Unlocking the Value of Community-scale Storage for Consumers

VOLUME II: TECHNICAL APPENDIX

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I. Introduction

This study assesses the value of household, community-scale, and transmission-scale storage in the Australian electricity market. We focus on a societal cost and benefit perspective, considering the benefits that each of the three storage options provides to the energy system and society collectively, relative to the total installed cost of each storage option. Specifically we find that:

- Household and community-scale storage projects can tap into additional revenue streams that include local reliability and avoided distribution costs. This expands and diversifies their value proposition relative to the wholesale energy and FCAS revenue that transmission-scale storage projects exclusively rely on.
- Community-scale storage projects are able to take advantage of economies of scale, which can result in reduced costs relative to smaller household storage projects.
- The ability to tap into additional value streams and reduced upfront costs supports a positive business case for community-scale storage projects. Especially if these projects are built in locations suffering from distribution congestion and local reliability issues, community-scale storage can provide significant value to Australian energy consumers.

In this study, we estimate storage costs, market value, local reliability value, and avoided distribution costs for the three types of storage projects discussed above. The Volume I summary report for this study summarises our key findings and discusses options for addressing barriers to realising community-scale storage potential. This technical appendix (Volume II of our report) provides details about the development of storage costs and each value stream we analyse. Additionally, this appendix discusses the sensitivity cases that we explore to verify our assumptions.[1]

FIGURE 1 below summarises our approach to estimating the value of each of the three storage project types.

[1] This volume focuses exclusively on the value of storage to the electricity market – not its broader value to the Australian economy. It therefore excludes any discussion of the potential of supporting a nascent community storage industry or other economic factors, e.g., job creation.

