Cell-level Comparisons between Literature and Industry for Lithium-Sulfur, Lithium-Ion, Lithium-Oxygen, and other Next-Generation Batteries

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Abstract

A set of 212 lithium-sulfur, lithium-ion, lithium-oxygen, and other next-generation experimental battery articles was reviewed, and 15 articles provided at least one cell-level performance metric and/or a complete set of information to calculate it. This subset was compared against 27 commercial technologies in key metrics across various energy storage applications using an Excel database tool. While many high cell-level specific energy batteries are reported in the literature, there is a lack of demonstrated high cell-level specific power batteries for any chemistry. Li-S applications are comparable to Li-ion in terms of specific power and generally have higher specific energy, but also exhibit lower cycle life. In future work and as more articles include cell-level information, this tool can be expanded to include thousands of data points, enabling development of new models via machine learning and other methods to predict relationships between battery structure and performance. Additionally, the tool would become more useful for industry experts to effectively search and sort through the vast amount of knowledge accessible in research journals.

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1. Introduction

Battery technologies have helped to better the standard of living of millions of people through renewable energy [1–4], electric vehicle [1, 5–10], consumer electronic [11–13], medical [14–17], unmanned aerial vehicle (UAV) [18, 19], military [3, 20–22] and other applications. Batteries will continue transforming these sectors as systematic improvements are made in a range of key areas including specific energy [1, 3, 8–10, 23], specific power [1, 23–25], affordability (i.e. low-cost) [1, 26–37], cycle life [1, 24, 38–44],

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safety [1, 23, 45, 46], and storage characteristics [1, 47–50].

Much of current battery research is focused on next-generation chemistries (e.g. Li-S, Li-air, Si-anode, redox flow). Many important studies have been conducted that compare components and component-level performance [1, 3, 4, 6, 9, 51–53], or extrapolate what theoretical performance might be like with an optimized design (e.g. cell-level performance) [4, 9, 10, 54]. Other articles provide cost-estimate models for new battery chemistries [31] such such as "BatPaC" [36, 55] or use visual charts such as Ragone and radar charts to compare component-level aspects of their work with other technologies [51].

This study furthers these endeavors by introducing a searchable, sortable visual database tool and by using the tool to compare cell-level data from literature and industry.

To obtain this data, experimental next-generation battery articles (e.g. lithium-sulfur, lithium-air, lithium-oxygen, silicon anode, Zn-air, redox flow) were reviewed, and information from the 15 articles that either included enough information to calculate or directly reported some type of cell-level performance (Figure 1) was added to the database. At least one of the several key technical metrics mentioned earlier (cell-level specific energy, cell-level specific power, affordability, cycle life, safety, and storage characteristics) were calculated or a qualitative ranking assigned for each of these 15 articles. Industry data from the previously mentioned applications (renewable energy, electric vehicles, consumer electronics, medical, UAV, military) and other applications were obtained from datasheets, consumer sales sources, and personal communications with companies. Finally, a comparison within the literature articles, between literature and industry data, and for various chemistries (Figures 3, 4, and **??**, respectively) is summarized using Ragone plots or searchable, sortable, customizable radar charts created within the database tool.

2. Methods

2.1. Level of Information Reported

Because considered articles came from a variety of search methods, to help reduce bias and establish a general trend, several hundred articles were used (for the full list of articles, see Supporting Information). The search methods consisted primarily of Web of Science keyword search alerts, Web of Science and Science Direct keyword searches, and cited/citing article links to those mentioned. Examples of keywords include “lithium-sulfur”, “lithium-air”, “silicon anode”, “flow battery”, “specific energy”, “specific power”, and “cell-level.”

From a master list of articles, those that were experimental in nature were manually sorted from those that were theoretical, computational, or a review article, resulting in the 212 experimental articles considered for review. The experimental articles were manually evaluated to determine whether they reported or included enough information to calculate a cell-level metric. If sufficient information was included, experimental details from these articles were extracted and used to calculate cell-level metrics. Due to the differences in type of information reported and cell-design, each article required an individualized approach to make cell-level calculations (see for example, Table **??**). It was also noted whether a paper with cell-level information made a claim to commercial potential of the battery and if a cell-level metric or set of metrics from the article was comparable to or exceeded that of a commercialized state-of-the-art solution.

