2020 Grid Energy Storage Technology Cost and Performance Assessment

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Acronyms

AC	alternating current
Ah	ampere-hour
BESS	battery energy storage system
BLS	U.S. Bureau of Labor Statistics
BMS	battery management system
BOP	balance of plant
BOS	balance of system
C&C	controls & communication
C&I	civil and infrastructure
CAES	compressed-air energy storage
DC	direct current
DOD	depth of discharge
DOE	U.S. Department of Energy
E/P	energy to power
EPC	engineering, procurement, and construction
EPRI	Electric Power Research Institute
ESGC	Energy Storage Grand Challenge
ESS	energy storage system
EV	electric vehicle
GW	gigawatts
HESS	hydrogen energy storage system
hr	hour
HVAC	heating, ventilation, and air conditioning
kW	kilowatt
kWe	kilowatt-electric
kWh	kilowatt-hour
LCOE	levelized cost of energy
LFP	lithium-ion iron phosphate
MW	megawatt
MWh	megawatt-hour
NHA	National Hydropower Association
NMC	nickel manganese cobalt
NRE	non-recurring engineering
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
PCS	power conversion system
PEM	polymer electrolyte membrane
PNNL	Pacific Northwest National Laboratory
PSH	pumped storage hydro
PV	photovoltaic
R&D	research & development
RFB	redox flow battery
RTE	round-trip efficiency

SB	storage block
SBOS	storage balance of system
SCADA	sensors, supervisory control, and data acquisition
SM	storage module
SOC	state of charge
USD	U.S. dollars
V	volt
Wh	watt-hour

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Lithium-ion Batteries

Capital Costs

Cost data for each technology came from a variety of sources including literature and discussions with battery vendors, power conversion systems (PCS) vendors, systems integrators, EPC firms, and project developers as well as estimates produced by energy research firms. Costs were adjusted to 2020 US dollars (USD) using producer price index data for the electric power distribution industry from the U.S. Bureau of Labor Statistics (BLS) (U.S. BLS, 2020). Where value year is not specified, 2020 values should be assumed.

The cost categories developed for this report was socialized with industry stakeholders (Black & Veatch, 2020; Industry Stakeholder, 2020b) and national laboratory experts who provided additional insight and clarity. For example these discussions yielded insights on the role of the system integrator who receives storage modules, containerizes them, installs HVAC and fire suppression, and integrates with PCS to provide a turnkey system. BESS installation and interconnection with the grid is done through an EPC contract (Industry Stakeholder, 2020b).

For both lithium-ion NMC and LFP chemistries, the SB price was determined based on values for EV battery pack and storage rack, where the storage rack includes the battery pack cost along with cost for racks with cables in which the battery packs are located. To translate from EV to stationary storage context, adjustments related to grid-specific battery product aspects, stationary system integration, and scaling were applied with respect to power and energy capacity (Black & Veatch, 2020; Frith, 2020a; Goldie-Scot, 2019; Wood Mackenzie, 2020b). This overcomes the limitations where discounts or premiums are applied with respect to power capacity, but no adjustments are made for fixed power as the E/P ratio changes (Wood Mackenzie, 2020b). For EV battery pack price data, a 30% premium was added to make the values comparable to stationary systems by accounting for racking costs (additional cabling, labor, etc.) along with advantages related to scaling for EV battery packs vs. stationary energy storage battery racks (Baxter, 2020a; Frith, 2020a, 2020b; Goldie-Scot, 2019). Historical learning rates[1] for the SB range from 14-16%, while SBOS ranges from 8-9%, PCS from 13-14%, and C&C between 11-13% (Goldie-Scot, 2019; Lisa-Hsieha, Panb, Chiang, & Green, 2019; Wood Mackenzie, 2020b).

