Cost Projections for Utility-Scale Battery Storage: 2023 Update

Wesley Cole and Akash Karmakar

National Renewable Energy Laboratory

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Executive Summary

In this work we describe the development of cost and performance projections for utility-scale lithium-ion battery systems, with a focus on 4-hour duration systems. The projections are developed from an analysis of recent publications that include utility-scale storage costs. The suite of publications demonstrates wide variation in projected cost reductions for battery storage over time. Figure ES-1 shows the suite of projected cost reductions (on a normalized basis) collected from the literature (shown in gray) as well as the low, mid, and high cost projections developed in this work (shown in black). Figure ES-2 shows the overall capital cost for a 4-hour battery system based on those projections, with storage costs of $245/kWh, $326/kWh, and $403/kWh in 2030 and $159/kWh, $226/kWh, and $348/kWh in 2050. Battery variable operations and maintenance costs, lifetimes, and efficiencies are also discussed, with recommended values selected based on the publications surveyed.

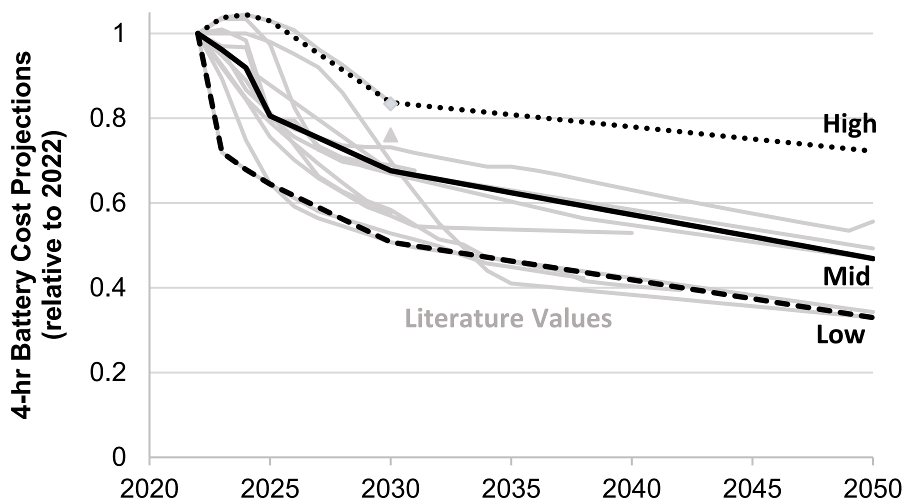

Figure ES-1. Battery cost projections for 4-hour lithium-ion systems, with values normalized relative to 2022. The high, mid, and low cost projections developed in this work are shown as bolded lines.

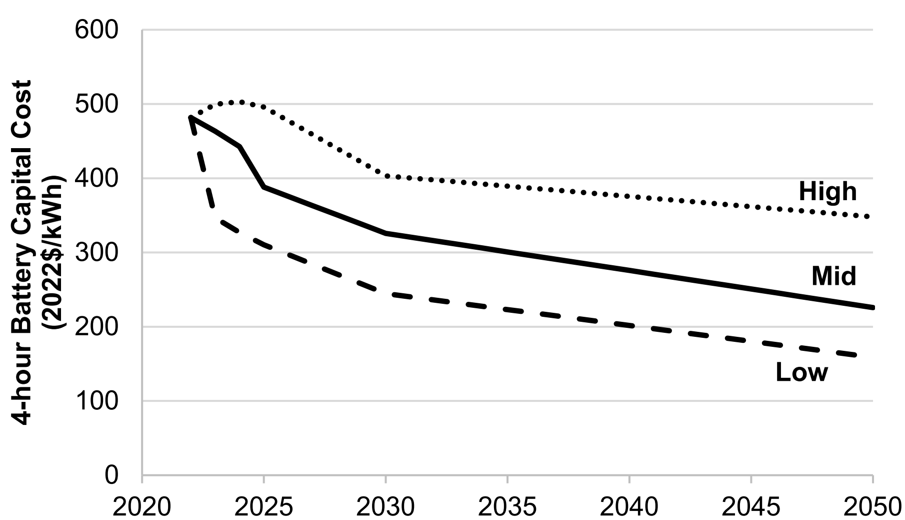

Figure ES-2. Battery cost projections for 4-hour lithium-ion systems.

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1 Background

Battery storage costs have changed rapidly over the past decade. In 2016, the National Renewable Energy Laboratory (NREL) published a set of cost projections for utility-scale lithium-ion batteries (Cole et al. 2016). Those 2016 projections relied heavily on electric vehicle battery projections because utility-scale battery projections were largely unavailable for durations longer than 30 minutes. In 2019, battery cost projections were updated based on publications that focused on utility-scale battery systems (Cole and Frazier 2019), with updates published in 2020 (Cole and Frazier 2020) and 2021 (Cole, Frazier, and Augustine 2021). There was no update published in 2022. This report updates those cost projections with data published in 2021, 2022, and early 2023.