2.2. Visual Database via Radar Chart

Cell-level performance of characteristic commercial technologies from the high-impact applications highlighted in this work were obtained from online datasheets, retail websites, and personal communications with companies. Experimental battery articles are compared with commercial solutions.

2.2.1. Tool Features

The tool offers versatile features to visually display the database information using sorting and filtering. A demonstration of the various features is provided in the supporting information. Best-in-Class sorting is a feature useful for identifying leaders in particular categories and can be helpful in evaluating the potential of ones own work in comparison with commercial technologies. In addition, it may provide insight for those looking to find available options or compare their products against competition.

When evaluating whether or not a technology meets the needs of a particular application, custom filtering can help in comparing the oftentimes multiple minimum requirements involved. Data from multiple categories that is below a particular value can be excluded, resulting in a condensed and more complexly sorted list.

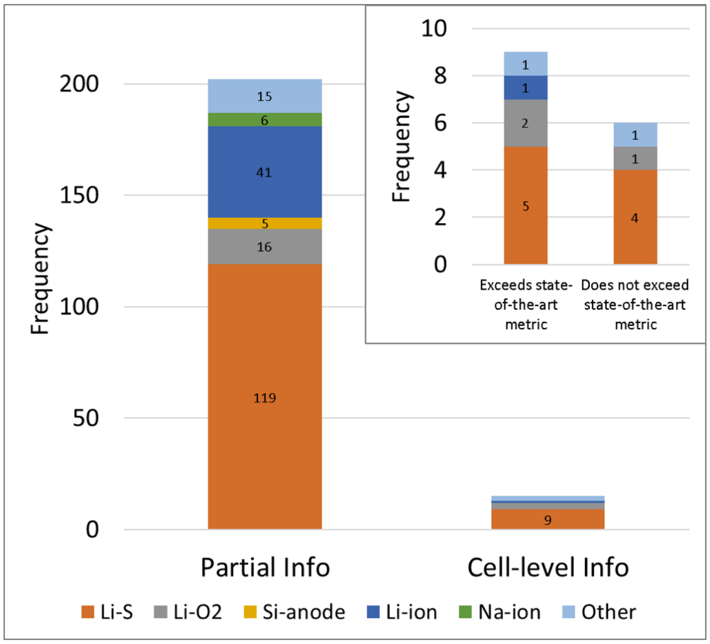

Figure 1: Assessment of 212 lithium-sulfur and other next-generation battery literature through 2017 in comparison with state-of-the-art. There are 15 articles that report sufficient information to determine cell performance criteria such as specific energy and specific power. Within these 15 articles, some were even competitive with state-of-the-art commercial technologies in that a metric or combination of metrics was comparable with state-of-the-art technologies (e.g. high specific energy, high affordability).

Because not all criteria are essential to know for each application, for simplicity, criteria can be manually added or removed. When the above two techniques (Best-in-Class Sorting and Custom Filtering) do not properly refine the data, technologies can similarly be manually included or excluded.

3. Results and Discussion

3.1. Assessment of Next-Generation Literature

This research reviews 212 experimental battery articles up until 2017 with a focus towards Li-S articles (Figure 1). Other types of batteries considered include lithium-air, silicon anode, lithium-ion, and flow batteries. Ones that either include enough information to calculate or directly report cell-level performance are shown in Table 1. The first set [27, 46, 56–60] represent articles that cite manufacturing potential, include a complete set of component information to make cell-level calculations, and do not directly report these metrics. The second set [61–64] consists of those that directly report a metric at the cell-level and do not include a complete set of component level information to calculate cell-level metrics. The third set consists of articles that include a complete set of component level information and report a cell-level metric [65–67].

