Battery Key Performance Projections based on Historical Trends and Chemistries

Presenter: Blake Tiede

Authors:
Blake Tiede (HX5) | blake.a.tiede@nasa.gov
Cody O’Meara (NASA) | cody.a.omeara@nasa.gov
Ralph Jansen (NASA) | ralph.h.jansen@nasa.gov

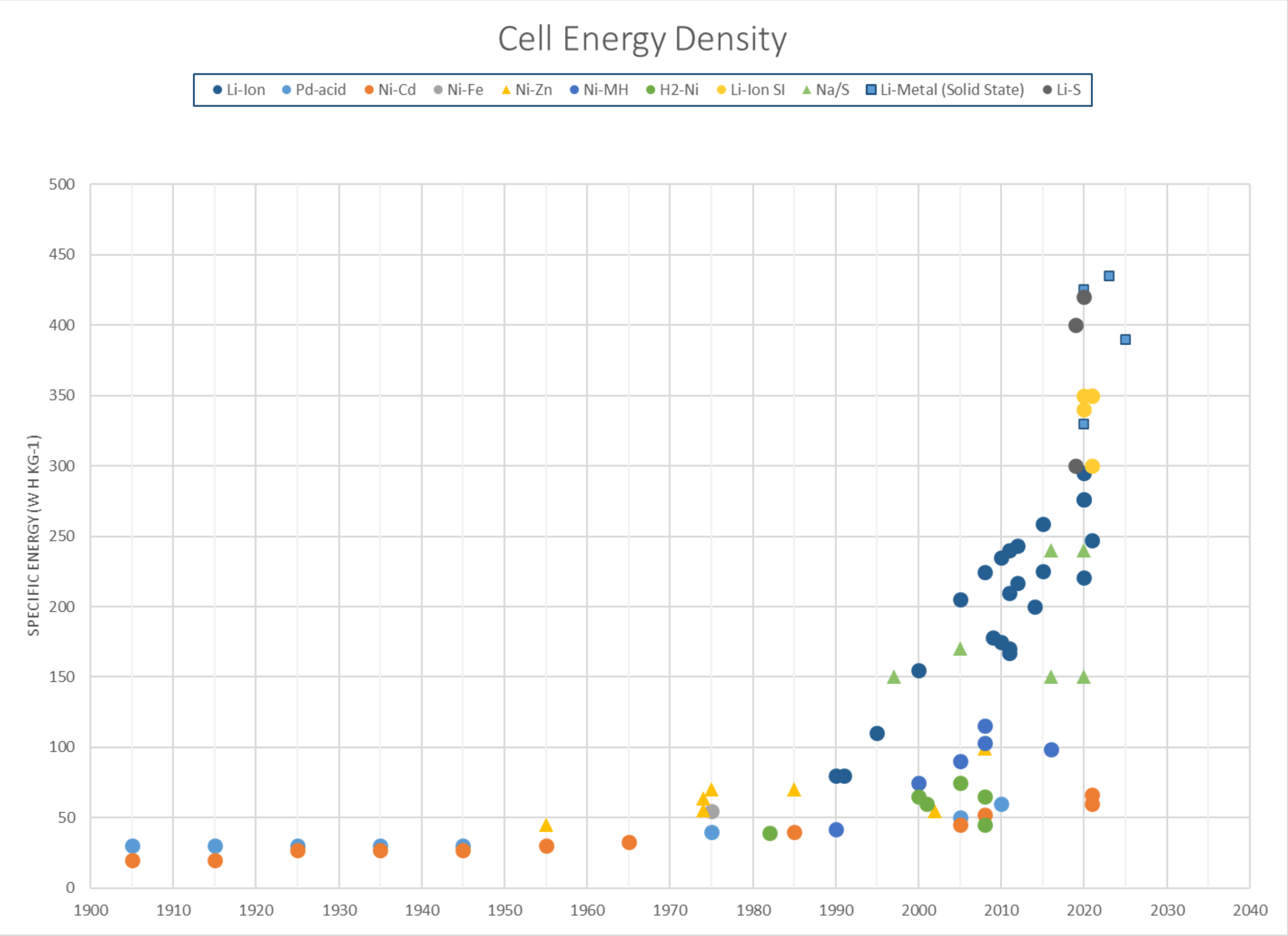
NASA Glenn Research Center

Battery Specific Energy Density Paper Motivation

- Electrified Aircraft Propulsion (EAP) includes fully electric, hybrid electric, and turboelectric approaches to provide power to electric motors which drive propulsors to create thrust
- EAP implementation is highly dependent on increasing mass-based specific energy density
- Misra provides an overview of battery specific energy needs for future aircraft calling out ranges between 250 to 1000 Wh/kg [1] (watt-hour per kilogram)
- Focus specific energy density was the focus of this study with further research into discharge efficiencies
  - Specific energy density is an important starting point for range and fuel savings analysis
  - Other factor areas are heavily dependent on implementation would be better for a vehicle study such as cost, volumetric energy density, cycle life, and so on