The projections in this work focus on utility-scale lithium-ion battery systems for use in capacity expansion models. These projections form the inputs for battery storage in the Annual Technology Baseline (NREL 2022). The projections are then utilized in NREL's capacity expansion models, including the Regional Energy Deployment System (ReEDS) (Ho et al. 2021) and the Resource Planning Model (RPM) (Mai et al. 2013).

2 Methods

The cost and performance projections developed in this work use a literature-based approach in which projections are generally based on the low, median, and highest values from the literature. Table 1 lists the publications that are presented in this work. Because of rapid price changes and deployment expectations for battery storage, only the publications released in 2022 and 2023 are used to create the projections. In addition to the publications in Table 1, we also include a 2020 report by the Electric Power Research Institute (EPRI 2020) for operations and maintenance (O&M) and performance assumptions, but we do not use their cost projection because it was published before 2022.

There are a number of challenges inherent in developing cost and performance projections based on published values. First among those is that the definition of the published values is not always clear. For example, dollar year, online year, duration, depth-of-discharge, lifetime, and O&M are not always defined in the same way (or even defined at all) for a given set of values. As such, some of the values presented here required interpretation from the sources specified. Second, many of the published values compare their published projection against projections produced by others, and it is unclear how much the projections rely upon one-another. Thus, if one projection is used to inform another, that projection might artificially bias our results (toward that particular projection) more than others. Third, because of the relatively limited dataset for actual battery systems and the rapidly changing costs, it is not clear how different battery projections should be weighted. For example, should projections published in the latter half of 2022 be given higher weight than those published earlier? Or are some organizations better at making projections or capturing supply chain disruptions, and therefore should be given higher weight?

In the interest of providing a neutral survey of the current literature, all cost projections included in this report are weighted equally. As we performed our review of published projections, we found that many of them cited either the previous updates of this report, or they cited the Annual Technology Baseline, which also relies on this cost projection report for its inputs. Thus, including all of the latest published projections would create known redundancies (per the second challenge listed above) and were therefore excluded from this work. In some cases, our previous work was provided as a starting point for projections, and then adjustments were made to better capture analysts' view of battery storage pricing. If that was the case, we considered the projection unique and included it in our survey.

Table 1. List of publications used in this study to determine battery cost and performance projections. In several cases consultants were involved in creating the storage cost projections. In these instances we list the consulting firm first, followed by the organization they are supporting.

Organization	Source
AES Indiana	AES Indiana 2022 Integrated Resource Plan (AES Indiana 2022)
BNEF	Bullard (2023)
Brattle	Newell et al. (2022)
Charles River Associates (CRA) / Duke Energy	Duke Energy and CRA (2022)
E3 / New York Department of Public Service (NYDPS) / New York State Energy Research and Development Authority (NYSERDA)	New York's 6 GW Energy Storage Roadmap (NYDPS and NYSERDA 2022)
E Source	Jaffe (2022)
Energy Information Administration (EIA)	Annual Energy Outlook 2023 (EIA 2023)
Ascend Analytics / Grant Public Utility District (PUD)	Grant PUD Integrated Resource Plan 2022 (Grant PUD 2022)
Guidehouse	Guidehouse (2021)
International Energy Agency	World Energy Outlook 2022 (IEA 2022)
IHS / PJM	Huntington and Wang (2022)
Lazard	Lazard (2023)
Pacific Northwest National Laboratory (PNNL)	Viswanathan et al. (2022)
Siemens / Public Service Company of New Mexico (PNM)	PNM and Siemens (2022)
Tri-State Generation & Transmission Association	All-Source Solicitation 30-Day Report (2022)
Wood Mackenzie	Wood Mackenzie (2022)

All cost values were converted to 2022$ using the consumer pricing index. In cases where the dollar year was not specified, the dollar year was assumed to be the same as the publication year. When future costs were presented in nominal dollars, they were converted to real dollars using the inflation rate specified by the document. If no inflation rate was found in the document, we found used the inflation rate assumed in other recent documents produced by the same organization.

We only used projections for 4-hour lithium-ion storage systems. We define the 4-hour duration as the output duration of the battery, such that a 4-hour device would be able to discharge at rated power capacity for 4-hours. In practice that would mean that the device would charge for more than 4 hours and would nominally hold more than its rated energy capacity in order to compensate for losses during charge and discharge.