Typically, technologies are able to sustain higher learning rates during the initial scale-up and manufacture but can experience a 50% reduction as the technology achieves a sufficient state of maturity. For this study, we have based 2030 price projections on a learning rate of 10% which assumes the technology has reached manufacturing maturity. Should the technology continue to achieve the 14-16% learning rates of the past decade, the 2030 cost projections would be significantly lower. For example, at a 14% learning rate, the SB cost is estimated at $78/kWh for a 100 MW, 10h LFP system, with a total installed cost of $216/kWh; the corresponding numbers for NMC are $83/kWh and $222/kWh respectively. A pathway to $200/kWh of installed cost could be achieved by an increase in the learning rates for the SB to 16%, along with marginal increase in learning rates for other components. Learning rates are discussed in greater detail later in this section.

[1] Learning rate is the percentage drop in price for each doubling of cumulative deployed power or energy capacity.

The SBOS for the lithium-ion systems was estimated to be approximately 23-30% of the SB cost found in the literature (Frith, 2020a; Goldie-Scot, 2019; Wood Mackenzie, 2020b). The lower end of this range was used to provide the estimates in this analysis, resulting in higher/more conservative cost projections. Since rack costs were already accounted for in the SB price, the price of a container with cables, contactors, HVAC, and fire suppression is estimated to be 23% for this study with other costs already contained in system integration.

The SBOS cost is determined by both the energy and power capacity of the system. For systems with a higher power-to-energy ratio, higher currents associated with high-power levels require thicker cabling and contactors/fuses with higher current ratings, while systems with higher E/P ratio require more racks/containers with associated rack-to-rack cabling. HVAC sizing is related to power flow, while fire suppression and safety depend more on total energy content with some dependence on power flow. Different weights were assigned for power and energy based on data from Frith (2020a) and the $/kW and $/kWh components of SBOS were derived. Scaling was applied with respect to both energy and power to separately estimate the $/kW and $/kWh components of the SBOS. This approach allows estimation of SBOS price for any E/P ratio and any power and energy level. A 7% learning rate was applied to SBOS for the 2030 projected cost.

For power equipment, the PCS cost estimate for lithium-ion was found to follow trends in solar photovoltaic (PV) inverter cost after discussions with various experts and representatives from energy research firms (Baxter, 2020a; Ramasamy, 2020; Vartanian, 2020; Wood Mackenzie, 2020a). Solar PV inverter cost, however, typically underestimates PCS cost by approximately 20% (Baxter, 2020a; Vartanian, 2020). Discussions with a PCS vendor indicated a typical cost of $45/kW for utility-scale PCS at low volume (Austin, 2020). Typically, PCS costs do not include additional hardware such as safety disconnects since these are site dependent. PCS price estimate with and without additional hardware was obtained from conversation with multiple vendors (Baxter, 2020a). The number without additional hardware aligned with prices reported by BloombergNEF (Goldie-Scot, 2019) at the 20-50 MW level and Wood Mackenzie (2020b) at the 10 MW level, but was higher at low power levels and lower at higher power levels. This is because the discount applied by the Wood Mackenzie study is steeper at higher power levels and the premium is less at low power levels. A 3% adder was applied for National Electrical Manufacturer Association-rated housing for outdoor installation (Austin, 2020).

C&C includes non-recurring engineering (NRE) costs for the energy management system software and establishing the data pipeline, along with associated hardware costs for computers, controls, sensors, supervisory control and data acquisition (SCADA), and data storage (Baxter, 2020d). While it is difficult to quantify NRE costs, it is assumed that as project MW capacity increases by an order of magnitude, the investment in engineering and design staff time will increase marginally to ensure the asset is being used optimally. This analysis assumes a doubling of staff labor for every 10x increase in MW capacity, based on our inference during stakeholder discussions that labor does not scale linearly with MW capacity level since some of it is fixed and benefits from scale. Since the battery management system (BMS) feeds the detailed DC parameters to the central or master BMS computer and the safety hardware is already incorporated in SBOS costs it is assumed that the computers needed for the energy management system to communicate with the master BMS have significant room for the parts count to decrease with scaling. Similarly, the hardware associated with SCADA transmits the same number of parameters such as market price and grid conditions, while hardware associated with data pipeline has a sunk cost with marginal increases associated with system MW capacity. Hence, these costs are assumed to double with every 10x increase in MW capacity. Since the parts count does not increase proportionately with system capacity, it is assumed that the cost of integration increases only 50% for every 10x increase in power from 1-10 MW and 33% from 10-100 MW.