FIGURE 1: STUDY METHODOLOGY

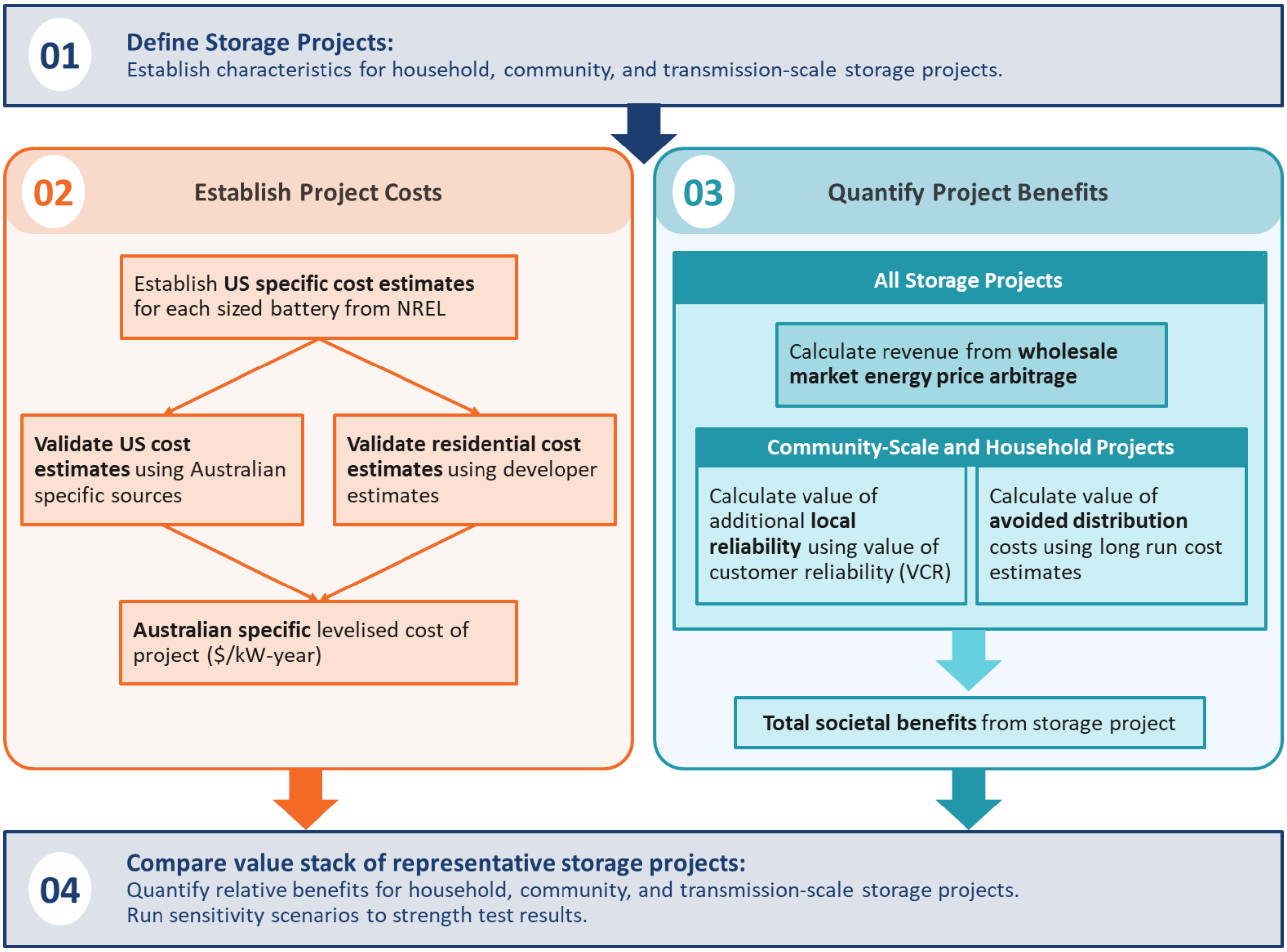

TABLE 1 summarise they key base case assumptions in our analysis for each of the three storage project types. The remainder of this appendix discusses those assumptions in further detail.

TABLE 1: BASE ASSUMPTIONS FOR COMMUNITY-SCALE, TRANSMISSION-SCALE, AND HOUSE PROJECTS

	Data Source	Community-Scale	Transmission-Scale	Household
Energy Value	AEMO 5-minute energy prices from 2017 to 2022	Average annual energy-only revenue from optimal battery dispatch simulated using Brattle's bStore model. Discounted by 10% to account for periods of unavailability during distribution and outage events	Same as community-scale without 10% derate	Same as community-scale
Local Reliability Value	AER data for VCR, SAIDI, DNSP customers, outage probabilities, use by event, and load weightings	Value of reliability for entire storage capacity calculated as VCR multiplied by average outage hours per year	NA	Annual value of reliability for a single customer calculated as VCR multiplied by average outage hours per year multiplied by average usage per hour during outage events
Avoided Distribution Benefit	LRMC estimates from DNSP TSS adjusted for inflation	2x LRMC estimates from DNSP TSS for high voltage distribution capital investments	NA	2x LRMC estimates from DNSP TSS for low voltage distribution capital investments
Battery Cost	NREL Annual Technology Baseline Moderate case for 4-hr li-ion batteries adjusted for inflation	NREL ATB Mid-case estimate in 2023 for "commercial scale" 4-hr battery. Levelised across 15 years using a levelisation factor of 8%	"Utility scale" 4-hr battery levelised same as community-scale	"Residential scale" 4-hr battery levelised same as community-scale. Soft-costs are reduced by 50% to account for lower Australian market-specific factors relative to U.S. data.

II. Storage Costs

Battery storage costs are sourced from NREL's ATB model.[2] This model provides a consistent set of technology costs for a variety of different generation assets including residential, commercial (community-scale), and utility-scale (transmission-scale) storage projects. These cost estimates are based on a bottom-up cost model that accounts for major components, including the lithium-ion battery pack, inverter, and the balance of system (BOS), and other soft-costs needed for the installation. We use these United States cost estimates as the base assumption for our Australian cost estimates.

We focus on cost estimates for 2028 to represent a near-term outlook for storage project costs. Storage projects have recently experienced a reversal in the long-term declining cost trend due to supply-chain shortages and bottlenecks resulting from the Covid-19 pandemic and the Russian Invasion of Ukraine.[3] However, we anticipate that these are short-term market impacts, and expanding economies of scale and technological improvements will continue to drive storage costs down over the long-term horizon.

We use cost estimates from NREL's Annual Technology Baseline (ATB) because the ATB model provides an internally consistent set of cost estimates for storage projects of various sizes and configurations, and granular bottom-up detail on the various elements of the total installed cost. While these cost estimates are developed for the United States, we validated the data to ensure its applicability to the Australian market.

First, we compared utility-scale storage cost estimates from NREL with utility-scale project costs from CSIRO.[4] The "moderate case" NREL forecast aligns closely with utility-scale storage project costs from CSIRO's Global NZE post-2050 forecast.[5] See **FIGURE 2**.