We report our price projections as a total system overnight capital cost expressed in units of $/kWh. However, not all components of the battery system cost scale directly with the energy capacity (i.e., kWh) of the system (Ramasamy et al. 2022). For example, the inverter costs scale according to the power capacity (i.e., kW) of the system, and some cost components such as the developer costs can scale with both power and energy. By expressing battery costs in $/kWh, we are deviating from other power generation technologies such as combustion turbines or solar photovoltaic plants where capital costs are usually expressed as $/kW. We use the units of $/kWh because that is the most common way that battery system costs have been expressed in published material to date. The $/kWh costs we report can be converted to $/kW costs simply by multiplying by the duration (e.g., a $300/kWh, 4-hour battery would have a power capacity cost of $1200/kW).

To develop cost projections, storage costs were normalized to their 2022 value such that each projection started with a value of 1 in 2022. We chose to use normalized costs rather than absolute costs because systems were not always clearly defined in the publications. For example, it is not clear if a system is more expensive because it is more efficient and has a longer lifetime, or if the authors simply anticipate higher system costs. With the normalized method, many of the differences matter to a lesser degree.

We defined our low, mid, and high projections as the minimum, median, and maximum point, respectively in 2023, 2024, 2025 and 2030. The minimum and median points were also defined in the same way because the minimum and median projections extended through 2050. The maximum projection in 2030 did not extend through 2050. One projection showed only a 5.8% cost decline from 2030 to 2050, so we used this as the basis for extending the highest cost 2030 projection through to 2050. In other words, the highest cost projection in 2030 was assumed to decline by 5.8% through 2050.

Points in between 2025, 2030, and 2050 were set based on linear interpolation between years with values assigned. To convert these normalized low, mid, and high projections into cost values, the normalized values were multiplied by the 4-hour battery storage cost from Ramasamy et al. (2022) to produce 4-hour battery systems costs.

To estimate the costs for other storage durations (i.e., durations other than 4 hours), we assign separate energy costs and power costs such that

$$\text{Total Cost (\$/kWh)} = \text{Energy Cost (\$/kWh)} + \text{Power Cost (\$/kW)} / \text{Duration (hr)}$$

To separate the total cost into energy and power components, we used the relative energy and power costs from Augustine and Blair (2021). These relative shares are projected through 2050, enabling an approach for calculating the cost for any duration of energy storage. Because we focus primarily on multi-hour battery configurations, we caution against using this approach to calculate battery storage costs with less than one hour duration.

The method employed in this work relies solely on literature projections. It does not take into account other factors that might impact costs over time, such as materials availability, market size, and policy factors. Unless these and other factors are not captured in the work surveyed, then they will not be reflected in the projection produced here.

3 Results and Discussion

The normalized cost trajectories with the low, mid, and high projections are shown in Figure 1. The high projection follows the highest cost trajectory through 2030. This includes cost increases through 2025, with costs only being lower than the 2022 costs starting in 2026. After 2030, the high projection declines by 5.8% as described in the methods section. The mid and low projections have initial slopes being steeper than later slopes, indicating that most publications see larger cost reductions in the near-term that then slow over time. By 2030, costs are reduced by 47%, 32%, and 16% in the low, mid, and high cases, respectively, and by 2050 are reduced by 67%, 51%, and 21%, respectively.

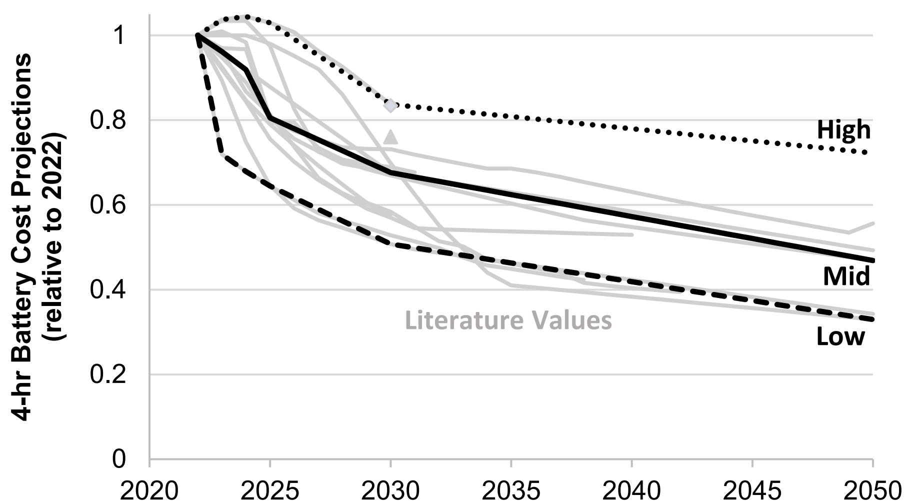

Figure 1. Battery cost projections for 4-hour lithium-ion systems, with values relative to 2022. The high, mid, and low cost projections developed in this work are shown as bolded lines. Published projections are shown as gray lines. Figure values are included in the Appendix.