Grid integration consists of a transformer, busbars, safety breakers, meters, and installation/integration of these components. Transformers receive nominal scaling with respect to power capacity (Baxter, 2020b), while for busbars and safety breakers the disconnects scale marginally with power capacity. As described earlier, for C&C hardware we have assumed the meter cost is expected to double for every 10x increase in power. Assigning nominal labor hours required, installation is found to be 3-7% of the total cost and scales with power capacity.

Estimates for systems integration, EPC, and project development costs were determined from conversations with an energy storage expert (Richard Baxter, Mustang Prairie Energy) and the PNNL research team (Baxter, 2020b). Systems integration assigns a markup to SB, SBOS, and PCS hardware, and applies an estimated profit margin to the entire ESS cost including C&C. The EPC contractor applies markup and profit on all costs including system integration, while the project developer applies markup and profit on all costs including EPC. A combined markup and profit range of 20-30% was provided, for 2020 the markup and profit are set to 20% combined, with this number increasing to 25% in 2030.[2] Hardware is primarily where prices are expected to drop by 2030 (Baxter, 2020b, Pre-publication). To provide an estimated price range for 2020, low and high values were set to 0.9 to 1.1 times the nominal values for each category. Table 1 provides a detailed category cost breakdown for a 10 MW, 40 MWh lithium-ion NMC BESS, with a comprehensive reference list for each category.

The learning rates for the SB range from 14-16%, while the SBOS ranges from 8-9%, PCS from 13-14%, and C&C between 11-13% (Goldie-Scot, 2019; Wood Mackenzie, 2020b). For the SB , this was estimated to be a 10% learning rate. To realize the higher learning rate for the SB, significant advancements must occur including cheaper raw materials, higher energy density and specific energy, manufacturing improvements, high plant utilization, and commoditization of lithium-ion technologies. However, the 2020 price used does not leave much room for improvement (Baxter, 2020b). Additionally, recent safety incidents have triggered significant actions related to adding more safety requirements for BESS. Some of these include new National Fire Protection Association requirements and additional certification testing (such as UL 9540A). NFPA 855 and the International Fire Code require the ESS to be listed to UL 9540. This triggers many safety-related protections and measures for an ESS and is a minimum product safety standard. The overall product standard UL 9540 is critical to ensure all components function safely together. The NFPA 9540a fire test is in its infancy, as demonstrated by the fourth edition in a short period of time. Nevertheless, this test methodology is critical to determine how a particular battery will perform under thermal runaway conditions, identify if a location is safe for installation, and decide how best to protect exposure equipment and structure (Paiss, 2020). These testing and safety requirements are expected to add to the cost of both the SB and SBOS (Baxter, 2020c). Hence, a 10% learning rate is used for DC SB, weighing the positives associated with lower cost materials, higher specific energy, utilization, and superior manufacturing practices against higher costs related to safety. The price range was established using learning rates of 7% and 14%.

[2] Markup and profits as a percentage are expected to grow in order to keep the total markup and profits constant, since hardware costs are expected to drop.

For SBOS, a 7% learning rate was applied since most of the components (cables, disconnects, containers, HVAC) have little room for improvement and cost reductions opportunities are limited to more efficient processes to containerize the DC system, coupled with higher safety-related costs. The price range was established using learning rates of 4% and 10%. For power equipment, the learning rates used by the literature are considered to be very steep at 13-14% (Goldie-Scot, 2019; Wood Mackenzie, 2020b). The PCS prices are already quite low for utility-scale systems; therefore, the learning rate is expected to be only 3% over this time period, with some opportunity for price reduction based on novel developments for PCS and leveraging on solar PV developments for the DC-DC converter. Lastly, C&C has an estimated learning rate of 7%, lower than the 13-14% used in aforementioned reports.