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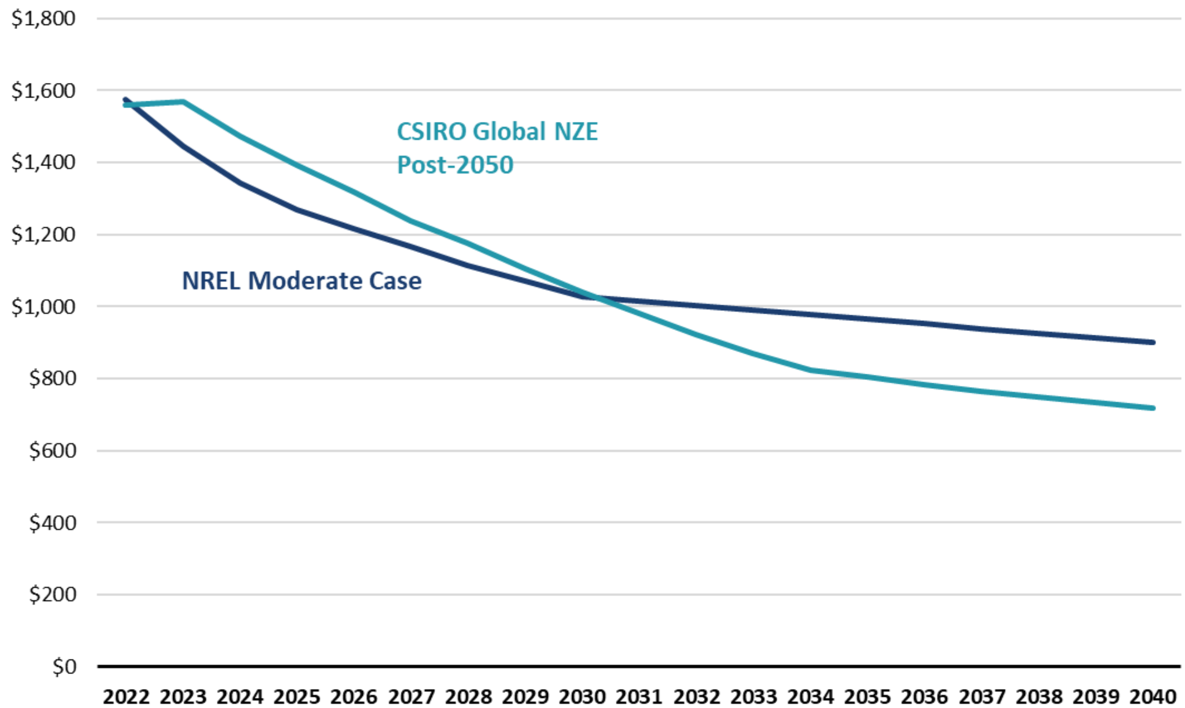
2 See https://atb.nrel.gov/

3 See: https://about.bnef.com/blog/lithium-ion-battery-pack-prices-rise-for-first-time-to-an-average-of-151-kwh/. We inflate NREL cost estimates to 2022$ using a US inflation rate of 15%. See https://www.bls.gov/data/inflation_calculator.htm. We use a USD to AUD conversion rate of 1.4. See https://www.forbes.com/advisor/money-transfer/currency-converter/usd-aud/?amount=1 as of February 1, 2023

4 See: https://publications.csiro.au/publications/publication/PIcsiro:EP2022-2576

5 Global NZE by 2050 is the scenario in which Australia achieves net-zero emissions after 2050.

FIGURE 2: UTILITY SCALE CAPEX ESTIMATES (2022 USD/KW)



We also looked into residential storage cost estimates in the US and in Australia to develop an Australian specific adjustment factor to ensure our residential cost estimate aligned with observed residential storage costs in the Australian market. Residential storage project cost estimates have a wide range based on the sizing of the project, the manufacturer of the battery cell, and the installer. Overall, we find that the NREL estimate for a 5 kW / 12.5 kWh project of $26,295 AUD ($18,782 USD) is within the range of estimates provided by US developers across a range of US states.[6] Data on Australian household storage projects suggests that they may be priced lower, with costs closer to $17,680 AUD ($12,629 USD) for a 13 kWh project.[7] We believe this deviation in residential storage costs between the US and Australian is driven in part by reduced soft-costs including sales-tax, labour, and profit margins in the Australian market relative to the US market.[8]