The resulting total system cost for a 4-hour battery storage device is shown in Figure 2. The 2022 starting point of $482/kWh is taken from Ramasamy et al. (2022). Although there is uncertainty in the 2022 cost (which is discussed later), we use a single cost for 2022 for convenience as we apply these costs in our long-term planning models (applying the same costs in 2022 means that the 2022 solution will not change as we shift from a “high” to a “mid” to a “low” cost projection for storage). By definition, the projections follow the same trajectories as the normalized cost values. Storage costs are $255/kWh, $326/kWh, and $403/kWh in 2030 and $159/kWh, $237/kWh, and $380/kWh in 2050. Costs for each year and each trajectory are included in the Appendix.

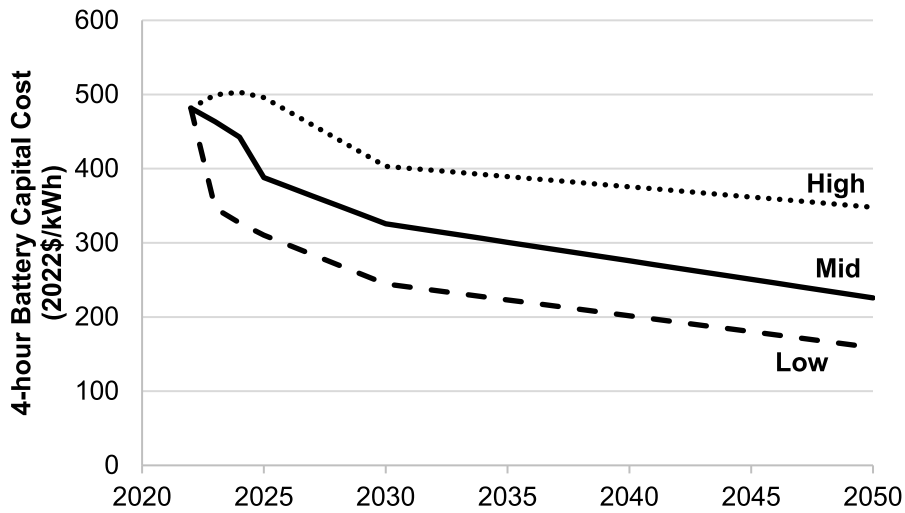

Figure 2. Battery cost projections for 4-hour lithium-ion systems.

These values represent overnight capital costs for the complete battery system. Figure values are included in the Appendix.

One of the key assumptions in our projections is the choice of the starting point. A higher or lower starting point would shift the set of projections up or down relative to the change in magnitude of the starting point. To better assess the quality of our starting point, we compared the value from NREL's cost estimate from Ramasamy et al. (2022) with other recently published values (shown in Figure 3). This comparison shows that our starting point is on the high end but generally within the range of estimated current pricing. This higher starting point is the single largest driver for why this year's cost projections are higher than those previously published.

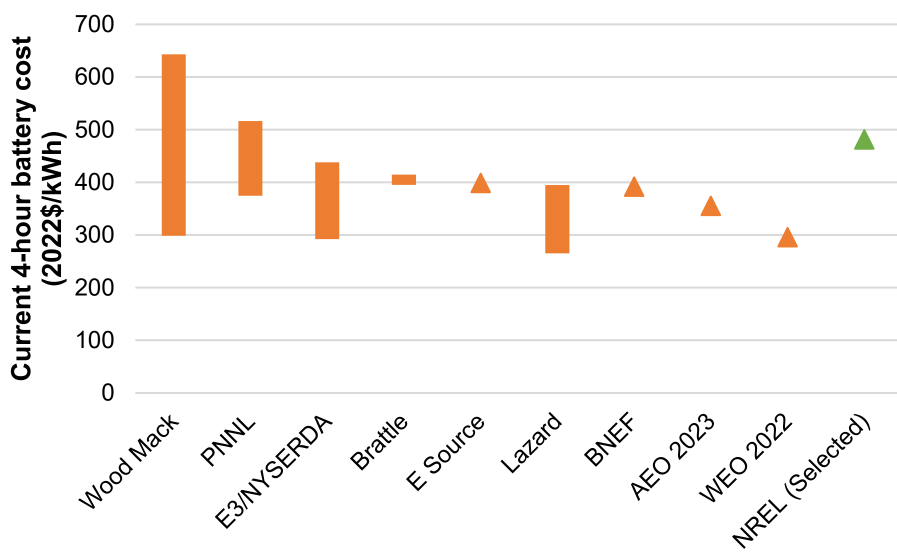

Figure 3. Current battery storage costs from recent studies. The NREL value (Ramasamy et al. 2022) was selected as the 2022 starting cost for this work.