Chemistry	Year	Claim	Info	Reported	Competitive	Ref.	DOI
Li_2S_6	2016	Y	Y	N	N	[56]	10.1021/acsnano.6b06369
Li_2S_6	2017	Y	Y	N	N	[57]	10.1002/aenm.201700537
Li-S	2017	Y	Y	N	N	[58]	10.1016/j.carbon.2016.10.035
Li-S	2013	Y	Y	N	N	[59]	10.1002/anie.201300680
Li-S	2016	Y	Y	N	Y	[27]	10.1039/c6ta08828g
Plating[1]	2017	Y	Y	N	Y	[46]	10.1039/C6EE02888H
Li-air	2017	Y	Y	N	N	[60]	10.1016/j.jpowsour.2017.08.052
Li-S	2017	Y	N	Y	Y	[61]	10.1021/acsnano.6b07603
Li-S	2012	Y	N	Y	Y	[62]	10.1016/j.electacta.2012.04.005
Li-S	2015	Y	N	Y	Y	[63]	10.1038/srep14949
Li-air	2013	Y	N	Y	Y	[64]	10.1016/j.jpowsour.2013.02.008
Li-ion	2015	Y	N	Y	Y	[68]	10.1002/adfm.201502833
Li-S flow	2015	Y	N	Y	N	[65]	10.1021/acs.nanolett.5b02078
Li-S	2017	Y	Y	Y	Y	[66]	10.1016/j.nanoen.2017.07.002
Li-air	2010	N	Y	Y	Y	[67]	10.1016/j.jpowsour.2010.01.022

Table 1: Level of information reported in various literature. Information from experimental battery articles concerning citing commercial viability (Claim), including enough information to determine cell-level performance metrics (Info), directly reporting it (Reported), and competitiveness with state-of-the-art technology (Competitive) are shown. Y indicates Yes, whereas N indicates No. Footnote 1: The results and theory from this paper published by John Goodenough and Helena Braga have been a subject of controversy [69] doi: 10.1039/c7ee01318c; because the paper included necessary information to calculate cell-level performance, it is included in this list.

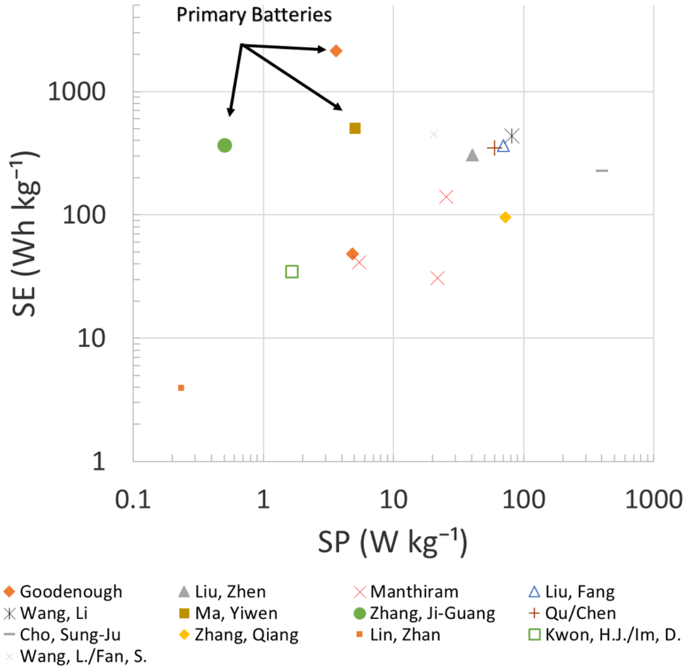

Figure 2: Ragone plot comparison of specific energy and specific power with literature. Goodenough and Manthiram refer to Goodenough and Manthiram groups, respectively. There is a trade-off between specific energy and specific power, as well as a lack of representation above 100 W/kg for specific power in the literature. Arrows highlight which batteries are primary batteries (i.e. cycle life of 1). In the case of EV and RE applications, the two batteries highlighted are used in both applications.