Cell Data Gathering

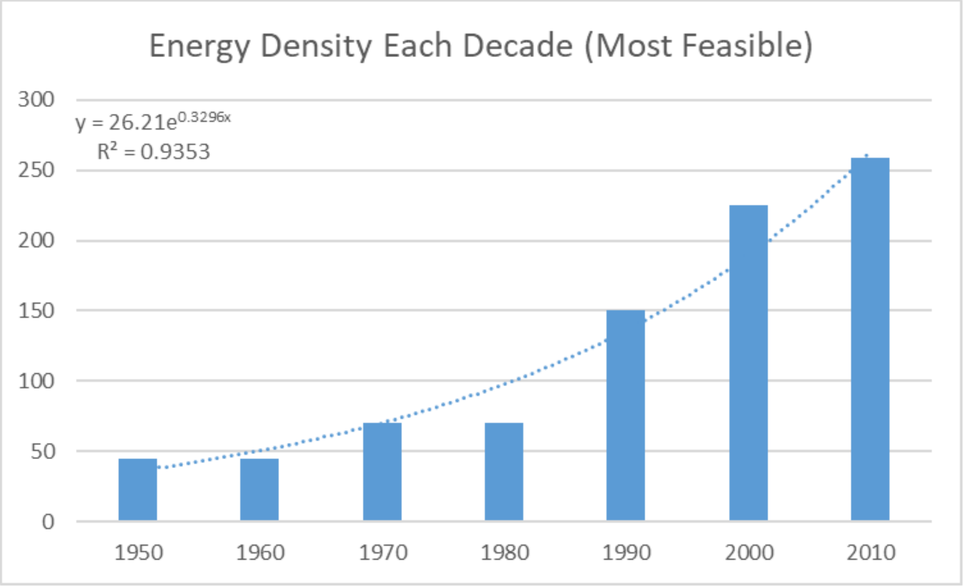
- All examples selected have an EAP, thin-haul, regional, and single aisle markets use case potential
- Cell availability includes mostly commercial examples, with a few experimental chosen
- Projections include different chemistries and availability to varying degrees
- Goal of projections is to pick a trend that is to continue

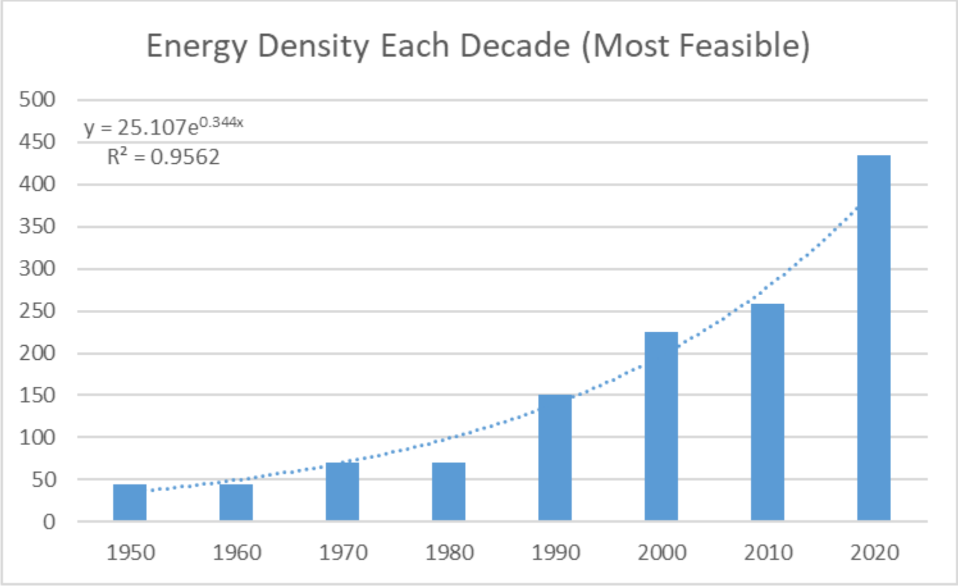


Cell and Chemistry Filtering Criteria

- Included battery technologies applicable to MW class Electrified Aircraft Propulsion systems that are applicable to the thin-haul, regional, and single aisle markets
- Is there a more feasible prototype available of the same chemistry in a similar timeframe (example: two competing Lithium Metal batteries where one has a larger capacity)
- Does the technology advertise statistics at a C-rate feasible for thin-haul/regional/single isle and list a corresponding specific energy density at that C-rate?