Table 1. Price Breakdown for Various Categories for a Lithium-ion NMC BESS

Cost Category	Nominal size	2020 Price	Content	Additional Notes	Source(s)
Escalation Rate			Provides escalation rate	Costs adjusted to 2020 USD using producer price index data for electric power distribution industry from BLS	U.S. BLS (2020)
Cost Category Validation			System integrators provided agreement on cost categories		Black & Veatch (2020); Industry Stakeholder (2020b)
SB	40 MWh	$185/kWh	SB price obtained from multiple reports and a system integrator	30% premium applied to EV battery pack price available from reports	Baxter (2020a); Frith (2020a); Frith (2020b); Goldie-Scot (2019)
BOS	10 MW	$9.9/kW	BOS cost as percent of SB cost	BOS cost is 23-30% of SB cost; lower end of range used in this study to get $/kW component	Frith (2020a); Goldie-Scot (2019); Wood Mackenzie (2020b)
BOS	60 MWh	$32.7/kWh	BOS cost as percent of SB cost	BOS cost is 23-30% of SB cost; used lower end of range and PNNL approach to get $/kWh component	Frith (2020a); Goldie-Scot (2019); Wood Mackenzie (2020b)
BOS			Additional safety requirements that may impact BOS cost		Baxter (2020c); Paiss (2020)
PCS	10 MW	$73/kW	PCS cost estimate for lithium-ion follows trends in solar PV inverter cost and includes cost for additional equipment such as safety disconnects which are site specific	Cost aligns with numbers provided by PCS vendor for utility scale	Austin (2020); Baxter (2020a); Goldie-Scot (2019); Ramasamy (2020); Vartanian (2020); Wood Mackenzie (2020a)
C&C	10 MW	$7.8/kW	Source provides estimate for C&C	This study approach for scaling across various power levels	Baxter (2020d)
System Integration		10% markup on hardware and 10% profit on sum of above rows	System integration cost as percent of line items above		Baxter (2020b)
EPC		15% markup and 5% profit on sum of above rows	EPC cost as percent of line items above		Baxter (2020b)

Cost Category	Nominal size	2020 Price	Content	Additional Notes	Source(s)
EPC tasks			System integrator indicates BESS installation and interconnection with grid is done through EPC contract		Industry Stakeholder (2020b)
Project Development		5% markup and 15% profit on sum of above rows	Project development cost as percent of line items above		Baxter (2020b)
Grid Integration	10,000 kW	$24.9/kW	Source provides estimate for grid integration	Study approach for scaling across various power levels	Baxter (2020b)
Fixed O&M			Source started research projects to determine O&M		Minear (2020)
Fixed O&M			Provided O&M range		Aquino, Zuelch, and Koss (2017)
Fixed O&M			Provided O&M cost for lead-acid battery system		Raiford (2020)
Fixed O&M			Provided O&M cost as percent of capital cost for zinc-bromine flow battery system		Sapien (2020)
Basic variable O&M			Provided variable basic O&M cost		Aquino et al. (2017); Black & Veatch (2012); Hunter et al. (In Press); Mongird et al. (2019); Raiford (2020); S. Wright (2012)
Performance metrics			Cycle life as a function of DOD		DiOrio, Dobos, and Janzou (2015); Greenspon (2017)
Performance metrics			RTE		Aquino et al. (2017); DiOrio et al. (2015); Greenspon (2017); EASE (2016)
Learning rates			Learning rates for various cost categories		Goldie-Scot (2019); Wood Mackenzie (2020b)
Learning rates				2020 pricing structures may leave less room for aggressive learning rates	Baxter (2020b)

The hardware related items such as meters, computers, and sensors are not expected to drop significantly in price, leaving only the NRE costs for software development for cost reduction. The learning rates used were the same as for SBOS. A nominal 4% learning rate was assigned to system integration, EPC, project development, and grid integration, with 6% and 2% to establish the range. Table 2 shows the learning rates used to establish price ranges for year 2030.