6 Storage estimates in MA (Brattle's headquarter location) range from $16,433 to $22,247. MA tends to be a slightly more expensive markets compared to other states. See Energy Sage: https://www.energysage.com/local-data/energy-storage-cost/ma/

7 See SolarChoice: https://www.solarchoice.net.au/residential/battery-storage-price/

8 The Behind the Meter (BTM) storage market in the US was 960MW in 2020 and the BTM storage market in Australia was 333MW as of 2021. With a population 10% that of the United States' population and a BTM storage market 33% the size, the Australian market is comparatively larger. See

As an additional point of comparison, we considered the residential solar markets in the US and Australia. As with storage costs, residential solar system costs vary significantly based on region, manufacturer, and installer. On average, residential solar system costs are around $3.59 AUD ($2.57 USD) per watt across the US prior to any federal tax incentives.[9] Australian rooftop solar costs approximately $1.57 AUD ($1.12 USD) per watt, excluding up-front incentives available through the Renewable Energy Target (Small-scale Technology Certificate - STC discount).[10] Overall, residential solar systems are 57% cheaper in Australia than in the US for a comparable system. Since soft-costs account for approximately 20% to 25% of total costs in both markets, we assume that solar soft-costs are similarly cheaper.[11]

The difference in soft costs between the US and Australian residential storage market may be slightly less dramatic than in the solar market, because both markets are emerging and have not yet reach steady state economies of scale. Nearly a third of Australian households have installed solar panels with some states reaching over 80% penetration on eligible homes while solar has only been installed on 4% of single-family homes across the US.[12] This difference in market penetration in the US solar market relative to the Australian solar market is more dramatic than in the storage market. Accordingly, the contrast in soft costs in the storage market is also likely to be lower.

Taking into account lower soft costs observed in the Australian solar market, storage market penetration levels, and residential storage cost estimates from developers in both markets, we apply a 50% reduction in soft-costs to align our residential storage cost estimate from NREL with residential storage costs in Australia.

https://www.nrel.gov/docs/fy22osti/83045.pdf and https://www.energy-storage.news/australia-surpassed-1gwh-of-annual-battery-storage-deployments-during-2021/

9 See: https://www.forbes.com/home-improvement/solar/cost-of-solar-panels/

10 Solar Choice estimates a 6kW system costs $6,430. A 6kW system can earn approximately $3,000 through the STC program. This results in a total cost of $9,430 or $1.57/watt. See Solar Choice https://www.solarchoice.net.au/residential/solar-power-system-prices/ and In Style Solar https://instylesolar.com/blog/south-australian-solar-rebates-government-incentives/

11 See Solar Reviews https://www.solarreviews.com/solar-panel-cost/massachusetts#installers and ABC https://www.abc.net.au/news/science/2023-02-16/solar-panel-prices-fall-decade-installation-rooftop-renewables/101966764

12 See https://www.theguardian.com/environment/2023/feb/28/solar-already-australias-largest-source-of-electricity-as-rooftop-capacity-hits-20gw-consultancy-says and https://pv-magazine-usa.com/2022/10/28/nearly-4-of-u-s-homes-have-solar-panels-installed/

III. Wholesale Market Participation

Wholesale market activities include energy arbitrage and FCAS revenue and are the primary way that transmission-scale storage projects earn revenue. We assume that all three project types (household, community-scale, and transmission-scale) are able to tap into these markets and earn comparable revenue.

We used Brattle's bStore model[13] to optimally dispatch batteries against 5-minute historical energy prices from AEMO. We performed this analysis across a six-year timeframe from 2017 through 2022 to account for a range of market price conditions when estimating storage energy value. Batteries earn revenue in the wholesale energy market through energy price arbitrage which is driven by market price volatility. A short, yet volatile, weather or market event could result in unusually high energy revenue for a single year, and vice versa, so performing this analysis across a longer time frame helps to capture the upswings and downswings in wholesale energy revenue potential. We perform this analysis for each Australian state using prices from NSW, QLD, SA, TAS, and VIC.

Modelled batteries have the following attributes:

- All batteries have a 4-hour duration
  - Household batteries are modelled as 5 kW / 20 kWh storage projects
  - Community-scale batteries are modelled as 600 kW / 2,400 kWh storage projects
- Transmission-scale batteries are modelled as 60 MW / 240 MWh storage projects
- All batteries have 85% round-trip efficiency
- All batteries have a 24 hour look-ahead into energy prices. The granularity of insight into 5-minute energy prices diminishes across this period to reflect increasing uncertainty in the market so that by the end of this 24-hour period, dispatchers only have hourly average estimates for 5-minute energy prices.