Decade Trends

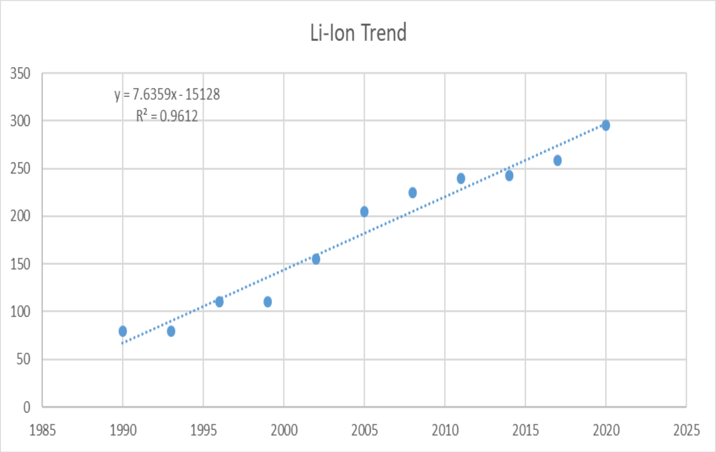

Energy Density Each Decade (Most Feasible)


Energy Density Each Decade (Most Feasible)

- Decade trends give a projection for overall EAP capable batteries while not considering specific chemistry trends
- Projected with and without the full 2020’s decade
- 2020’s most likely going to have a similar Specific Energy Density due to research efforts being put into scalability

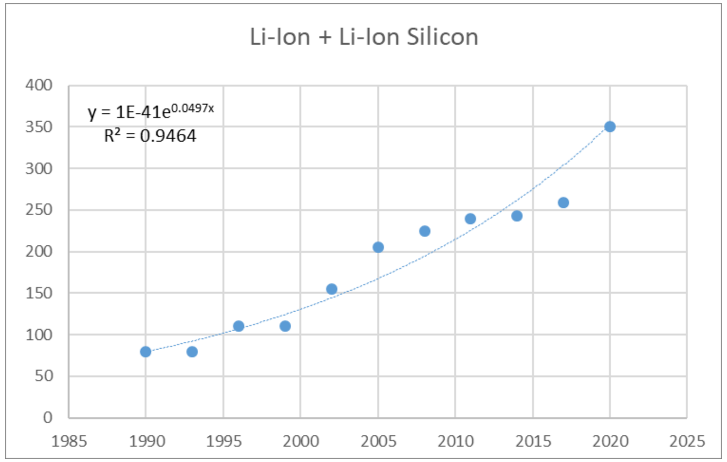
Li-ion & Li-ion/Si Chemistry Trends

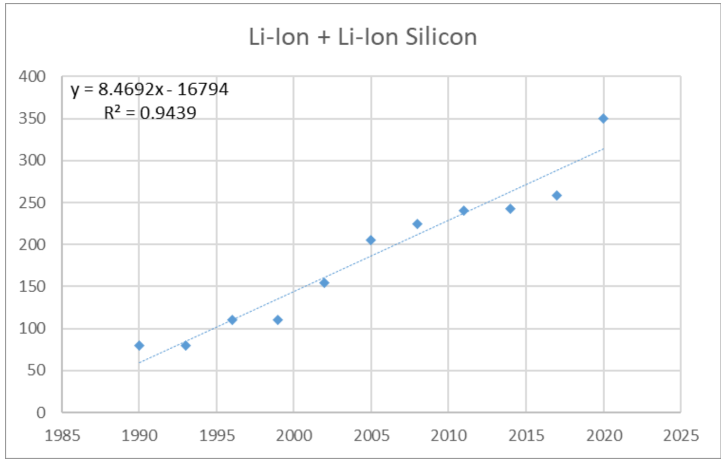
- Chemical trends are meant to look at the specific driving factors that are increasing Specific Energy Density
- Up until the late 2010's, innovation driven by Panasonic
  - "S-Curve" formation appeared to be forming
- Late 2010's innovation driven by Tesla
  - Manufacturing improvements in late 2010's
  - Chemistry improvements introducing Silicon