Table 2. Learning Rates Used to Establish Lithium-ion 2030 Capital Cost and Fixed O&M Ranges

Component	Low Price	Point Estimate Price	High Price
DC SB ($/kWh)	14%	10%	7%
DC SBOS ($/kWh)	10%	7%	4%
DC-DC converter ($/kW)	7%	3%	2%
PCS ($/kW)	7%	3%	2%
C&C ($/kW)	10%	7%	4%
System integration ($/kWh)	6%	4%	2%
EPC ($/kWh)	6%	4%	2%
Project Development ($/kWh)	6%	4%	2%
Grid Integration ($/kW)	6%	4%	2%
Fixed O&M ($/kW-year)	6%	4%	2%

Regarding cost differences between LFP and NMC systems, while LFP batteries use cheaper cathode raw materials, their lower specific ampere-hour (Ah) and watt-hour (Wh) capacity require more passive elements for cell manufacture per unit Wh capacity. This results in a marginal decrease in the cell and module cost. Due to the need for more racks and associated cabling, the DC SB cost difference between LFP and NMC for stationary systems is lower than for EV packs. Additionally, due to the need for more containers, inter-rack cables, fuses to accommodate the larger footprint of LFP DC system relative to NMC, and the DC system cost difference between the two chemistries is negligible.

O&M Costs

O&M cost data for battery systems is currently limited, although multiple groups have recently started research projects in this area (Minear, 2020).[3] Aquino et al. (2017) estimated that the fixed O&M cost lithium-ion to be in the range of $7-14/kW-year. A fixed O&M cost for lead-acid batteries provided by Raiford (2020) was found to be $8/kW-year, which corresponds to 0.86% of the direct capital cost for a 4-hour system. Zinc-bromine batteries, on the other hand, which require significant maintenance in terms of periodic full discharges to mitigate zinc dendrite nucleation and growth, have a fixed O&M cost of 2% of capital cost (Sapien, 2020). While there are limited data availability for fixed O&M details for other battery technologies, for this study the fixed O&M was set to 0.43% of direct capital cost, about 25% of the zinc-bromine battery system. The actual value, specific to each technology, will depend on the capital cost; hence, the reported fixed O&M varies with power capacity and E/P ratio. Note that while labor-related costs are not expected to change with duty cycles, deep repair and refurbishment costs may depend on how the BESS is operated. The fixed O&M range for the year 2020 was set to 0.9 to 1.1 times the nominal values for each category. The fixed O&M learning rate was in the 2-6% range.

[3] EPRI Energy Storage Integration Council is working toward releasing information on O&M costs that will include a range of costs for service agreements, slated for publication in 2020.

For basic variable O&M, there is inconsistent nomenclature regarding what this category consists of. Due to the lack of detailed justification regarding what comprises basic variable O&M for each technology, this work sets the basic variable O&M to be $0.5125/MWh and is derived here based on the average across various technologies (Table 3). Depending on duty cycle, the energy throughput will vary, thus affecting total basic variable O&M costs.

Table 3. Variable O&M Estimate Calculation for Energy Storage Systems

Reference(s)	Technology	Value ($/MWh)
Raiford (2020)	Lead Acid	1
Hunter et al. (In Press)	Hydrogen	0.5
Aquino et al. (2017); S. Wright (2012); Black & Veatch (2012)	CAES	0.25
Mongird et al. (2019)	Non-specific	0.30
	Average	**0.5125**

Performance Metrics

A range of cycle estimates was provided throughout the literature for lithium-ion of up to nearly 6,000 cycles with lower DOD (DiOrio et al., 2015; Greenspon, 2017). The analysis conducted here estimates that lithium-ion LFP can typically provide 2,000 cycles at 80% DOD, while NMC systems provide 1,200 cycles for the same DOD, due to positive electrode dissolution and associated increased capacity loss at the negative electrode. In the next phase, more detailed cycle life data for LFP and NMC chemistries will be obtained. For example, based on 70% capacity at end of life, lithium-ion batteries have demonstrated a cycle life of approximately 8,000 cycles at 80% DOD (R. B. Wright & Motloch, 2001).

The calendar life of lithium-ion batteries ranges with some stating > 5 years or as high as 20 years (R. B. Wright & Motloch, 2001) and others in the range of 5-15 years (Dubarry, Qin, & Brooker, 2018). This report estimates a 10-year calendar life at 80% DOD, also assuming 5% of that time will also be allocated to downtime. A cycle life of 2,000 cycles for LFP and 1,200 for NMC is assumed with a 5% increase in total cycles each by 2030.