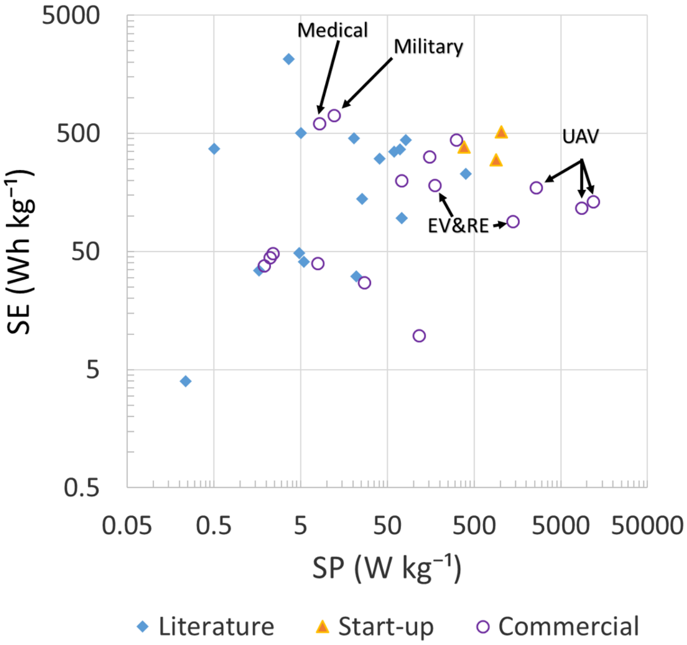

Figure 3: Ragone plot comparison of specific energy and specific power among literature, startups, and commercial solutions. Goodenough and Manthiram refer to Goodenough and Manthiram groups, respectively. There is a trade-off between specific energy and specific power, as well as a lack of representation above 100 W/kg for specific power in the literature. Arrows highlight batteries from medical, military, electric vehicle (EV), renewable energy (RE), and unmanned aerial vehicle (UAV) applications. In the case of EV and RE applications, the two batteries highlighted are used in both applications.

For the first set, cell-level performance was calculated from component-level information. The component-level information from each paper typically required an individualized approach to calculate cell-level performance due to cell configurations (e.g. coin cell vs. flow cell) and reported information (e.g. areal loading thickness vs. molarities) differing between papers.

For the second set, some component-level information was not present that would be necessary to calculate a cell-level performance metric. This made it infeasible to make reasonable cost predictions.

The percentage of experimental articles that contain some type of cell-level information and the importance of this type of information is consistent with observations by various groups [70–73]. Including both comprehensive component-level information and cell-level metrics provides an opportunity for industry to easily make evaluations and comparisons of cutting-edge battery research and helps research groups narrow down key system limitations [31, 73]. This can help researchers compare potential for impact and high-priority gaps in knowledge. Quantities of materials such as electrolyte and lithium metal are often left unmeasured or unreported [73]. By tracking and reporting these material types and quantities (e.g. "100 μL 1M LiTFSI in DME/DIOX (1:1) used as electrolyte" or "50 mg, 2 cm^2 dia. lithium metal foil used as anode"), failure mechanisms may be easier to elucidate because the performance of many next-generation chemistries change drastically based on parameters [61] such as excess electrolyte or lithium [73]. With an increase in reported information, these trends could be analyzed in broader ways through methods such as machine learning [70]. Because processing methods and characterization parameters can vary drastically and the number of parameters are often extensive, many articles with such information are essential for reliable insights [70].

This perspective is not meant to detract from the importance of understanding fundamental chemistries [9, 51] and cross-component and system-level challenges [3] of next-generation energy storage technology. An interdisciplinary approach that balances basic studies of chemistry systems and battery components with a knowledge of practical energy storage application requirements is required for successful implementation of next-generation technologies.

Due to lack of reported information and the subjective nature of storage characteristics and safety categories, for the purposes of this study, qualitative rankings are assigned based on chemical composition and material choice. For example, literature batteries that contain additives such as $LiNO_3$ [71] are given

