Key Evaluation Parameters for Application-Specific Lithium-Ion Battery Cell Selection

In this LinkedIn blog, I address the importance of key evaluation parameters in battery cell selection for specific applications. The topic of selecting appropriate lithium-ion battery (LIB) cells to meet system requirements presents a challenge and sparks controversial discussions within the industry.

This blog post emphasizes the need to consider application-specific requirements and constraints, such as the required Charge/Discharge C-Rate, energy, lifetime, safety, energy and power density (both gravimetric and volumetric), and cost ($/kWh) when selecting the most suitable LIB technology. Additionally, this blog discusses the impact of cell selection on overall system design and performance, as well as the crucial role of cell characterization in ensuring the safety and reliability of the final product. Initially, it is essential to differentiate between the requirements of each application. For example, in the case of Electric Vehicles (EVs), high LIB energy density is required for an extended driving range, and the cell's fast-charging capability (i.e., high charging power) is also essential. Conversely, for stationary applications, fast-charging is not a priority; instead, cells must meet use-case specific requirements such as prolonged discharge times and extended lifespans (typically >10000cycles and/or 20 years).

1. Energy and Power Density

The Ragone plot, introduced by David V. Ragone in 1968, stands as one of the most prominent methods for providing a rough idea of the energy and power density of various energy storage technologies. However, this method is primarily used for visualization and often overlooks other key parameters such as cost or lifetime. Therefore, a more comprehensive methodology is necessary, one that incorporates the trade-offs between these crucial parameters while considering the diverse chemistries and formats of cells. Figure 1 illustrates the Ragone plot for LIBs with different chemistries, drawing on a database of approximately 600 LIBs. It is important to note that the values provided for these parameters are approximate mean values and intended only to illustrate general trends.

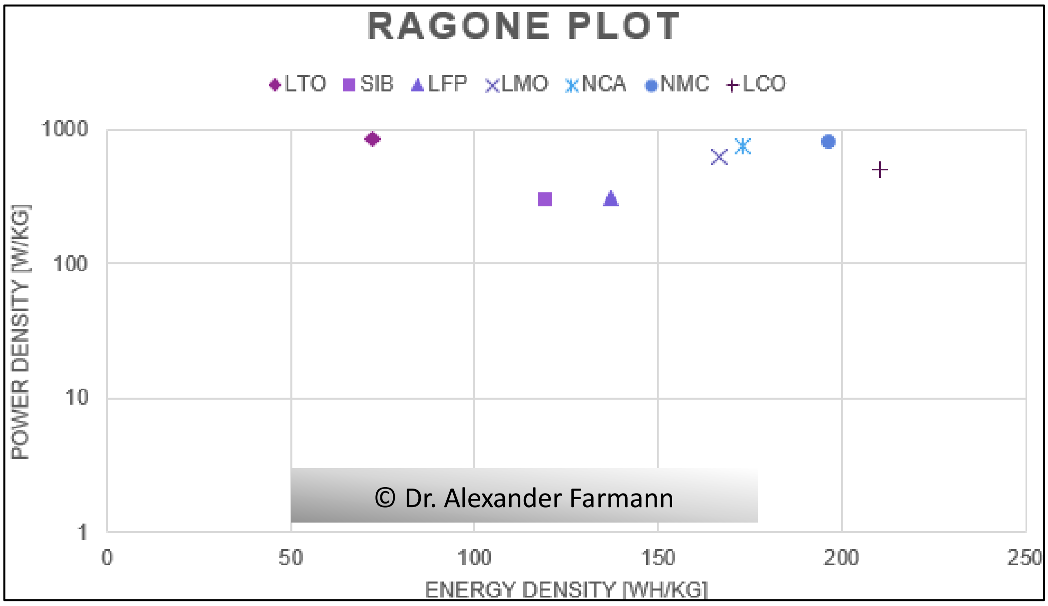

Figure 1: Ragone Plot of different LIB chemistries and formats.

Based on the data presented in Figure 1, along with additional references, the following observations can be made:

1. LIBs utilizing lithium titanate oxide (LTO) anodes demonstrate the highest power density compared to other cell chemistries. However, their energy density tends to be lower.
2. LIBs that employ nickel manganese cobalt oxide (NMC) and nickel cobalt aluminum oxide (NCA) cathodes exhibit the highest energy densities. It should be noted that the small variance depicted in the figure may be attributed to the relatively few NCA-based LIBs included in the database.

3. Lithium iron phosphate (LFP)-based LIBs are predominantly manufactured by Chinese companies. In contrast, Japanese, European, and American companies are key producers of LIBs with LTO and NMC chemistries.