With respect to RTE, the literature typically provided estimates between 77-98% (Aquino et al., 2017; DiOrio et al., 2015; EASE, 2016; Greenspon, 2017). PNNL testing of grid-scale batteries in the past yielded an AC-AC RTE of 83–87% over 1.5 years of testing, while RTE for a battery > 5 years old was only 81%. A system RTE of 86% was used in this work.

Based on an extensive literature review and testing of lithium-ion systems conducted by the research team, the response times for the DC portion of the ESS contained in this report were assumed to be < 1 second. However, it has been shown that inverter response times can range from approximately 1-4 seconds to reach the rated power which affects the estimated overall response time of the system. Therefore, the response time assumed here for lithium-ion systems is assumed to be between 1-4 seconds.

Performance metrics are expected to remain relatively stable through 2030 for both lithium-ion chemistries. A marginal increase in RTE is assumed at 88%, along with a 5% increase in cycle life at 80% DOD for both chemistries.

Losses due to RTE were estimated based on an assumed electricity cost of $0.03/kWh and the RTE. The cost due to loss is determined to be $0.005/kWh for 2020 and $0.004/kWh for 2030.

R&D Trends in Lithium-ion Batteries

Price reduction for lithium-ion batteries is enabled by a combination of inexpensive raw material prices, higher energy density, efficient manufacturing and efficiencies of scale (Frith, 2020c). Rapid developments in lithium-ion battery research and development (R&D) are enabled by collaboration between EV manufacturers and R&D organizations (Industry Stakeholder, 2020a). Research areas include improving material properties, cell design, manufacturing improvements and safety. R&D trends in various areas are captured below.

Cathode

There is an R&D trend to reduce cobalt content in lithium-ion batteries because of expected resource constraints and humanitarian issues in its extraction in the world's major production region (Lefebvre, 2020), and due to increasing nickel content (Industry Stakeholder, 2020a). Shifting toward nickel-heavy batteries could generate new hurdles as batteries using more nickel are less stable and require more advanced material engineering (Industry Stakeholder, 2020a). Tesla has already announced plans to eliminate cobalt in its cells (Lyons, 2020).

The stability of the cathode and electrolyte at high voltages is an important area of research (Lefebvre, 2020). Layered cathodes destabilize at > 4.2 volt (V) vs. lithium (Dahn, 2020; Lefebvre, 2020; Li et al., 2019). The presence of cobalt helps to stabilize the layered structure, while the inclusion of manganese and aluminum provides chemical stability (Industry Stakeholder, 2020a; Lefebvre, 2020). However, Dahn (2020) showed that 5% cobalt did not suppress phase distortion, while aluminum, manganese, and magnesium did. However, these dopants reduce initial capacity by 10-15%. Avoiding this capacity reduction may be a promising area of research.

Toward the goal of removing dependence on cobalt and nickel, cation-disordered rock salt transition metal oxides, a new class of materials,[4] is being actively researched. This class of promising compounds opens up a wide mix of transition metal choices and some offer notably higher capacities than incumbent layer oxides, although they do possess challenges that require further study (Cle´ment, Lun, & Ceder, 2020; Lefebvre, 2020).

Cost reduction and an increase in specific energy may also be facilitated by using stabilized lithium-metal powder or other methods that introduce extra lithium inventory without complicating the requirements for the manufacturing environment. Since the cathode usually is the source of lithium inventory in the cell, less cathode material may be needed, reducing cost and weight (Industry Stakeholder, 2020a). Such methods may also shorten the cell formation duration, which is a cost-saving opportunity.

Anode

The negative electrode comprises a lower percentage of cell cost at approximately 10% (Schrooten, 2020a). The use of synthetic graphite in lithium-ion batteries has a higher coulombic efficiency and better rate capability (Schrooten, 2020a, 2020b). Use of natural graphite has the potential to decrease cost further. Using silicon instead of graphite anodes is being explored under a collaboration between

[4] Not layered.

Daimler and Sila Nanotechnologies (Industry Stakeholder, 2020a; Sila Nanotechnologies Inc., 2020). Its engineered design gives with volume buffering to accommodate expansion (Lefebvre, 2020) and allows easy drop-in integration into conventional manufacturing processes (Lefebvre, 2020). However, material fatigue due to expansion and contraction is still expected to be an issue.