Li-Ion Trend

Plateau in 2010's and continuing expansion

Silicon tech positioned future expansion


Li-Ion + Li-Ion Silicon

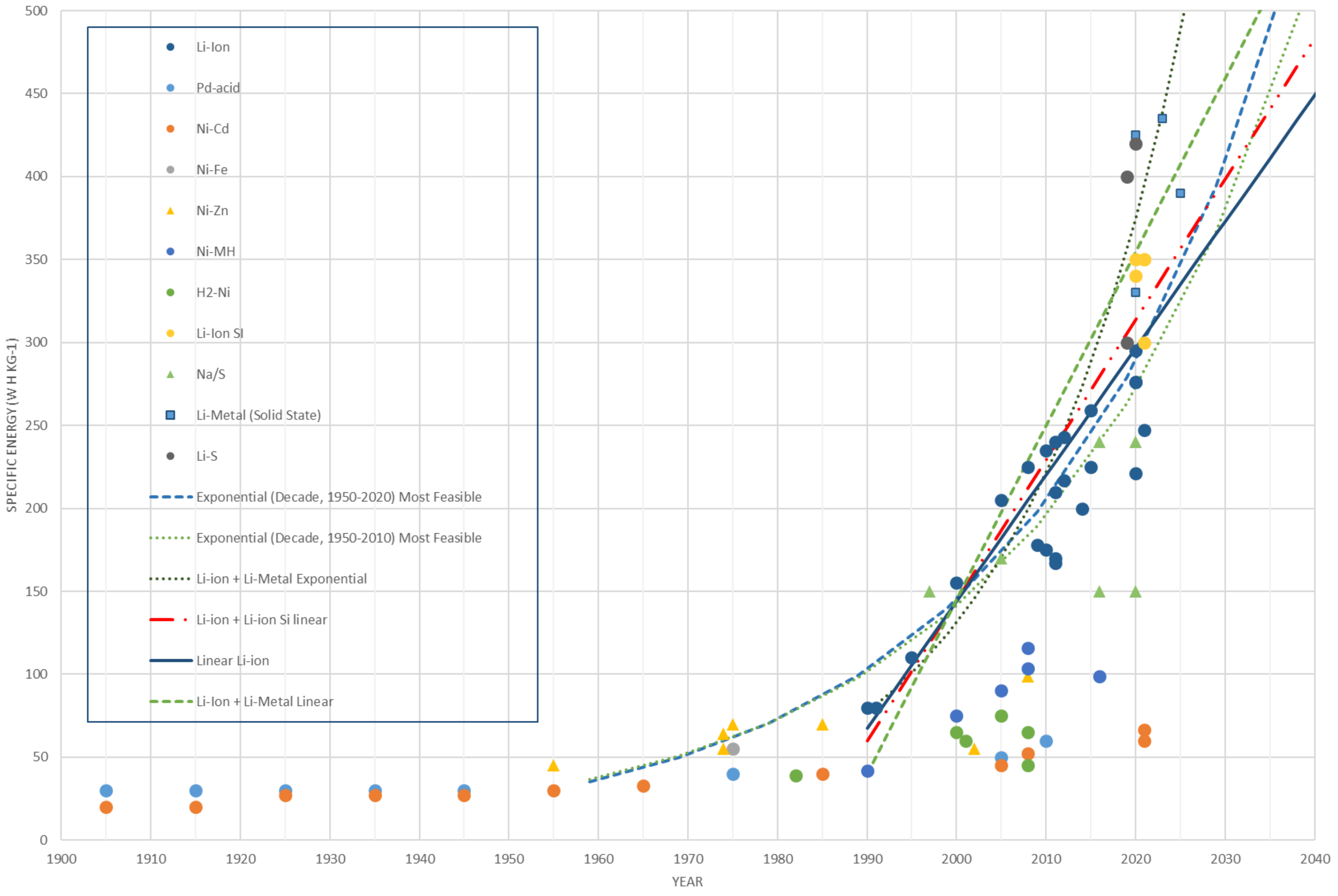

Li-Ion + Li-Ion Silicon

Projections for 2030,2040, and 2050

- Battery examples presented to EAP for thin-haul, regional, and single aisle markets and EV examples used
- For the emerging technologies, least viable were removed from consideration
  - Example: near future Li-Metal removed battery that had achieved 0.2 Ah cell size in exchange for 20 Ah engineering sample
- Linear Li-Ion is the most conservative estimate
- Li-ion + Li-Metal most extreme trend
  - Li-Metal promising due to high energy density, low pack knockdown factor
  - No history at these sizes to project
- Li-ion Silicon viewed as natural evolution of the Li-ion battery
- Projections based on max state-of-art value provided in the year
- Li-S is under consideration by EAP, however only low C rates have been achieved
- Looking for trends in individual chemistry (“S-Curve”), gathering info about theoretical max