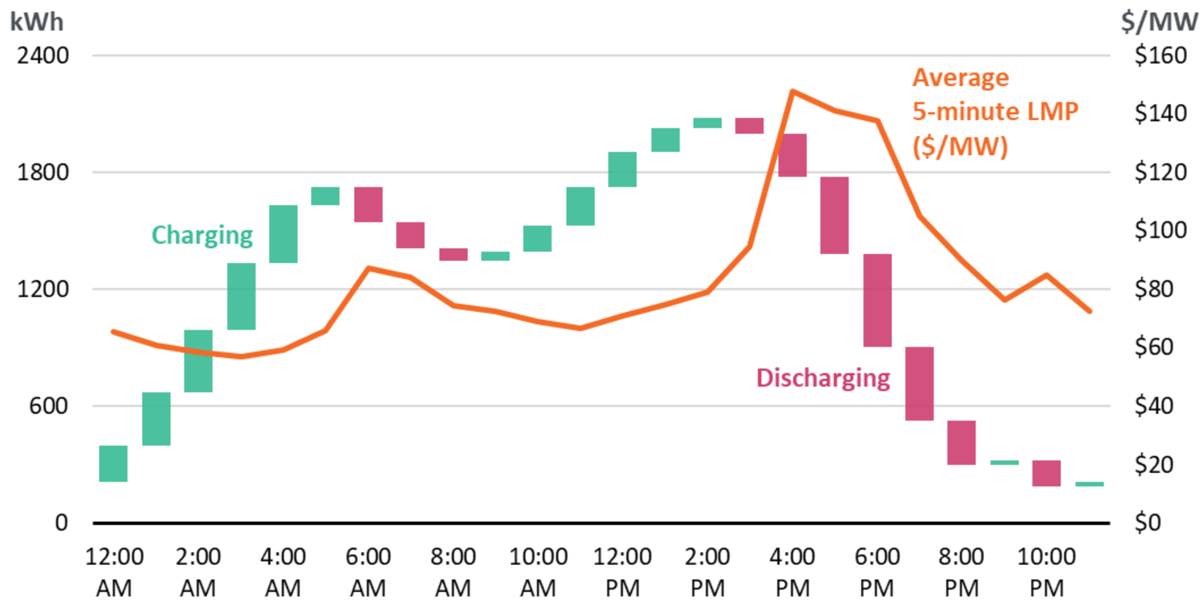
Brattle's bStore model provides an optimal dispatch pattern for each storage project type. See **FIGURE 3** for a daily average dispatch pattern. We calculate final energy values by making the following adjustments. We take the average yearly energy value for each state across the study period and, using NEM generation weights from the AEMO 2022 ISP[14], calculate a generalised

[13] See: https://www.brattle.com/practices/electricity-wholesale-markets-planning/electricity-market-modeling/bstore/

[14] The rounded weights are NSW: 63 (30%), QLD: 66 (32%), SA: 12 (6%), VIC: 54 (26%), and TAS: 12 (6%).

weighted average energy value for Australia. Household and community-scale energy revenues are reduced by 10% to account for periods of unavailability during distribution and outage events. We assume that during most hours residential and community-scale batteries can act unimpeded, but there may be certain times when its wholesale market activities are constrained to provide other resilience or congestion services. These services take priority over wholesale energy arbitrage and we account for this constraint by conservatively reducing energy revenues by 10%.

FIGURE 3: AVERAGE STORAGE PATTERN (600KW/2400KWH STORAGE ASSET IN QUEENSLAND)



We did not calculate revenue opportunities from FCAS. While these markets are currently profitable for storage projects, we anticipate that an influx of storage capacity into the Australian capacity market will materially reduce the revenue potential from these types of market offerings. Given the challenging nature to model ancillary service prices, and to maintain a conservative value estimate, we exclude this value stream from our analysis. Further, since all storage projects have the potential to provide FCAS, the comparative value potential between each sized asset will remain very similar whether this value stream is included in the analysis or not.

