The aviation industry is increasingly interested in advancing electrified flight via battery systems. This can be attributed to growing interest in reducing tailpipe emissions and the advances in battery technology that have seen energy densities increase tenfold over the past decade [1]. Over the years, there has been a notable adoption of battery-electric systems in airplanes, with various battery types being utilized, including Nickel-Cadmium (Ni-Cd) [2], Sealed Lead-Acid [3], and Li-Ion batteries [4], each possessing distinct capacities. However, significant challenges prevent the widespread adoption of batteries as the primary energy carrier. While battery-electric aircraft demonstrate superior end-to-end efficiency compared to Brayton-cycle engines, the specific energy of battery systems remains a significant limitation [5]. Various metrics such as energy density, power density, cyclability, safety, and abuse tolerance are generally employed to evaluate the performance of battery cells. Numerous efforts such as ARPA-E’s Propel 1K [6] are underway to improve these performance metrics. Successful improvements in these areas have the potential to profoundly impact the development of large-scale energy systems and contribute to the reduction of aviation-induced emissions. Nevertheless, sectors such as urban air mobility (UAM), regional air travel, and the short-range aviation market can already benefit from the implementation of electrified propulsion architectures. Before diving into a universal metric for accessing different batteries as a feasible energy carry, an overview of the potential cell chemistries is first provided.

Battery Cell Chemistries

Lithium-ion (Li-ion) batteries are extensively used in various industries due to their superior properties when compared to other battery types. Being the third lightest element, the use of lithium allows us to pack as many charged particles as possible per unit volume for the same weight of battery. This results in a significantly higher energy density and a long cycle life compared to lead-acid batteries, and low memory effects compared to Ni-Cd [7]. Nevertheless, when comparing the Li-ion battery performance with jet fuel, which has high gravimetric and volumetric energy densities of 12,000 Wh/kg and 9,600 Wh/L, the current state-of-the-art lithium-ion technology is able to achieve energy densities around 300 Wh/kg and 1,000 Wh/L [8,9]. A Li-ion battery cell is made up of several components, including a cathode anode (negative electrode), separator (porous membrane to isolate the electrodes), and liquid electrolyte. When the battery is being charged, lithium ions move from the cathode to the anode through the electrolyte. An electrochemical reaction generates battery energy, which is converted from chemical energy to electrical energy. Conversely, when the battery is being discharged, the lithium ions move back to the cathode. The separator acts as a physical barrier between the electrodes, but it's porous enough to facilitate the exchange of lithium ions between them through the electrolyte. The energy storage capacity of a lithium-ion battery depends on its charge acceptance and potential, which are associated with the crystalline structure and Gibbs free energy of the active material. Current areas of research involve the use of intercalation electrodes and conversion electrodes.

The most common cathode materials include Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide LMO, Lithium Iron Phosphate (LFP), Lithium Nickel Cobalt Aluminum oxides (NCA), and Lithium Manganese Oxide (NMC). Of these NCA and NMC show the most precise due to their high specific capacity, at 200 mAh/g, moderate-to-high specific power, and high cycle and calendar life, with 1000-1500 cycles [10,11]. However, they have similar thermal stability to LCO batteries. Has a higher cycle life of 1000-2000 cycles compared to NCA [12]. For the cathode, the proportions of nickel, manganese, and cobalt can be adjusted to achieve the desired performance characteristics. Nickel increases lithium extraction capacity and specific energy, while manganese improves power capability and thermal stability. Cobalt increases structural stability and cyclability. That said, the rapid improvement of cells and seen intercalation ability of the cathode and graphite-based anode are both approaching their upper limits theoretical limits meaning a flatting of potential specific energy densities at the cell level.