One of the other challenges with using the normalized cost reductions to develop our projections is that projections that start at a higher value than our starting point might see greater cost reduction potential, and thus have a high percent reduction but still never have a low $/kWh cost. Conversely, projections that start lower than our starting point might have smaller cost reduction potential on a percentage basis but achieve very low $/kWh costs. However, we still prefer to use the normalized cost reduction numbers because of the large discrepancy in starting costs across published projections, and because it helps to obviate the challenge of different cost and system definitions in the different publications.

Figure 4 shows the cost projections for the power and energy components of the battery. These components are combined to give a total system cost, where the system cost (in $/kWh) is the power component divided by the duration plus the energy component.

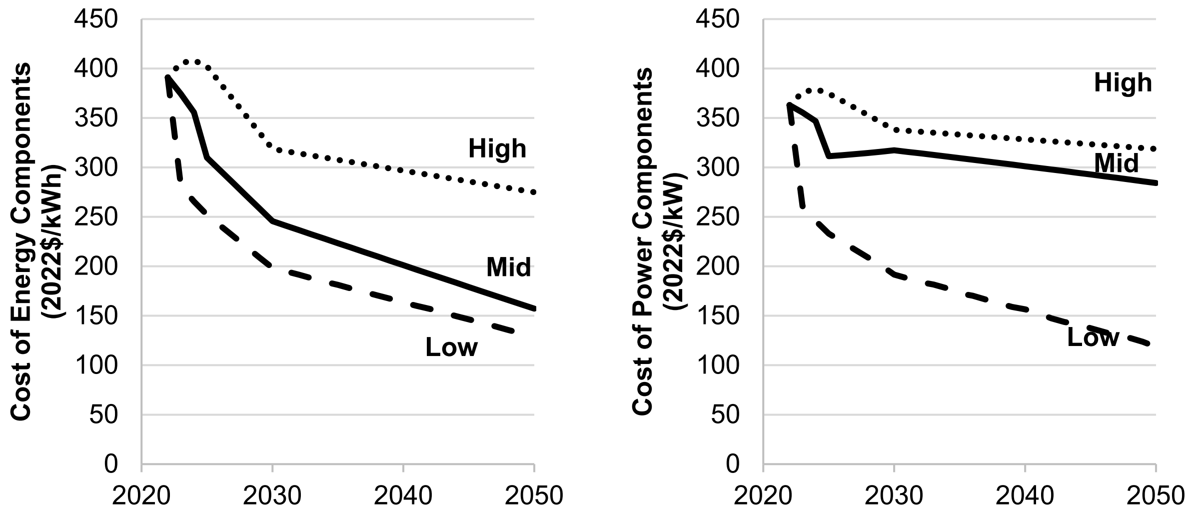

Figure 4. Cost projections for energy (left) and power (right) components of 4-hour lithium-ion systems. Note the different units in the two plots.

These power and energy costs can be used to specify the capital costs for other durations. Figure 5 shows the cost projections for 2-, 4-, and 6-hour duration batteries (using the mid projection only). On a $/kWh basis, longer duration batteries have a lower capital cost, and on a $/kW basis, shorter duration batteries have a lower capital cost. Figure 5 (left) also demonstrates why it is critical to cite the duration whenever providing a capital cost in $/kWh or $/kW.