We additionally did not calculate revenue opportunities from capacity because there is not a capacity market in Australia beyond the Reliability and Emergency Reserve Trader (RERT) function. The RERT enables AEMO to enter into contracts to ensure the availability of reserves and reliability of supply but relies primarily on demand response and generation assets such as standby diesel generators.[15] The proposed Capacity Incentive Scheme will apply to transmission-connected storage, but community-scale and residential batteries can also provide capacity.[16] In fact a Brattle paper found that small-scale sources of capacity, like community-scale and residential batteries are much more cost effective sources of capacity than larger transmission-scale batteries.[17]

IV. Local Reliability Benefits

Household and community-scale storage can provide local reliability benefits during outages. The value of reliability can be a challenge to quantify given how varied the value of avoiding an outage may be for any individual customer, but can best be measured using an estimate of the value of customer reliability (VCR). This is the monetary value a customer would be willing to pay to avoid losing electricity service. See **TABLE 2** for our estimates of reliability benefits for household and community-scale storage projects.

We use 2021 VCR values from AER for each state to estimate the cost of each lost kWh. These values are weighted averages that take into account when outages typically occur, how long outages last, and what climate zone each customer is in.

We additionally calculate the average number of outage hours in each state using an average number of outage minutes experienced across a range of Australian electric utilities weighted by the number of customers in each service territory. Outage duration is measured using a System Average Duration Interruption Index (SAIDI), which represents the number of minutes the average customer was without power during the year. This does not include outages caused by "force majeure" events that are difficult to predict or forecast, such as extreme weather events caused by climate change, that could ultimately provide additional reliability value for community-scale and household storage projects (not modelled in this study).

[15] See https://aemo.com.au/en/energy-systems/electricity/emergency-management/reliability-and-emergency-reserve-trader-rert

[16] See https://www.energy.gov.au/news-media/news/capacity-investment-scheme-power-australian-energy-market-transformation

[17] See https://www.brattle.com/wp-content/uploads/2023/04/Real-Reliability-The-Value-of-Virtual-Power_5.3.2023.pdf

TABLE 2: VALUE OF LOCAL RELIABILITY

State	Value of customer reliability (VCR) $/kWh	Weighted average outage usage in each hour kWh	Weighted average outage duration per year Hours	Household value of lost load per year ($/kW-year)	Community-scale value of lost load per year ($/kW-year)
NSW	$26.82	0.78	1.8	$36.78	$46.98
VIC	$22.23	0.85	1.3	$23.56	$27.86
QLD	$24.65	0.74	2.3	$42.15	$56.65
SA	$31.44	0.74	2.1	$48.80	$66.25
TAS	$17.60	0.83	2.7	$39.02	$46.89

Note: Values shown in the table may not combine to produce the value of lost load estimates in the final column due to rounding.

The local reliability value (per kW) of community-scale storage is the VCR across an entire year, which is calculated as the VCR per kWh multiplied by the number of outage hours experienced in a year. This assumes that a community-scale storage project is able to serve all load up to its full capacity for every outage event across during the year. Storage projects may not be fully charged leading into an unexpected outage event, but a battery can alternatively serve critical loads that have a higher value of lost load. Our estimate of reliability value would be the same or higher if we were to assume that a storage asset enters an outage period with 50% charge but only serves critical load with a VCR that is at least double that of the average VCR.

For household projects, we additionally assume that a storage asset can serve all lost load during all outage events, but a single customer's load across an outage event may not require all of the storage capacity. Therefore, residential local reliability value is further limited by the average customer usage in each hour of outage. This estimate is calculated using average usage data from AER.

The deployment of storage facilities on distribution feeders can be combined with pre-existing distribution automation initiatives that allow for the necessary remote switching of distribution feeders to isolate faults and utilize storage assets as backup systems. To approximate the incremental cost of enabling the local reliability benefits attributed to community-scale storage, we reduced the local reliability benefits by 50% in the base case. Our low case assumes no local reliability benefits (e.g., a case in which distribution automation does not exist) and our high case assumes full local reliability value (i.e., a case in which distribution automation is pre-existing).

V. Avoided Distribution Investment Benefits

Distributed storage (both household and community-scale) can reduce upstream congestion during periods of high load. Installing and dispatching a battery to reduce the strain on the distribution system can avoid or defer additional buildouts of the local system. We quantify the value of this avoided distribution infrastructure using the long-run marginal cost of distribution assets from AusGrid's estimates of long-run marginal cost (LRMC) in the company's tariff structure statement.[18] We apply a 10% inflation rate on these 2019 values to arrive at a 2022 estimate.

We assume that a household battery is installed behind the meter at a customer's home and is able to provide congestion relief across the entire distribution system. Therefore, we assign residential storage projects the value of LRMC for low voltage. We assume that community-scale storage is located at a slightly more centralised location on the grid and assign only the high voltage LRMC to these batteries.