Commercial/ Start-up/Author	Chem.	SE (Wh kg^{-1})	SP (W kg^{-1})	Cycles to 80%	Afford. (Wh $\$^{-1}$)	Afford. (Wh cycles $\$^{-1}$)	Safety	Storage	ED (Wh L^{-1})	Ref
BPS*	Li-ion	181.0	177.9	450	0.391	158.248	4	3	207.0	[74]
Rayovac	NiCd	54.7	-	300	0.600	162.027	4	3	-	[75]
Rayovac Ultra	NiCd	38.1	-	300	0.312	84.268	4	3	-	[76]
Venom	LiPo	132.0	11876.5	200	0.962	173.160	3	2	-	[77]
Venom	LiPo	116.2	8713.8	200	0.722	130.000	3	2	-	[78]
Venom	LiPo	172.8	2591.9	200	0.807	145.322	3	2	-	[79]
X2Power	Li-ion	178.7	-	250	0.310	69.767	3	3	-	[80]
Rayovac	LiPo	135.7	-	250	0.150	33.755	3	3	-	[81]
Rayovac	Zn-air	602.2	8.2	1	0.852	0.852	5	5	1436.8	[82]
Saft	Li-SOCl2	704.8	12.2	1	0.781	0.781	3	5	-	[83]
Duracell Ultra	Pb-Acid	49.7	0.0	200	2.759	496.609	3	2	105.6	[84]
Panasonic/Tesla	Li-ion	317.4	153.9	500	4.020	1809.000	5	4	708.2	[85]
Panasonic/Tesla	Li-ion	197.4	73.1	3000	1.688	4556.250	5	4	105.8	[86]
Nuon	Li-ion	206.7	-	200	0.901	162.162	3	3	535.9	[87]
Empire Scientific	Li-ion	68.9	-	200	0.125	22.506	3	3	-	[88]
Energizer	Li/FeSS	437.5	312.5	1	1.617	1.617	2	3	-	[89]
Altairnano	LTO	89.1	1402.2	25000	1.281	16697.250	4	5	-	[90]
Victron Energy	Pb-Acid	9.7	116.6	400	-	-	3	4	9.8	[91]
Victron Energy	Pb-Acid	37.7	1.9	400	-	-	3	4	38.0	[91]
Victron Energy	Pb-Acid	44.4	2.2	400	-	-	3	4	75.0	[91]
Victron Energy	Pb-Acid	27.1	27.1	400	-	-	3	4	45.8	[91]
Victron Energy	Pb-Acid	48.0	2.4	500	-	-	3	4	74.3	[92]
Victron Energy	Pb-Acid	39.4	7.9	500	-	-	3	4	61.0	[92]
Oxis Energy	Li-S	297.9	893.6	80	-	-	4	3	212.9	[93]
Oxis Energy	Li-S	382.3	382.3	0	-	-	3	3	272.9	[93]
Sion Power	Li-ion	514.4	1028.8	120	-	-	3	3	-	[94]
Polyplus	Li-O2	800.0	-	1	-	-	4	3	-	[95, 96]
Polyplus	Li-H2O	1300.0	-	1	-	-	4	3	-	[95, 96]
Zhang, Ji-Guang	Li-O2	369.4	0.5	1	-	-	3	3	-	[67]
Qu/Chen	Li-S	350.0	60.0	30	-	-	4	3	-	[66]
Liu, Zhen	Li-S	305.4	40.4	140	6.161	862.577	3.05	3.05	-	[27]
Manthiram	Li-S	41.0	5.5	200	-	-	3	3	-	[57]
Manthiram	Li-S	30.8	21.9	200	-	-	3	3	-	[57]
Manthiram	Li-S	139.6	25.6	50	1.947	97.339	3	3	-	[56]
Liu, Fang	Li-S	365.0	70.0	66.0066	-	-	2.95	2.95	-	[61]
Wang, Li	Li-S	437.0	80.9	62.5	-	-	4.05	3.05	-	[62]
Ma, Yiwen	Li-S	504.0	5.0	1	-	-	3	3	-	[63]
Goodenough	Plating	2127.5	3.6	1	62.037	62.037	5	3	-	[46]
Goodenough	Plating	48.4	4.8	46	1.411	64.901	5	3	-	[46]
Cho, Sung-Ju	Li-ion	226.0	400.0	2000	-	-	3	4.05	-	[68]
Zhang, Qiang	Li-S	95.5	72.7	110	-	-	3	3.5	51.0	[58]
Zhang, Qiang	Li-S	95.5	72.7	180	-	-	3	3.5	50.4	[58]
Lin, Zhan	SS Li-S	4.0	0.2	68	-	-	4.5	4	8.1	[59]
Kwon, H.J./Im, D.	Li-O2	34.6	1.7	12	-	-	4	3	-	[60]
Wang, L./Fan, S.	Li-S	452.0	20.5	188	-	-	3	4	-	[64]
Li, C./Helms, B.A.	Flow	-	-	2	-	-	3	2	142.0	[65]

