The road towards high-energy-density batteries

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On December 17, 2023, the CEO of NIO took a road test of their newly released vehicle ET7. The mileage of 1044 km from Shanghai to Xiamen is achieved for one charge in the winter season. As the "energy source" of ET7, the cell of the lithium-ion battery has an energy density of 360 Wh/kg (Figure 1). The batteries were produced by Welion Co. Ltd. and developed together with engineers from NIO and scientists from the Institute of Physics (IOP), Chinese Academy of Sciences. The 360 Wh/kg energy density is the highest value for mass-scale production (GWh level). One of the core technologies is in situ solidification. Earlier this year, the team from IOP had also developed a rechargeable pouch-type lithium battery with an energy density of 711 Wh/kg (Figure 1), certificated by a third-party testing institute. This value is the world record for the full cell of rechargeable batteries. The 711 Wh/kg batteries could further expand the application scenarios of batteries, such as electric aviation and humanoid robots.

Improving the energy density is the key and long-term target in this field. The theoretical value of a battery can be obtained by the thermodynamic equation: $\varepsilon = \Delta G / m_a$, where ΔG is the difference of Gibbs energy of the redox reaction, m_a is the mass of all active substances. The theoretical energy densities of thousands of possible batteries have been calculated.[1] The highest value among all electrochemical batteries is 6294 Wh/kg for Li | F_2 battery. When it comes to actual batteries, energy density is calculated by the real discharge energy divided by the total mass of a battery. Since the battery has to contain inactive substances, such as electrolytes, conductive additives, binder, separator, current collector, conducting lead, and packaging materials, the actual energy density is always lower than the theoretical energy density.