We assume that the storage projects will be placed in areas of the grid with known congestion issues that will require a high level of investment to alleviate load constraints, and therefore double the LRMC estimate when calculating avoided costs. The strategic placement of these storage projects will result in greater than average benefits.

TABLE 3 summarises the avoided distribution costs in our analysis.

TABLE 3: AVOIDED LRMC OF DISTRIBUTION

Customer	Location on Grid	Voltage Level	Avoided Distribution Estimate ($/kW)
Household	Behind the meter	Low voltage	$61.82
Community-scale	Distribution grid near residential community	High voltage	$39.60[19]

[18] See https://www.ausgrid.com.au/-/media/Documents/Regulation/Reports-plans/Ausgrid-approved-TSS-2019-24.pdf page 64. We find that this estimate of the LRMC is similar to estimates found for VIC and SA. Estimates for TAS and QLD were slightly higher. Therefore, our estimate is a conservative one. We inflate cost estimates to 2022$ using an Australian inflation rate of 10%. See https://www.rba.gov.au/calculator/annualDecimal.html

[19] Some community-scale batteries may be installed behind-the-meter at locations such as community centers which would result in greater distribution benefits.

Customer	Location on Grid	Voltage Level	Avoided Distribution Estimate ($/kW)
Transmission-Scale	Transmission system similar to other transmission connected generation	Transmission	NA

VI. Sensitivities

To validate our findings, we analysed several sensitivity cases with variation in battery cost estimates, wholesale energy prices, local reliability benefits, and avoided distribution costs. **TABLE 4** summarises the sensitivity case assumptions.

TABLE 4: SENSITIVITY CASES

	Base Case	Low Value Case	High Value Case
Energy Value	Average energy revenue for 2017 through 2022	Single historical year with lowest value	Single historical year with highest value
Local Reliability Value	No local reliability value	Batteries avoid only half of base case outage minutes (e.g., due to low state of charge before event), resulting benefits reduced by 50% to represent incremental distribution automation costs	Average national VCR value for applicable voltage level, outage minutes of 3x national average, reflecting deployment in low reliability area
Avoided Distribution Cost	2x LRMC estimates from DNSP TSS, reflecting that distributed batteries will be deployed in areas with above-average need for distribution congestion relief	LRMC estimates from DNSP TSS, reflecting system average distribution value	3x LRMC estimates from DNSP TSS, reflecting targeted battery deployment to address highest cost distribution upgrades
Battery Cost	NREL ATB Mid-case projection for 2028	NREL mid-case estimate for 2023 battery costs, held constant in real terms	NREL ATB “advanced” case projection for 2028
Region	Weighted average benefits across Australian states	State with lowest net benefits	State with highest net benefits

We describe the rationale behind our sensitivity case definitions below.

STORAGE COST ESTIMATES

Low Case: We use storage costs from 2023 to reflect the currently higher prices of storage. These prices could potentially persist into the near-term if supply chain constraints do not alleviate as expected.

High Case: We use storage costs for 2028 from the advanced NREL ATB case. This case assumes a more aggressive reduction in storage costs and uses the lowest storage cost forecast observed by NREL across a range of studies.[20]

WHOLESALE ENERGY REVENUES

Low Case: We use the single year with the lowest wholesale energy prices to represent less volatile energy prices and low revenue. These revenues would come from moderate weather years where little volatility in the energy price is experienced and storage has muted energy revenue potential.

High Case: We use the single year with the highest wholesale energy prices to represent unexpectedly high wholesale energy revenues. These years may become more common as climate change and additional renewable generation adds to energy price volatility in the Australian market.

LOCAL RELIABILITY BENEFITS

Low Case: We use half the number of outage minutes that were assumed in the base case to model a case in which a battery asset is half-charged going into outage events and is therefore only able to serve half of the lost-load across the year.

High Case: We use three times the number of outage minutes to model a case in which battery assets are placed in regions of the grid where outage events are more prevalent. This sensitivity also captures a scenario in which there are the same number of outage minutes but the value placed on lost load is tripled. Both scenarios will result in greater benefits for the storage projects.

AVOIDED DISTRIBUTION COSTS

Low Case: We use the observed LRMC of distribution to model a scenario in which battery projects are placed in areas of the grid that do not require extensive infrastructure investments.