One variant of Li-ion batteries is those whose electrolytes are not liquid, but rather solid. These cells, termed solid-state batteries, offer advantages in weight, as a thin layer can be coupled with high-energy cathodes, as well as safety since the likelihood of mechanical failure of the solid electrolyte film is less [13]. One current drawback of these cells however is the small temperature range for peak performance – too low a temperature inhibits the electrothermal processes that lead to the movement of charged particles. [13]. Lithium-silicon batteries are another emerging class of cells that show promise. Instead of using the conventional graphitic carbon anode, Silicon is utilized due to its high-performance metrics. Li-Si batteries can reach specific capacities as high as 460 mAh/g [14] at a relatively lost cost due to the high availability of raw silica in nature. However, when compared to commercial battery types, Lithium-silicon batteries suffer from limited cyclability [15]. Lithium-sulfur batteries have also significantly improved over the past decades. Among the advantages of such chemistry, the most important is a high theoretical specific capacity (1675 mAh/g) [16], energy density (2600 Wh/kg) [16], low cost due to the high abundance of raw material in nature as well as being the byproduct of many oil and gas refineries [16]. However, some challenges are intrinsically limiting the development of Li-S batteries, such as non-monotonic discharge curves and high voltage hysteresis which can pose a challenge when developing battery management systems. Additionally, during cycling, volume changes up to 80% and exerts pressure on the cathode integrity with rapid loss of active materials [17]. Furthermore, intermediate reaction products (polysulfides) dissolve in the electrolyte and shuttle between the anode and cathode during the charging process, resulting in extraneous reactions in the electrodes, reducing the Coulombic efficiency [18]

Finally, we have metal-air batteries, which include Magnesium-air (Mg-air), Lithium-air (Li-air), Zinc-air (Zn-air), and Aluminum-air (Al-air). Despite the challenges of practical issues surrounding poor rechargeability, manufacturability and scale, and effective capturing air and extracting oxygen at high altitudes, estimated energy densities, determined to be between 42-58% of the theoretical energy density, fall between 3500 Whkg-1 [19]. Moreover, the use of Zinc offers the benefit of reducing cost as it is high abundance. This earth metal also possesses low equilibrium potential, environmental benignity, a flat discharge voltage, and a long shelf-life.

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Battery System Integration

Popular cylindrical 18650 lithium-ion cell: The cylindrical cell design offers a long life, is economical but is heavy and has low packaging density due to space cavities

The two most common lithium-ion battery formats are the jelly-rolled cylindrical cells and the prismatic pouch cells. While the former provides durability at the expense of low packaging density, the latter is characterized by a large surface area that is ideal for cooling, but requires a heavy protective case, adding a significant amount of weight to the overall battery pack. Additionally, lithium pouch-based designs have shown a promising energy density of about 711 Wh/kg. Lithium–ion batteries can be further classified based on the chemical composition of the cathode \cite{clarke\_lithiumion\_2021}.

How

Challenges

Discharge changes over time

Energy systms require thermal menegment – ther eis a sweet spot

Thermal management

Battery Management System (BMS): The BMS is responsible for the safe and reliable operation of a battery system

Fault detection

Heaviness of batter ypack

Powe electronic electromagnetic interference

Voltages above XX ft cause arging

Battery Degradation

For a given cell, removable energy and capacity can vary depending on rate, temperature,

and state of health (SOH), while power capability can vary by mode (charge/discharge),

state of charge (SOC), temperature, and SOH. SOC is an estimate of the ratio of charge

stored in the battery, and SOH is an estimate of the ratio of performance remaining in the

battery; generally, charge can be restored but performance cannot. For a given cell, SOH

depends both on cycling and calendar aging, the former depending on the characteristics

and frequency of discharge/charge cycles and the latter depending on storage conditions,

primarily duration, SOC, and temperature [44]. Cyclability is a qualitative measure of

the cell’s tolerance for high-rate charge and discharge and for wide-ranging SOC and

temperature. The SOH is also impacted by instances of abuse and tolerance for abuse.

Mechanical abuse includes vibration, impact, penetration, and water immersion; thermal

abuse includes operation at extreme temperatures, high and low; and electrical abuse includes elevated rates, short circuit, over-charge, and over-discharge.