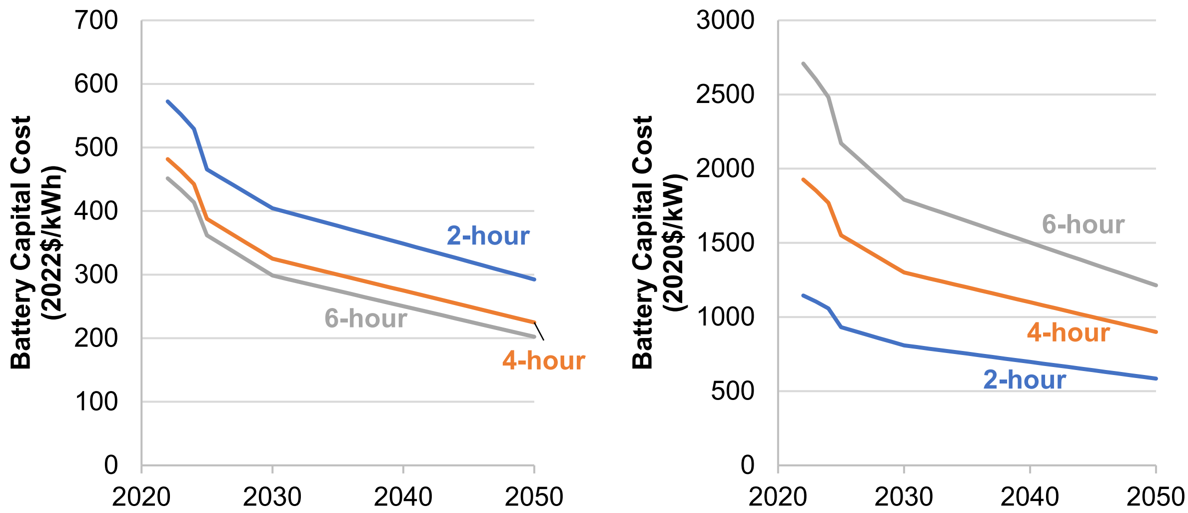

Figure 5. Cost projections for 2-, 4-, and 6-hour duration batteries using the mid cost projection. Left shows the values in $/kWh, while right shows the costs in $/kW.

To fully specify the cost and performance of a battery storage system for capacity expansion modeling tools, additional parameters besides the capital costs are needed. Figure 6 shows the range of variable operations and maintenance (VOM), fixed operations and maintenance (FOM), lifetime, and round-trip efficiency[1] assumptions from the publications surveyed. The rightmost point in the figure shows the value that we have selected to represent our 4-hour battery system. The VOM is often taken to be zero or near zero, and we have adopted zero for the VOM. This VOM is defined to coincide with an assumed one cycle per day and a given calendar lifetime. The three publications showing non-zero, but still small, VOM values indicate that there is not consensus that the VOM should be zero.

We have allocated all operating costs (at the one-cycle-per-day level) to the FOM. By putting the operations and maintenance costs in the FOM rather than the VOM we in essence assume that battery performance has been guaranteed over the lifetime, such that operating the battery does not incur any costs to the battery operator. The FOM has a much broader range of values. One of the primary differences in the level of FOM was whether augmentation or performance maintenance were included in the cost. Lower FOM numbers typically include only simple maintenance while higher FOM numbers include some capacity additions or replacements to address degradation. We have adopted a FOM value from the high end and assume that the FOM cost will counteract degradation such that the system will be able to perform at rated capacity throughout its lifetime.[2] The FOM value selected is 2.5% of the $/kW capacity cost for a 4-hour battery. We assume that this FOM is consistent with providing approximately one cycle per day.

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[1] Round-trip efficiency is defined as the system efficiency through a charge/discharge cycle. For example, it would include losses associated with cooling systems or battery control equipment.

[2] The Brattle publication (Newell et al. 2022) performs a detailed analysis of the operations and maintenance costs needed to keep the battery at rated capacity throughout its lifetime, and their reported cost is well-aligned with the value we have chosen. However, Brattle also assumed a lower storage cost than what we assume here, but has a similar total FOM cost, so based on their analysis an even higher FOM value for our projection might be justified.

If the battery is operating at a much higher rate of cycling, then this FOM value might not be sufficient to counteract degradation.