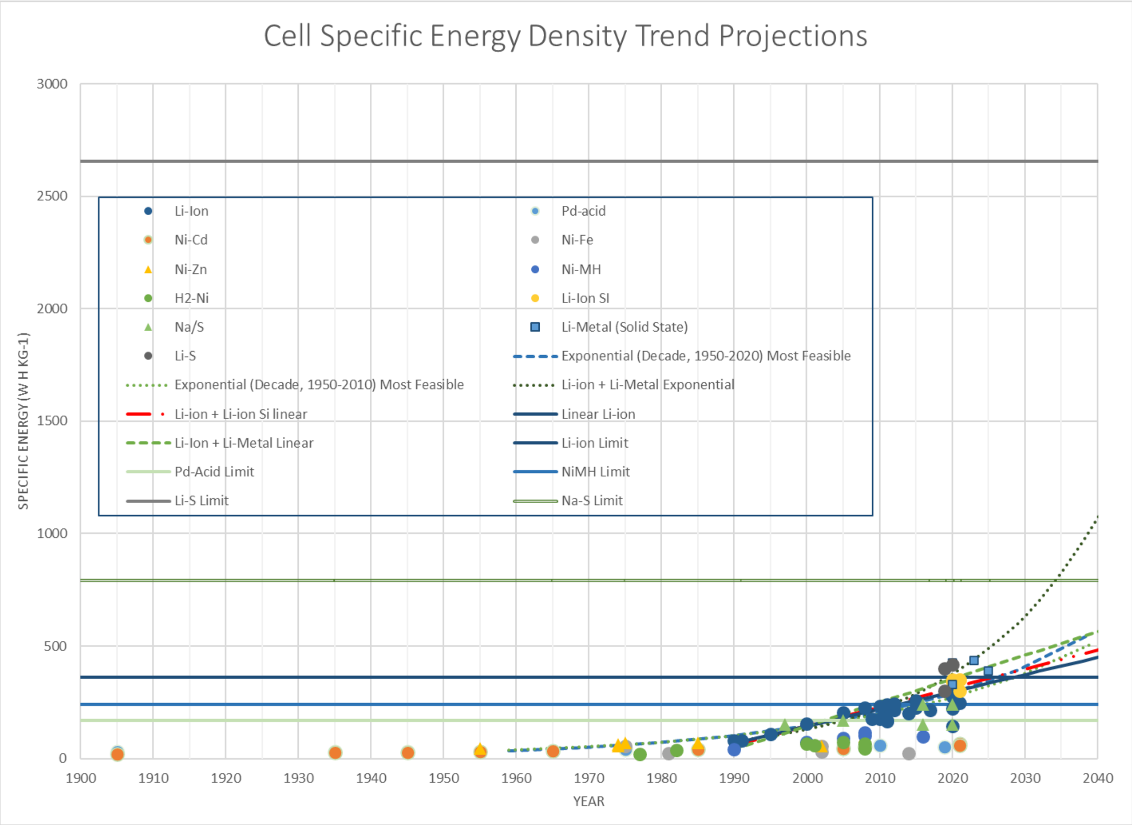
	Selected Trend
Conservative	Exponential (1950-2010) Most Feasible
Nominal	Production Batteries 1990 to 2022
Aggressive	Production Batteries Including Advanced Prototypes

Cell Specific Energy Density Trend Projections



Maximum Limits

- Each cell has a theoretical limit based on chemistry
- A percentage of the theoretical limit achieved can give an insight into how mature a chemistry is, or how close to maturity a chemistry may be
- Li-ion is difficult to measure maturity due to the mixture of chemistries, for the given calculation max Li-ion from acquired Power Sources Database used
- Lithium-Sulfur has large potential by this measure due to high theoretical limit and low realized energy density