Table 2: Summary of experimental data from industry. Six performance metrics – Specific energy (SE), specific power (SP), number of cycles to 80% capacity, affordability (energy affordability and lifetime energy affordability), safety, storage characteristics, and energy density (ED) – are given of characteristic technologies from commercial, start-up, and literature batteries. Safety and storage characteristics are assigned qualitative rankings based on the chemistry and the constituents of the cell/system. Commercial affordability data was obtained through online sources (see "Ref" column), whereas literature affordability data was estimated from raw material costs and complexity of processing. *BPS stands for Battery Power Solutions.

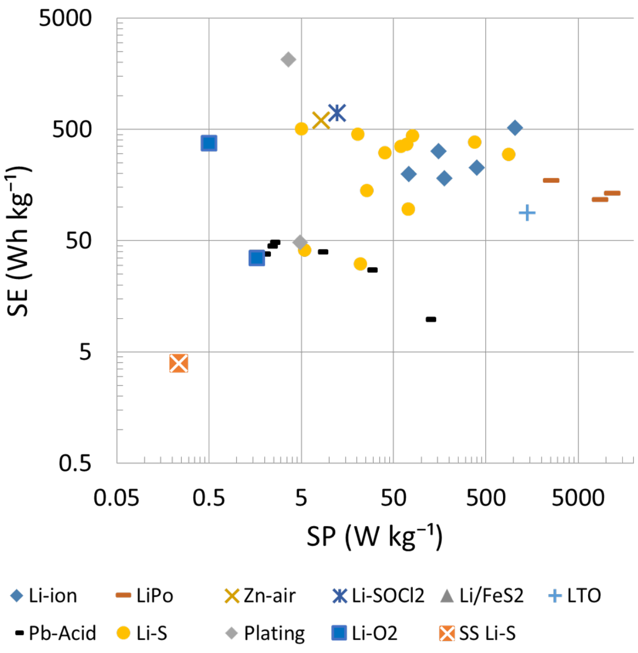

Figure 4: Ragone plot of various battery chemistries from literature and industry. There is a distribution of lithium-sulfur battery performance up to 500 Wh/kg and 1000 W/kg, separately. Other lithium metal and zinc-air chemistries similarly demonstrate high specific energies. The thin lithium-polymer technology ranks at the highest specific power.

lower safety rankings.

3.2. Ragone and Radar Data

Data is presented detailing Ragone plot comparisons within literature (Figure 2), among literature, start-ups, and commercial technologies (Figure 3), among various chemistries(Figure 4), and corresponding radar charts.

In literature, very high specific energies can be achieved (Figure 2); however, many fall short of specific power values obtained in industry (Figure 3). Interestingly, when considering all secondary literature batteries (i.e. non- primary batteries), there is not a significant trade-off between specific energy and specific power; rather, a generally increasing trend is observed. This could be related to the amount of excess materials in the battery and the battery's ability to function well with an optimized amount of excess material or to a trade-off not seen in metrics other than cell-level specific energy and specific power.

There are no start-up affordability data points due to lack of available information. This is to be expected, since estimating cost from components would require proprietary information from the, and the batteries are usually only available as evaluation cells or through private contracts.

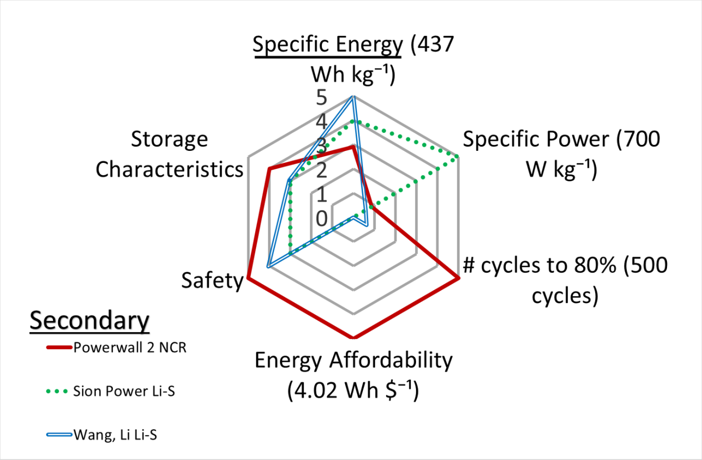

Figure 5: Radar charts containing the top example of cell-level specific energy from literature (red, solid), start-up (green, dash), and commercial (blue, double-solid) secondary battery data. The max ranking of "5" is scaled by the maximum value within the three examples considered. For example, the maximum specific power of the three examples included is 700 W kg^{-1}, hence this is scaled as the "5" or highest ranking for the specific power category.