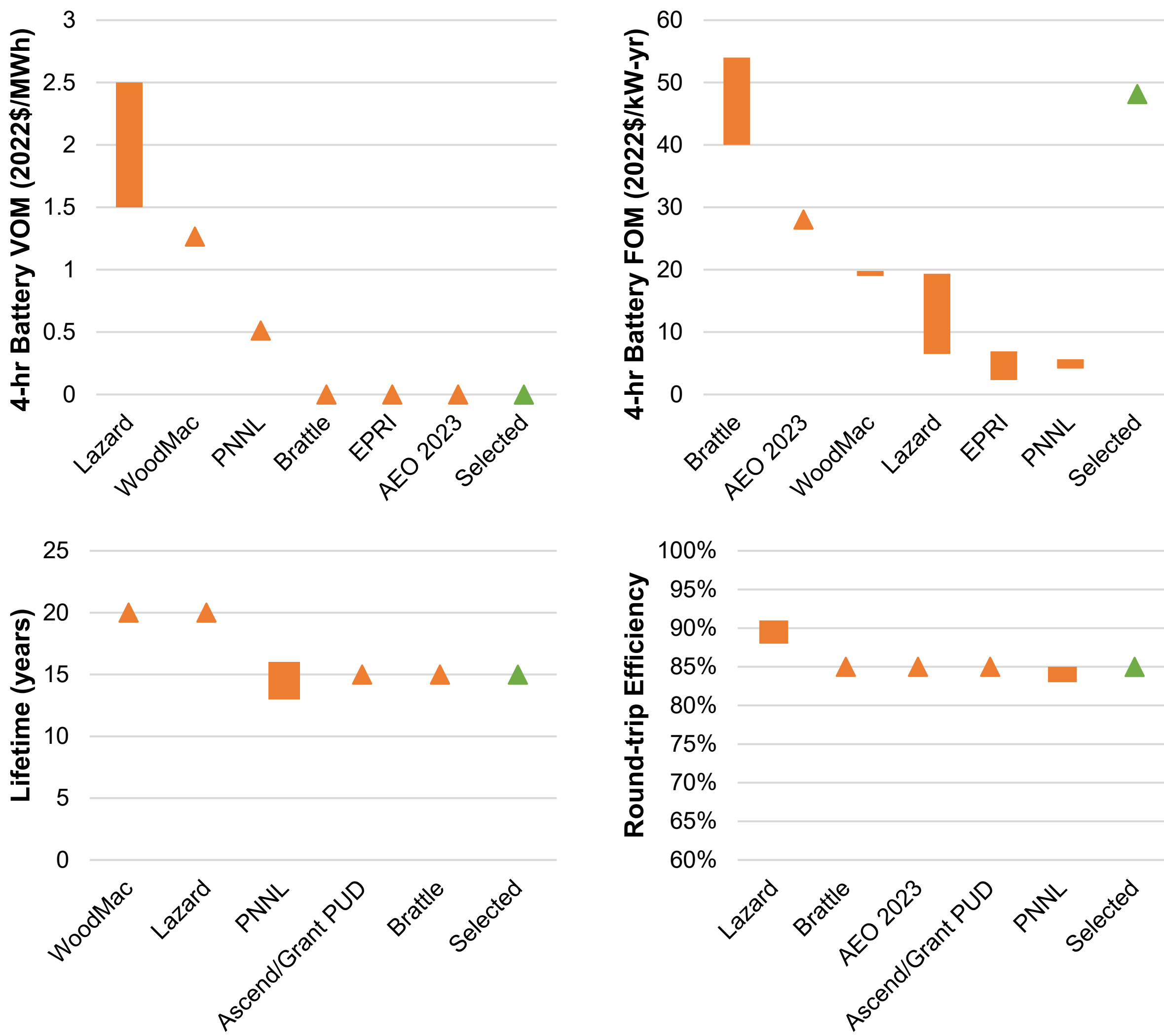

Figure 6. Variable O&M (top right), fixed O&M (top left), lifetime (bottom right), and round-trip efficiency (bottom left) from various published sources. The values selected for this study are the right-most values shown.

The lifetime we selected is 15 years, which is consistent with the median of the published values. The round-trip efficiency is chosen to be 85%, which is well aligned with published values.

4 Summary

Battery storage costs have evolved rapidly over the past several years, necessitating an update to storage cost projections used in long-term planning models and other activities. This work documents the development of these projections, which are based on recent publications of storage costs. The projections show a wide range of storage costs, both in terms of current costs as well as future costs. In the near term, some projections show increasing costs while others show substantial declines, with cost reductions by 2025 of -3% to 36%.

The cost projections developed in this work utilize the normalized cost reductions across the literature, and result in 16-49% capital cost reductions by 2030 and 28-67% cost reductions by 2050. The cost projections are also accompanied by assumed operations and maintenance costs, lifetimes, and round-trip efficiencies, and these performance metrics are benchmarked against other published values.

Many factors might influence how costs evolve going forward including market demand, supply chain expansions or constraints, interplay with other sectors such electric vehicles, and material costs and availability.

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Appendix

Table 2 includes the values that are plotted in Figure 1 and Figure 2. Figure 7 and Figure 8 show the comparison of the projections developed in this work relative to the projections that were produced in our last update (Cole, Frazier, and Augustine 2021). The 4-hour cost projections in this report are much higher in 2022 due to the updated initial cost from Ramasamy et al. (2022), and higher costs persist through 2050 because of that higher starting point. Higher normalized cost projections in this year's update also contribute to the higher costs throughout the projection horizon. This year's update is also the first to see increasing costs in the near term.

Table 2. Values from Figure 1 and Figure 2, which show the normalized and absolute storage costs over time. Storage costs are overnight capital costs for a complete 4-hour battery system.