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[20] See https://atb.nrel.gov/electricity/2022/utility-scale_battery_storage

High Case: We use three times the value of observed VCR to model a case in which battery assets are placed in locations of the grid where placement would avoid or defer the need for high-cost infrastructure projects.

REGION

Low Case: We use estimates for wholesale energy and local reliability from the lowest earning state in Australia reflecting the lowest observed scenarios in our analysis.

High Case: We use estimates for wholesale energy and local reliability from the highest earning state in Australia reflecting the highest observed scenarios in our analysis.

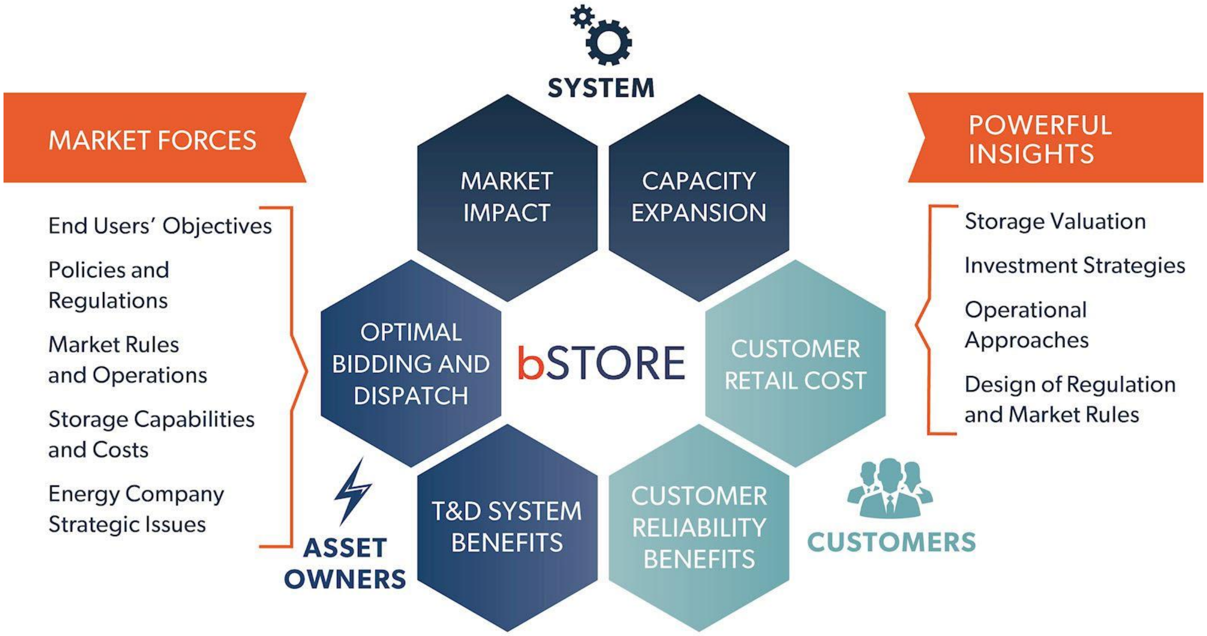
VII. The bStore Model

The bStore modelling suite is a storage simulation and decision-support platform used to assess the value of storage projects. bSTORE provides insights into key aspects of the value of storage, including:

- Co-optimisation across energy and ancillary service products
- Re-dispatch between day-ahead and 5-minute real-time markets
- Realistic foresight of future prices when dispatching into DA and RT markets
- Cycling limitations and degradation costs

FIGURE 4 provides an overview of the bStore modelling platform.

FIGURE 4: OVERVIEW OF THE BSTORE MODELING PLATFORM



bStore is highly configurable to account for the specific characteristics of the asset being analysed as well as the underlying market rules for the market in which the asset is operating. Key input parameters to bStore include:

- Battery capacity (MW and MWh)
- Round-trip efficiency
- Degradation characteristics, including cycling limitations, augmentation costs, anticipated reduction in MWh over time, and warranty/LTSA parameters
- Min/max state of charge
- Market services capable of being provided
- Any other restrictions on operations
- Anticipated foresight of future prices
- If co-located with solar:
  - Sizing of on-site solar (AC and DC MW)
  - Solar configuration (fixed or single axis tracking)
  - Solar/storage coupling (AC or DC)
  - Injection limit of combined system (MW)

The outputs of bStore include hourly charge/discharge and operations, revenues earned in total and across each market product, and high-level operational statistics such as cycle count and degradation.