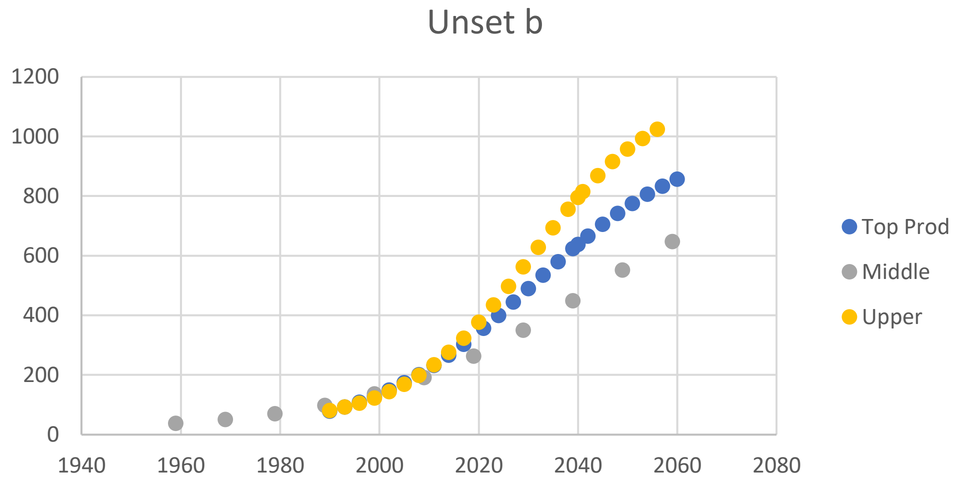


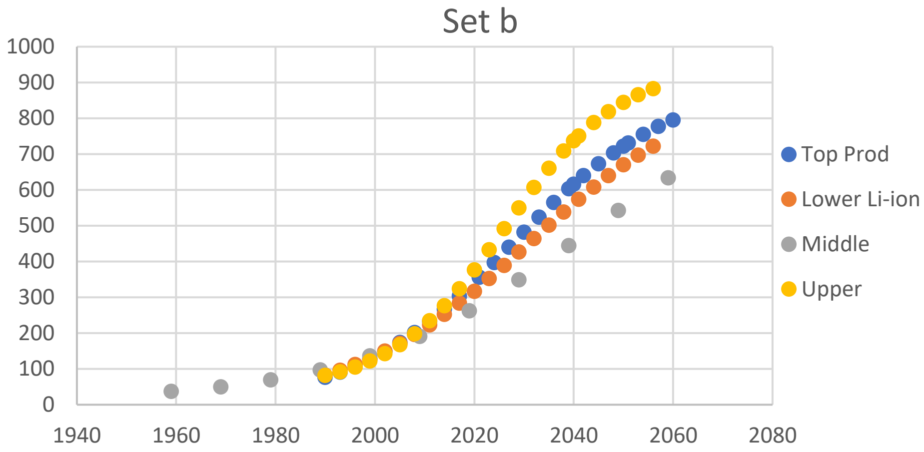
Chemistry	Theoretical Limit (Wh/kg) [6]	Achieved as of 2022 (Wh/kg)	Achieved/ Theoretical
$LiCoO_2/C_6$	568	275	48.4%
Pd-Acid	171	55	32.2%
NiMH	240	116	48.3%
Li-S	2654	420	15.8%
Na-S	792	240	30.3%

Packing Factor Info for Cell to Pack

- Cell knockdown depends on the chemistry, cell form factor, and application
- Lots of examples in EVs for Li-Ion
- Solid State batteries may achieve lower pack knockdown due to thermal stability
- A2Mac1 Automotive Benchmarking reports [3] shows that the state-of-the-art (SOA) packing factor is ~60% for soft-case pouch cells, ~70% for cylindrical cells, and has achieved 84.5% for hard-case prismatic cells with the BYD Blade battery design [7-8]
- Examples from these sources led 0.7, 0.8, and 0.9 to be the packing factor multipliers to apply to the conservative, nominal, and aggressive projections

S Curve Projection Creation



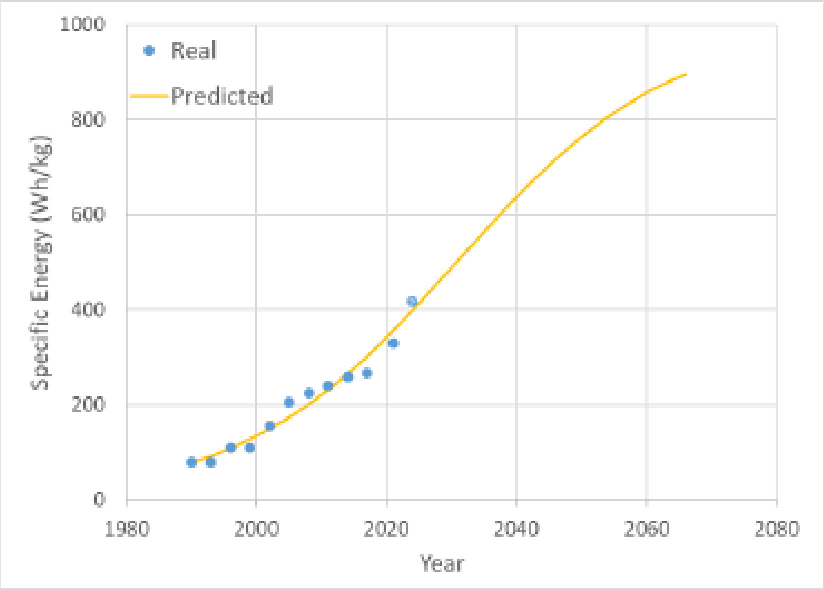


Boltzmann Sigmoid:

$$S(t) = a + \frac{b}{1 + e^{c(\tau - t)}}$$

- Different subsets of data point to different technology trends (name in charts not necessarily name of final trend)
- Boltzmann Sigmoid Function can be used to plot a S-Curve
- All S-Curves are solved by maximizing R^2 of the Sigmoid Function to the underlying projection
- Two projections created
  - One which set $b = 900$ to match up with previous work done which identified $900\ Wh/kg$ as a chemical pouch maximum
  - One which did not set b in order to account for and other factors researched that would push the pouch maximum above 900
- “Unset b” dataset preferred due to right hand limits that approximated theoretical chemistry better than anticipated, increased accuracy to underlying data

Error Analysis



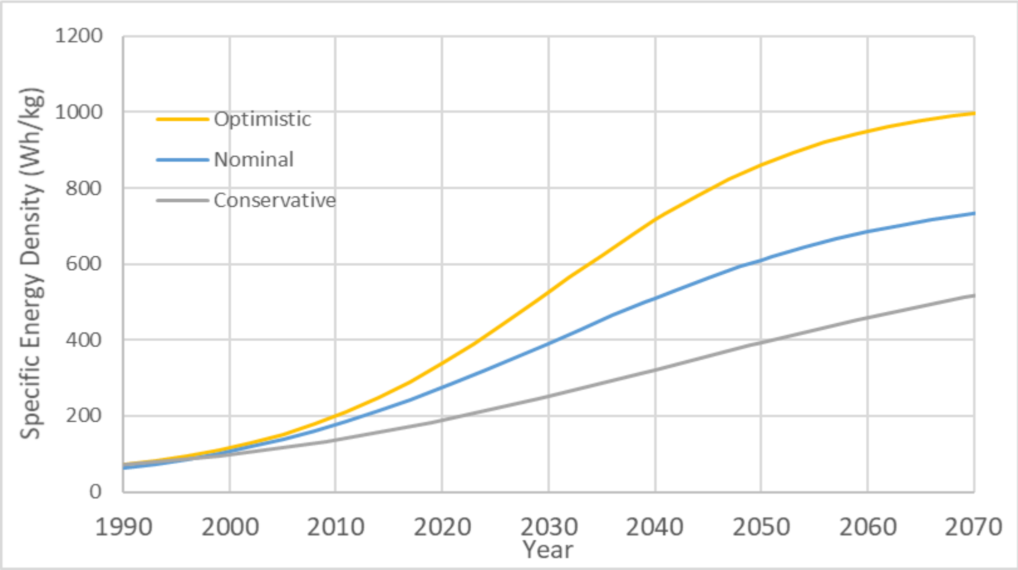
	Type	Equation	R^2
1950-2020 Best Performance	Exp	$y = 1.922 * 10^{-22} * e^{0.0344x}$	0.956
1990-2020 Li-ion + Si	Linear	$y = 8.4692x - 16794$	0.944
1990-2020 Li-ion + Li-Metal	Linear	$y = 9.6056x - 19065$	0.872

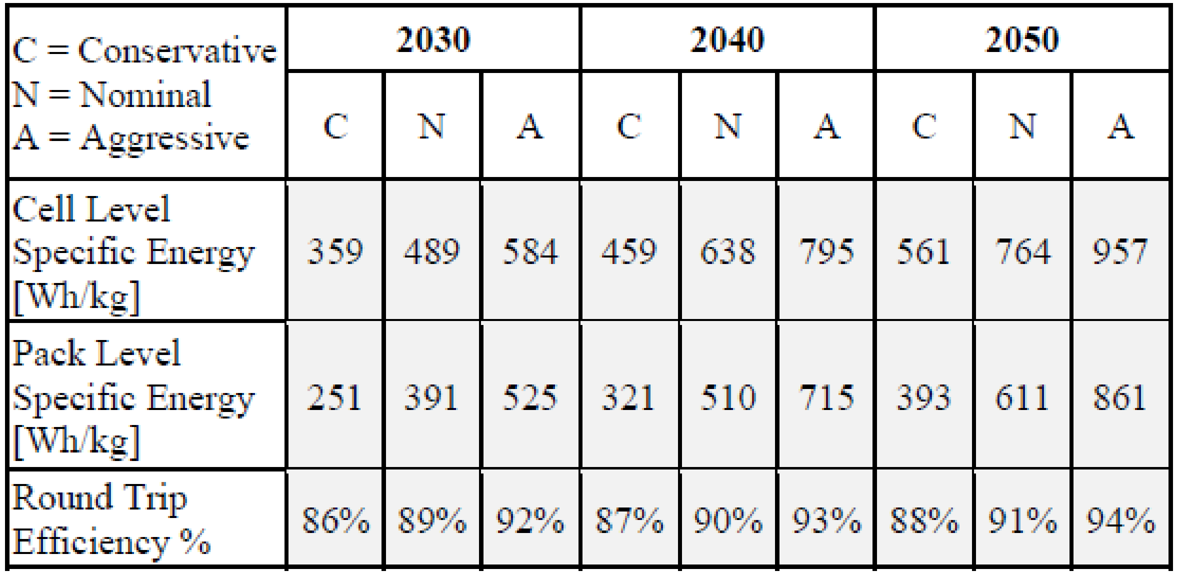
Nominal S-Curve projection and underlying data before the packing factor is applied. R^2 value of 0.96.