	Normalized Cost Reduction			4-hour Storage Costs (2022$/kWh)		
Year	Low	Mid	High	Low	Mid	High
2022	1.00	1.00	1.00	482	482	482
2023	0.72	0.96	1.04	347	463	500
2024	0.68	0.92	1.04	327	443	503
2025	0.64	0.81	1.03	310	388	496
2026	0.62	0.78	0.99	297	376	477
2027	0.59	0.75	0.95	284	363	459
2028	0.56	0.73	0.91	271	351	440
2029	0.54	0.70	0.88	258	338	422
2030	0.51	0.68	0.84	245	326	403
2031	0.50	0.67	0.83	240	321	400
2032	0.49	0.66	0.83	236	316	398
2033	0.48	0.65	0.82	232	311	395
2034	0.47	0.63	0.81	227	306	392
2035	0.46	0.62	0.81	223	301	389
2036	0.45	0.61	0.80	219	296	387
2037	0.45	0.60	0.80	215	291	384
2038	0.44	0.59	0.79	210	286	381
2039	0.43	0.58	0.79	206	281	378
2040	0.42	0.57	0.78	202	276	376
2041	0.41	0.56	0.77	197	271	373
2042	0.40	0.55	0.77	193	266	370
2043	0.39	0.54	0.76	189	261	367
2044	0.38	0.53	0.76	185	256	365
2045	0.37	0.52	0.75	180	251	362
2046	0.37	0.51	0.75	176	246	359
2047	0.36	0.50	0.74	172	241	356
2048	0.35	0.49	0.73	167	236	353
2049	0.34	0.48	0.73	163	231	351
2050	0.33	0.47	0.72	159	226	348

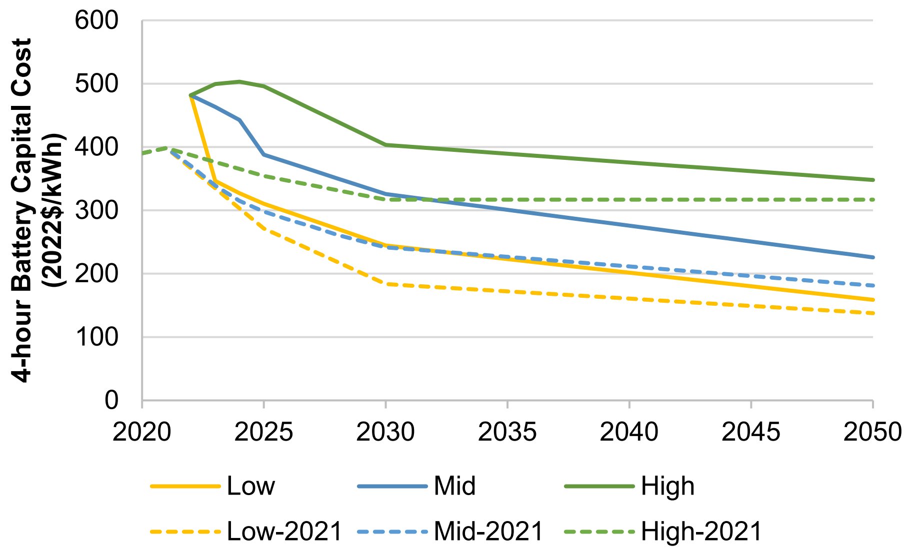

Figure 7. Comparison of cost projections developed in this report (solid lines) against the values from the 2021 cost projection report (Cole, Frazier, and Augustine 2021) (dashed lines).

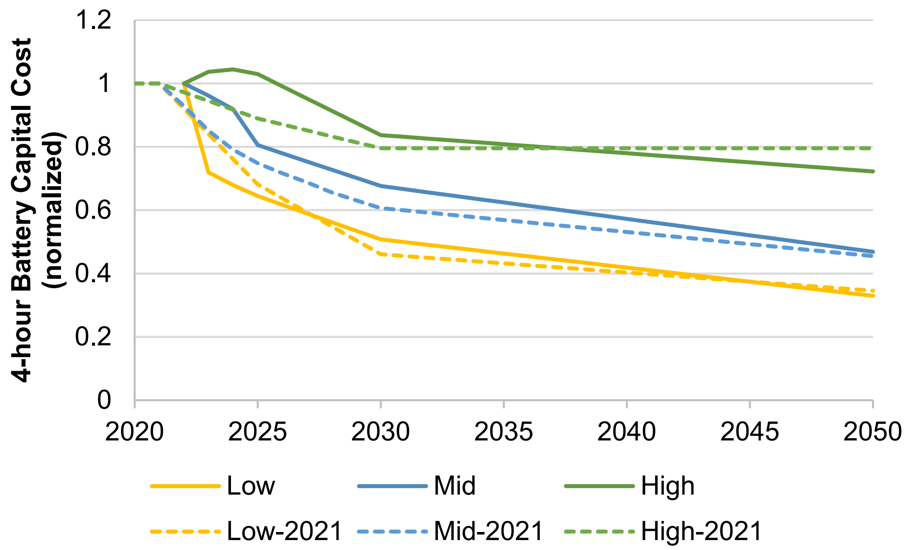

Figure 8. Comparison of cost projections developed in this report (solid lines) the values from the 2021 cost projection report (Cole, Frazier, and Augustine 2021) (dashed lines), with all values normalized to the "Mid" cost projection in the year 2020.