Electrolyte

As discussed earlier in the cathode section, electrolytes that are stable across a wide operating range are being explored. Developers are also trying to move away from $LiPF_6$ salt to LiFSI salt in spite of their lower conductivity and higher viscosity (Lefebvre, 2020) due to the latter's superior stability in the presence of water, thus improving cycle life by avoiding electrolyte and cathode degradation (Choi, 2020; Kaschmitter, 2020).

Cell Design and DC Storage Module Architecture

The choice of cell size and format can determine cost, performance, and safety. Small cells are better for heat dissipation, while increasing parts count and hence module assembly cost. Tesla recently switched from 18650 (18 mm diameter, 65 mm height) cells to 21700 (21 mm diameter, 70 mm height) cells and subsequently to 4680 (46 mm diameter, 80 mm height) cells (Lyons, 2020) in an attempt to balance heat dissipation vs. parts count and energy density. The series/parallel configuration of cells within a module can further affect module cost; connecting cells in series followed by connecting the strings in parallel requires monitoring all the individual cell voltages, while connecting the cells in parallel reduces the monitoring points substantially.

Separators

There are multiple vendors for separators that keep price competitive. Ceramic coatings on various cell components are often used to improve safety of high-energy cells but may add additional costs to the cell (Industry Stakeholder, 2020a). Specifically, ceramic coating on one or both sides of the separator is used to improve safety (Industry Stakeholder, 2020a; Lefebvre, 2020). Development of separators with proven safety is expected to be an area of continued R&D.

Manufacturing

Cathodes and anodes are made using a slurry method and need expensive solvents such as n-methyl-pyrrolidone, which is difficult to recover (Industry Stakeholder, 2020a), making dry coating processes attractive. Tesla bought Maxwell Technologies (Maxwell Technologies Inc., 2020) to acquire their dry coating process and announced a tables design that is expected to speed up manufacturing while improving performance (Lyons, 2020). Innovations in tab-to-cell connection can further improve cell reliability (Boyle, 2020).

Part of cell cost that may not be fully accounted for is formation, which is expensive. Right now, each battery manufacturer has their own formation process that involves, as an example, waiting for a prolonged time at certain temperatures following formation (Industry Stakeholder, 2020a). Streamlining of formation procedure can further reduce costs.

Recycling

It is unclear if waste treatment costs for used lithium-ion cells are incorporated in the price. In this study we have not factored in decommissioning costs, which can run quite high to ship hazardous material for suitable disposal.

Recycling reduces demand for raw materials, reduces imports, reduces material processing carbon footprint when recycling is done near cell manufacturing sites, and avoids waste treatment costs (De-Leon, 2020). Globally, there are 38 companies that recycle lithium-ion cells, with 16 providing automation equipment (De-Leon, 2020); however, these are mainly for recovery of copper, aluminum, and cathode materials. Since only 6% of lithium-ion cells are being recycled, there is significant room for improvement in this area. Beyond cost, material processing conditions and cell design affect chemical, structural, and electrical stability. Modification of processes to use recycled materials is expected to be a key to more environmentally sustainable lithium-ion cell manufacturing.

While 54% of graphite used is synthetic, 39% of all anodes are natural graphite (Kaschmitter, 2020). Synthetic graphite uses dirty feedstock from refineries, with a high carbon footprint, so recycling is expected to gain more prominence as focus shifts to making the manufacturing process greener (Deveney, 2020).

Lithium-Metal Batteries

Lithium-metal batteries have a higher specific energy and energy density. In the late 20th century, fire and explosions associated with lithium-metal telecommunications batteries halted work in this area (Lefebvre, 2020). Solid-state battery R&D is currently tailored toward developing lithium-metal batteries. One hurdle in its development is that high-voltage cathodes also require electrolytes with a stable voltage window but not all solid-state electrolytes are stable at high voltage (Lefebvre, 2020). Solid-state electrolytes work well with graphite and lithium-metal anodes in principle, but manufacturing will need to be reinvented to make it a plausible option.

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