Linear trends offered relatively poorer error performance especially for transformative technologies, but were considered due to linear being a conservative estimate

- Errors for underlying trends and S-Curve projections evaluated using R^2
- Both the S-Curve and the trend (Linear or Exponential) should be considered
- Data density was not considered in trend projection as to not skew results toward higher density regions
- Projection performance reliant on data picking methods due to all projections having low errors
- Low error amount comes from nature of the data (general continuous progress of tech development across multiple groups and low amount of output data considered in the projections due to using only best data points)

Pack Projection Creation





C = Conservative N = Nominal A = Aggressive	2030			2040			2050		
	C	N	A	C	N	A	C	N	A
Cell Level Specific Energy [Wh/kg]	359	489	584	459	638	795	561	764	957
Pack Level Specific Energy [Wh/kg]	251	391	525	321	510	715	393	611	861
Round Trip Efficiency %	86%	89%	92%	87%	90%	93%	88%	91%	94%

- Cell S-Curves need to be transformed to pack S-Curves
- Cell to pack transformation done by applying a packing factor multiplier
- Round trip efficiency also provided
  - NASA internal testing data has shown that a commercial 18650 cell designed for high power has an energy efficiency of 95% when discharged at a constant 3C rate
  - Real-world fast charging data of a 2021 Porsche Taycan has shown the ability to charge from 0% to 100% SOC with 90% efficiency [9][10]
  - 90% charging efficiency and a 95% discharging efficiency lead to a total round-trip efficiency of 86%

References

[1] A. Misra, "Energy Storage for Electrified Aircraft: The Need for Better Batteries, Fuel Cells, and Supercapacitors," in IEEE Electrification Magazine, vol. 6, no. 3, pp. 54-61, Sept. 2018, doi: 10.1109/MELE.2018.2849922.

[2] Mission “Analysis and Component-Level Sensitivity Study of Hybrid-Electric General-Aviation Propulsion Systems,” Journal of Aircraft, Vol. 55, No. 6, November–December 2018, doi: 10.2514/1.C034635.

[3] “A2MAC1 - automotive benchmarking ,” A2Mac1, 09-Aug-2021. [Online]. Available: https://portal.a2mac1.com/. [Accessed: 24-Nov-2021].

[4] Batteriesdatabase.com. [Online]. Available: http://www.batteriesdatabase.com/App/. [Accessed: 24-Nov-2021].

[5] D. Linden and T. B. Reddy, Handbook of Batteries, third edition. 2002.

[6] C.-X. Zu and H. Li, “Thermodynamic analysis on energy densities of batteries,” Energy & Environmental Science, vol. 4, no. 8, p. 2614, 2011.

[7] “BYD Blade prismatic battery cell specs and possibilities (update) - PushEVs.” https://pushevs.com/2020/05/26/byd-blade-prismatic-battery-cell-specs-possibilities/ (accessed Apr. 05, 2022).,

[8] “Here’s Why The Battery Pack of Tesla Model S Plaid is An Electrification Masterpiece - FutureCar.com - via @FutureCar_Media.” https://www.futurecar.com/5106/Heres-Why-The-Battery-Pack-of-Tesla-Model-S-Plaid-is-An-Electrification-Masterpiece (accessed Nov. 24, 2021).

[9] “Lucid Air DC Fast Charge Follow Up: Charging Losses Explained.” https://insideevs.com/news/550923/lucid-air-charging-losses-explained/ (accessed Apr. 06, 2022).

[10] K. Li and K. J. Tseng, "Energy efficiency of lithium-ion battery used as energy storage devices in micro-grid," IECON 2015 - 41st Annual Conference of the IEEE Industrial Electronics Society, 2015, pp. 005235-005240, doi: 10.1109/IECON.2015.7392923.