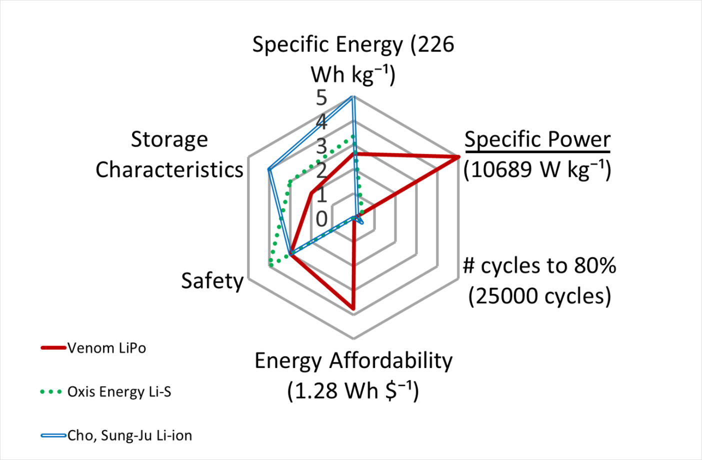

Figure 6: Radar charts containing the top example of cell-level specific power from literature (red, solid), start-up (green, dash), and commercial (blue, double-solid) battery data. The max ranking of "5" is scaled by the maximum value within the three examples considered. For example, the maximum specific energy of the three examples included is 437 Wh kg^{-1}, hence this is scaled as the "5" or highest ranking for the specific energy category.

Li-S, Li-ion, and Li-O2 batteries each have examples of high specific energy (Figure 4). Several Li-S and Li-ion data points are near each other, with Li-S generally exhibiting higher cell-level specific energy. One of the major differences is that the cycle life of the Li-ion batteries is generally higher than the Li-S batteries (Table 2).

The differences in shapes of the radar charts (Figures 5 and 6) illustrate that maximizing a single criteria does not necessarily produce the same kinds batteries. This supports the notion that multiple battery requirements change for a given application. Literature data is again noticeably lacking in terms of cell-level specific power.

4. Conclusion

A framework is provided to systematically integrate and compare experimental battery research data via a visual database tool aimed at helping to bridge the gap between science and industry. Cell-level data had limited availability in the literature. Reporting such information enables calculations of critical battery performance metrics including cell-level specific energy, cell-level specific power, and cell-level affordability estimates. Ragone and radar charts are used to compare technologies and identify trends across literature and industry.

While great strides have been made towards higher specific energy batteries, this study reveals that high specific power batteries are lacking in the literature. Cycle life information is typically available in most experimental secondary battery publications; however, metrics such as energy retention (alternatively, self-discharge) are often not reported. Safety is more difficult to quantify but can be done to some extent by reporting the aforementioned information and evaluating the energy, power, and materials. Safety can be more rigorously evaluated through shock, short-circuit, and puncture tests. Additionally, and as application-specific focuses arise, research groups may consider studying and reporting other metrics such as temperature performance, energy efficiency, volumetric energy and power density, fast charge characteristics, and voltage stability.

Ragone and radar charts supplied in the visual database tool are useful for planning and comparison purposes in both science and industry. The readers are encouraged to use these tools to inform their studies of high-impact battery chemistries. The visual database tool and relevant data are provided as an attachment for the reader.

Funding: This work was supported through a BYU Office of Research and Creativities (ORCA) Grant.

Acknowledgements: Thank you to Dr. Robert C. Davis for valuable feedback and direction, and to Dr. Richard Vanfleet, Dr. Dean Wheeler, and Kevin Laughlin for useful discussions.

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