The volumetric energy density pertains to the amount of energy that can be stored in each volume, while the gravimetric energy density refers to the energy stored per unit of weight. Eqs. 1-2 show the calculation method for gravimetric energy and power density – GED and GPD:

$$\mathrm{GED}\left[\frac{\mathrm{Wh}}{\mathrm{kg}}\right] = \frac{V\mathrm{nom}\ [\mathrm{V}] * \mathrm{Capacity}\ [\mathrm{Ah}]}{\mathrm{m}\ [\mathrm{Kilogram}]} \qquad \text{Eq. 1}$$

$$\mathrm{GPD}\left[\frac{\mathrm{W}}{\mathrm{kg}}\right] = \frac{V\mathrm{nom}\ [\mathrm{V}] * \mathrm{I\_DCh}\ [\mathrm{A}]}{\mathrm{m}\ [\mathrm{Kilogram}]} \qquad \text{Eq. 2}$$

The determination of the parameters may vary depending on their definitions and the specific conditions under which they are measured, such as the range used, and the current rate applied to the cell during testing. Moreover, the volumetric energy and power density can be determined using the cell volume instead of its weight.

2. Safety

Moreover, the importance of safety shall not be neglected. Depending on the target application, the LIBs may cause direct injury to human being. The safety level of the LIBs is often classified using the EUCAR hazard level reference list. The HL is defined in a range of 0 up to 7 referring to the severity of the respective hazard where the lowest level (i.e., HL = 0) indicates that no damage is detected and the highest level (i.e., HL = 7) refers to the case where an explosion is detected (See Table 1). In total, it can be stated that a LIB is defined as safe when the HL is lower than level 4. Safety measures in a lithium-ion battery pack equipped with BMS can be subdivided into internal or external methods. External methods mainly rely on hardware for lithium-ion battery pack protection against abuse conditions such cell bypass techniques where the weakest cell is temporarily or permanently bypassed. In this regard, fuses or contactors are used for protecting the battery system against short-circuiting, over-charging and over-discharging [1].

Table 1: Hazard levels definition according to EUCAR definition [1]

Level	Description	Criteria
0	No effect	No effect; no loss of functionality
1	Reversible loss of function	No defect; no leakage; no venting or fire detected; no explosion, temporary loss of functionality
2	Irreversible damage/ defect	No leakage; no venting or fire, no explosion but irreversibly damaged
3	Minor leakage or venting (i.e., Δmass < 50%)	No leakage; no venting or fire, no explosion. Weight loss < 50% of electrolyte weight. Light smoke
4	Major leakage or venting (i.e., Δmass ≥ 50%)	No fire or flame; no rupture, no explosion. Weight loss ≥ 50% of electrolyte weight. Heavy smoke
5	Fire or flame	No rupture, no explosion (i.e., no flying part)
6	Rupture	No explosion, but flying parts.
7	Explosion	Explosion (disintegration of the LIB)

3. Lifetime

Several factors influence the lifetime of LIBs, although they are beyond the scope of this current blog post. More critically, we must define what is meant by the 'lifetime' of an LIB, which can be categorized into two types: cycle lifetime and calendar lifetime. The requirements for LIB lifetime vary depending on the intended application and its specific use case. Cycle lifetime is assessed based on the amount of energy throughput; for example, in EVs, an energy throughput of 20-25 MWh is often expected over the battery's lifetime, until the LIB reaches 80% State of Health (SOH) [2]. Concurrently, the calendar lifetime of the battery system is typically projected to be 15-20 years. It's important to note that the lifetime warranty provided for the battery often corresponds to the expected lifetime of the vehicle or the respective system in which it is used.

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4. Cost

The cost of battery cells or systems is typically quantified in dollars per kilowatt-hour (\$/kWh). In recent years, a significant reduction in prices has facilitated the proliferation of new battery-powered products across both mobile and stationary applications, surpassing even the most optimistic forecasts. A key observation is that the higher the volumetric energy density of the LIB, the lower the cost tends to be. Despite this, the cost of the cell itself remains the principal factor driving overall battery system costs, as opposed to other system components. As LIB costs continue to fall, we can expect to see an increasing number of new battery-powered products entering the market. It is anticipated that cell costs will decline at a faster pace compared to other components of the battery system, such as cooling systems, power electronics, and Battery Management Systems (BMS). The cost at the cell or system level is determined using the following formula [Eq. 3]:

$$\text{Cost}[\$/\text{kWh}] = \frac{\text{Total cost per cell or system [\$]}}{\text{Cell or system energy content [kWh]}} \qquad \text{Eq. 3}$$

5. Current and Power Capability

LIBs that incorporate LTO anodes are notable for their superior charge and discharge capabilities, making them particularly well-suited for applications that require high charging power. In addition to their impressive power handling, LIBS using LTO anodes are also known for their longer lifespans compared to other LIB chemistries. However, it's important to acknowledge that these performance benefits come with a higher cost. To quantify these capabilities, the maximum charging and discharging current or power can be calculated using the following method or formula:

$$C_{\text{rate,dch}}[1/\text{h}] = \frac{I\text{max,dch [A]}}{\text{Capacity,dch [Ah]}} \qquad \text{Eq. 4}$$

$$C_{\text{rate,ch}}[1/\text{h}] = \frac{I\text{max,ch [A]}}{\text{Capacity,ch [Ah]}} \qquad \text{Eq. 5}$$

Fast charging can impose considerable stress on the battery's aging, safety behavior due to occurrence of the so-called lithium-plating [1]. Moreover, it affects the thermal management system, potentially leading to overheating issues, and can also have adverse effects on the overall lifetime of the LIB. Thus, it is essential to balance the desire for fast charging against these potential risks to ensure the longevity and safety of the battery. Figure 2 shows the power to energy ratio of the LIBs having various chemistries and formats from the database. As it can be seen, the investigated LIBs contain a diverse range of power and energy capabilities whereby the emphasis lies predominantly on high-powers LIBs.

