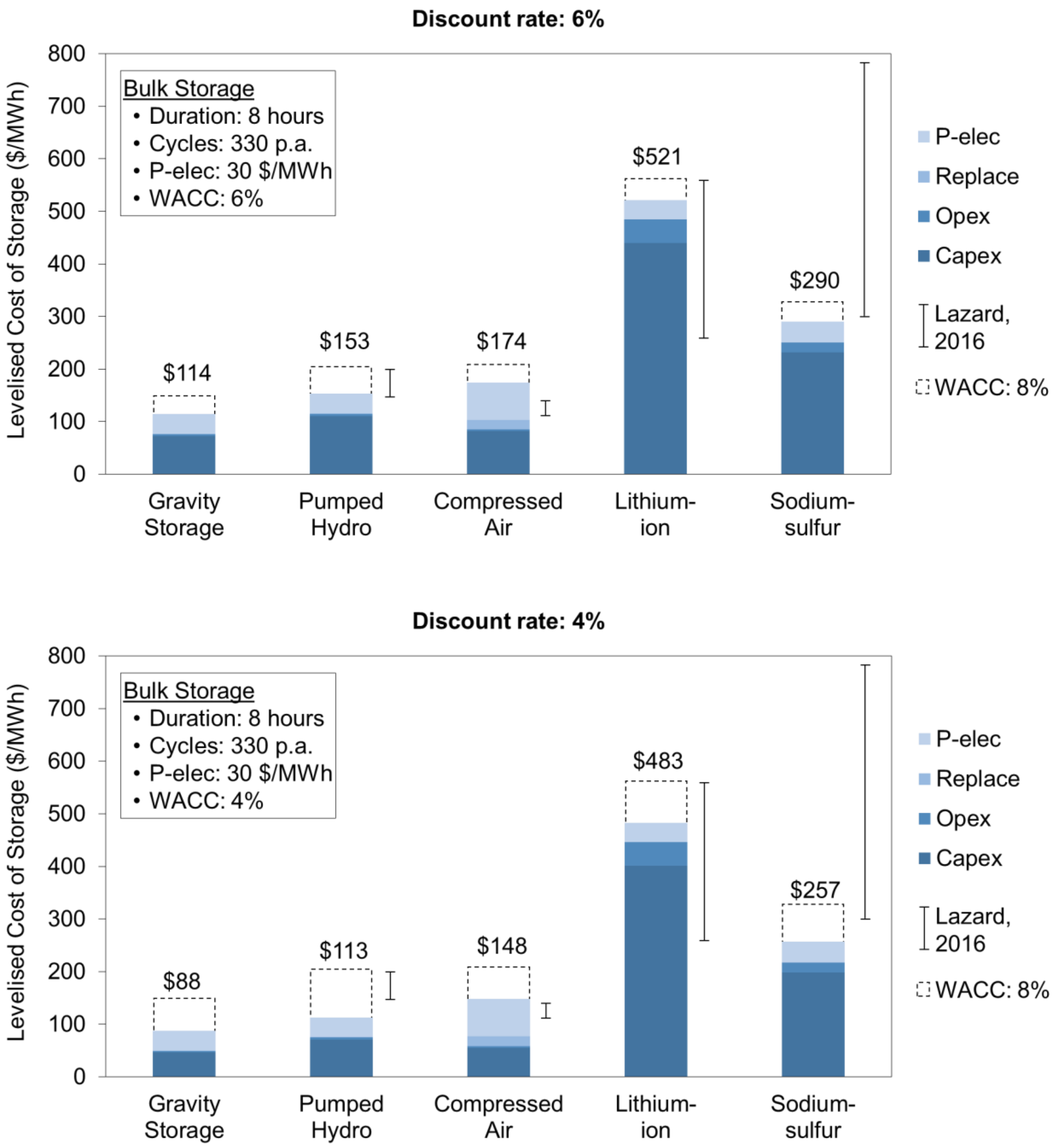

Figure 4 – Effect of reduced discount rate of 6% (top) and 4% (bottom) on LCOS of investigated technologies for bulk electricity storage.

Project Duration

This analysis determines LCOS with respect to individual lifetimes of the different technologies, i.e. 10, 15, 40 or 60 years. If constant project durations were assumed across all technologies, regardless of individual lifetimes, two effects could be observed:

- Project duration > individual lifetime: LCOS change relative to whether new capital costs outweigh future revenues or vice versa

- Project duration < individual lifetime: LCOS increase, because suboptimal future revenues are earned

At fixed project duration of 65 years, LCOS for Gravity and pumped hydro storage remain unchanged as it represents their optimum, i.e. 60 year lifetime plus 5 years construction (see Fig. 5). For CAES, revenues for an additional 20 years of operation outweigh the additional capital cost for a new plant in year 45 slightly and reduce LCOS from 208 to 206 $/MWh. The opposite is the case for battery storage technologies with LCOS increasing from 562 to 678 $/MWh for lithium-ion and 327 to 354 $/MWh for sodium-sulfur.