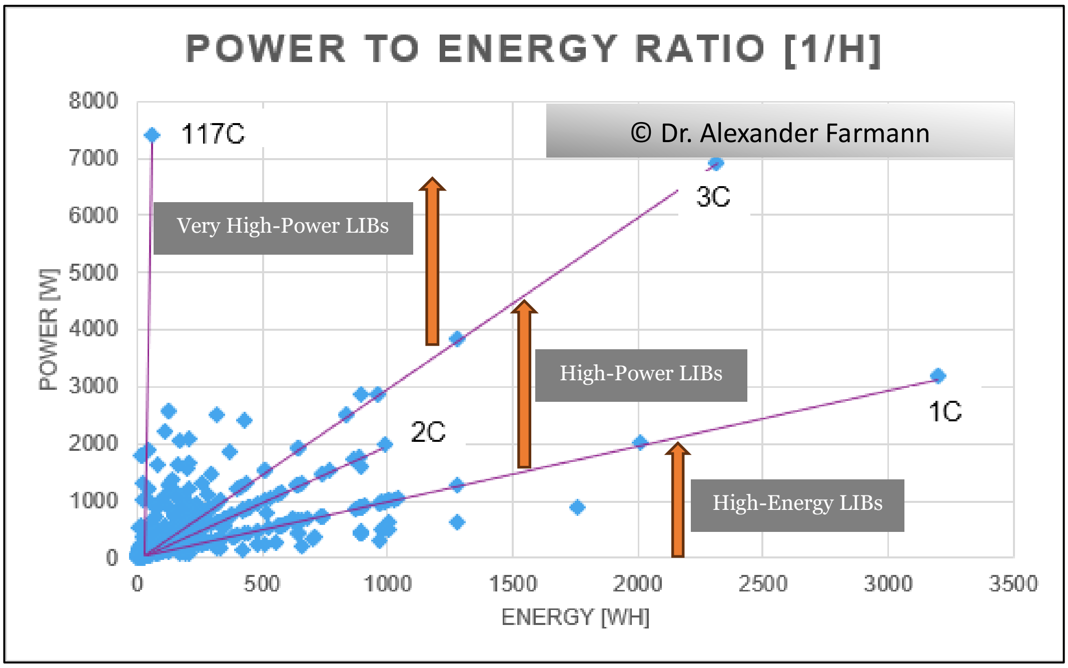

Figure 2: Discharge Power to Energy ratio of different LIB chemistries and formats.

6. Impact on System Design

When designing a battery system, it is critical to consider not only the charging current capability and associated thermal management but also the physical characteristics of the battery cells in relation to the entire battery module or system. These characteristics include:

- Cell volume to battery module/system volume ratio [%]
- Cell weight to battery module/system weight ratio [%]

These ratios are important because they directly influence the volumetric and gravimetric energy density of the battery system. Therefore, higher ratios suggest that a larger portion of the battery system's volume and weight is dedicated to energy storage, which generally leads to a higher energy density of the system. This is a desirable outcome in many applications where space and weight are at a premium, such as in EVs and portable electronics. It's important for these ratios to be maximized within the constraints of safety, durability, and cost-effectiveness to create an efficient and practical battery system.

Summary

In summary, the selection of LIBs for various applications hinges on a balance of several key parameters, which include:

- High lifecycle: The ability of the battery to withstand high amount of charge and discharge cycles without significant degradation.
- Low cost: The economic feasibility of the battery in relation to its performance and lifespan.
- High energy density: The amount of energy stored in a given volume, which is crucial for applications where long duration between charges is needed.
- High power density: The ability to deliver substantial power quickly, important for applications requiring high acceleration-rate.

It is worth noting that high energy density and high-power density are typically trade-offs; optimizing a battery for one often means compromising on the other. Therefore, the specific requirements of the intended use-case determine the prioritization of these parameters in the LIB selection process.

References

[1] A. Farmann, "Comparative study of reduced-order equivalent circuit models for state-of-available-power prediction of lithium-ion batteries in electric vehicles", Ph.D. thesis, RWTH Aachen University, 2019, ISSN 1437-675X.

[2] EUCAR, Battery requirements for future automotive applications; EG BEV & FCEV; 2019.