At fixed project duration of 11 years, the optimum for lithium-ion battery storage (10 year lifetime + 1 year construction), its LCOS remain unchanged. Because this duration is suboptimal for all other technologies, their LCOS increase as a result of uncaptured future revenues.

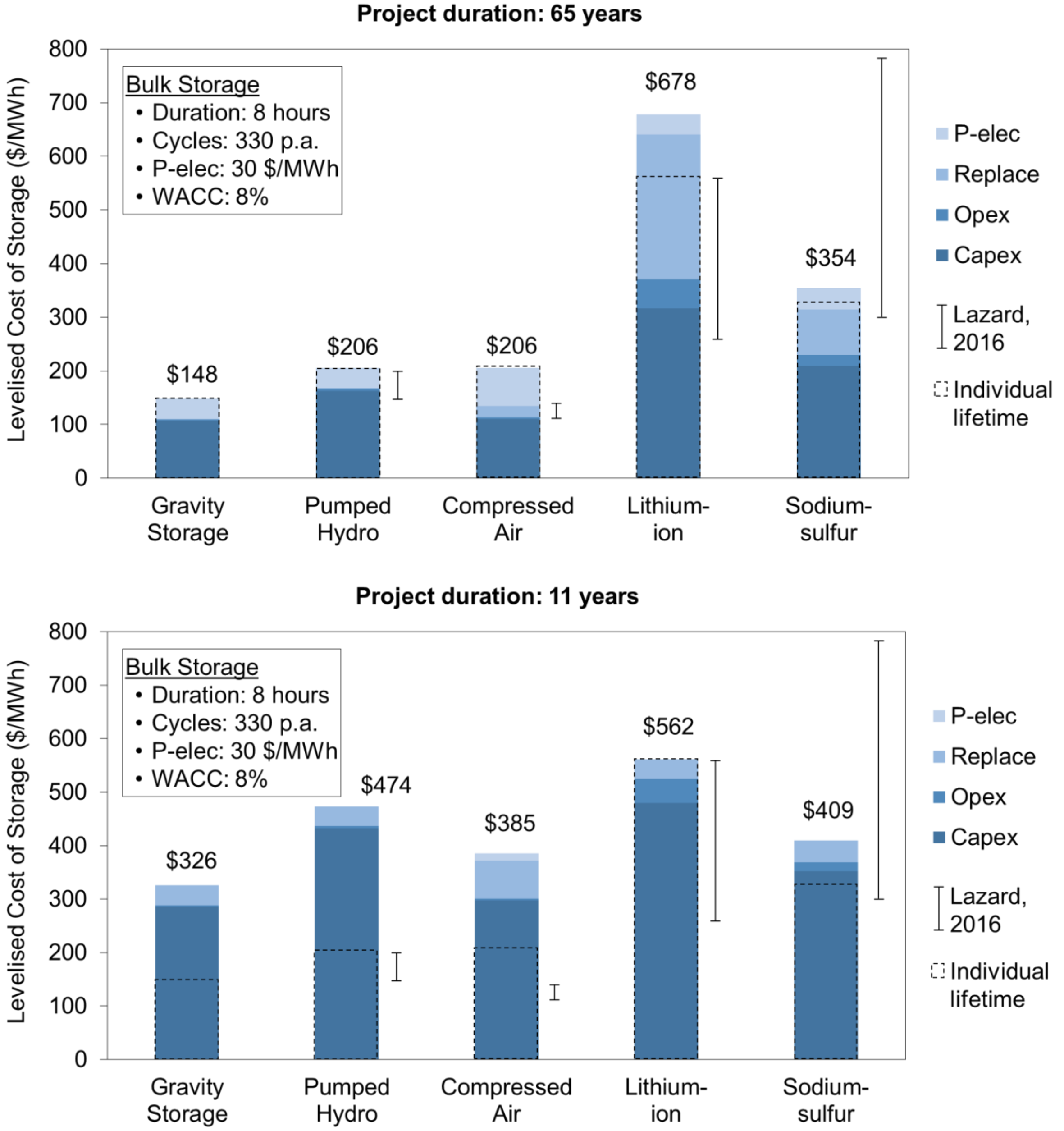

Figure 5 – Effect of fixed project duration of 65 years (top) or 11 years (bottom) on LCOS of investigated technologies for bulk electricity storage.

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