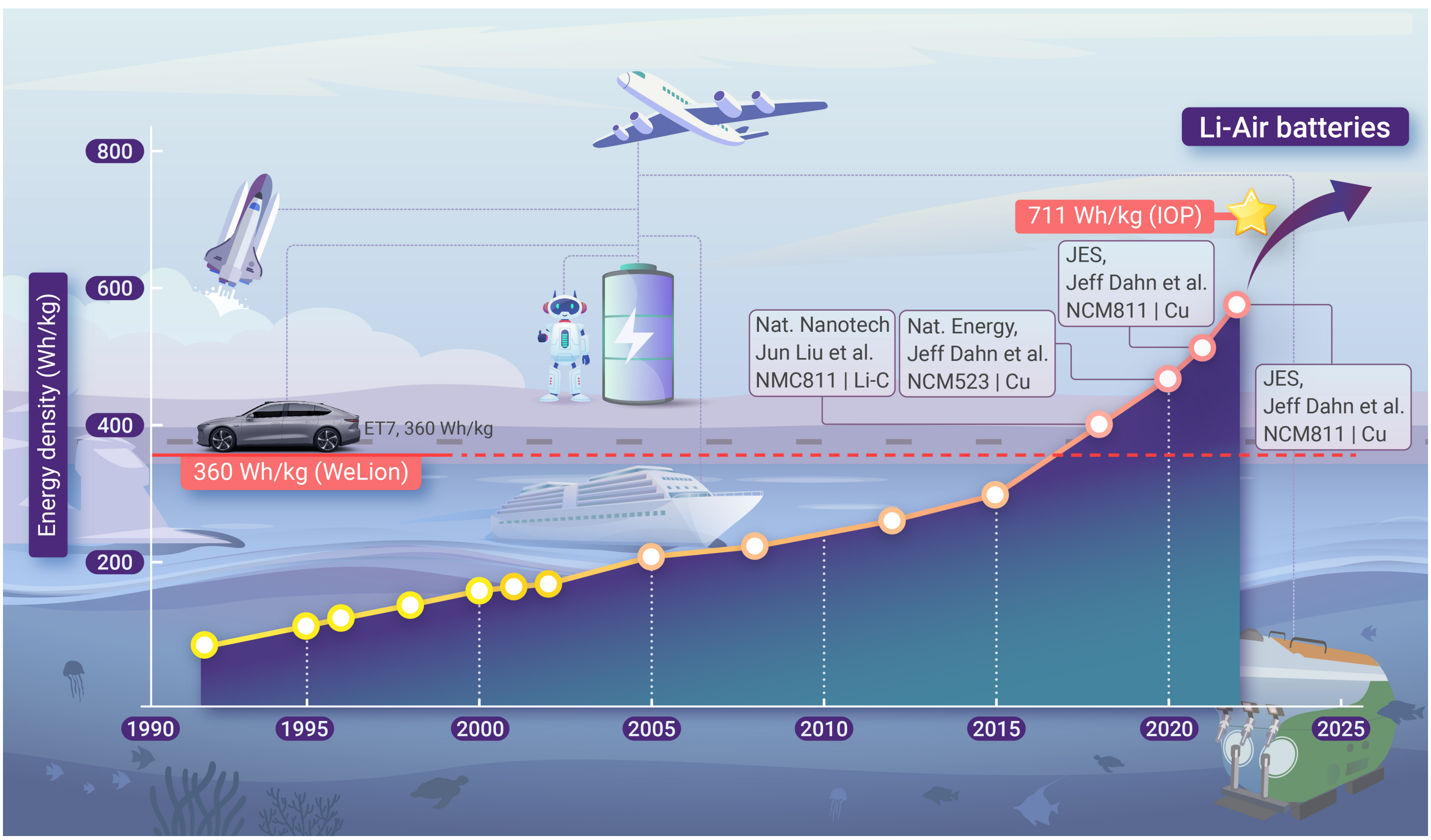

Figure 1. The road towards high energy density batteries With the increase of battery energy density, its application will gradually expand to consumer electronics, electric vehicles, electric aircraft, electric ships, and many other fields. The embedded graph shows the highest energy density in that year of rechargeable practical pouch cells in the last 30 years.

Realization of the 360 Wh/kg LIB is based on several technologies, including in situ solidification,[2] ultra-thin solid electrolyte coated cathode,[3] solid electrolyte coated separator, and high-capacity nano-Si/C composite anode.[4] In the future, it is believed that higher energy density lithium-ion batteries can be achieved by using high-capacity cathode, high-capacity Si anode, and solid battery technologies. The 711 Wh/kg pouch-type lithium battery using high-capacity $Li_{1.2}Ni_{0.13}Co_{0.13}Mn_{0.54}O_2$ cathode and lithium metal anode exhibits a volumetric energy density of 1653.65 Wh/L (after the 1st discharge).[5] The energy density improvement benefits from the extending charge/discharge voltage ranges of lithium-rich cathode. The layered structure of the cathode remains stable in a deep extent of Li^+ de/intercalation. Further, the balance between energy density and cycling performance of lithium anodes with different thicknesses is investigated and the cycling performance of large-area capacity lithium anodes is optimized through interface modifications. The technical combination of high mass loading cathode, thin lithium anode, ultra-thin current collectors foil, and lean electrolyte makes the mass ratio of cathode active substances reach more than 60%, much higher than that in commercialized lithium-ion batteries (~48%).

When designing high-energy-density lithium batteries, the material system is the priority factor. Batteries using silicon-based and lithium metal anode could achieve high energy density due to their super high specific capacity (4200 mAh/g for Si; 3860 mAh/g for Li) and ultra-low electrode potential (-3.04 V vs SHE for Li; ~-2.64 V vs SHE for Si). For the cathodes, there are several potential systems: intercalation type, phase transition, and gas type (F_2, O_2, Cl_2, $SOCl_2$). Intercalation cathode has balanced performances among the current cathode materials, such as the lithium-rich cathode. Conversion cathodes show huge potential among solid cathode materials, especially for their element-friendly, such as the sulfur and CF_x electrode. The gas cathode is the material with the highest energy density in thermodynamic calculation. Though energy density is the most vital factor that determines the cruise for vehicles and aircraft, it is certainly not the only factor when evaluating whether a battery is suitable for various scenarios. It should be mentioned that for most applications, balanced performances are required. The real application of lithium batteries depends on the worst of all properties. Therefore, the actual energy density of a battery varies significantly for different applications, especially pursuing long cycle life, high rate, and low volume variation.

Throughout the history of battery development (Figure 1), the first commercialized lithium-ion batteries were produced in 1991 by SONY and applied in consumer electronics with an energy density of around 80 Wh/kg. The battery used $LiCoO_2$ as the cathode, petroleum coke as the anode, and $LiPF_6$-PC as the electrolyte. Since then, the commercialization of lithium-ion batteries has been going on for more than 30 years, and the energy density of lithium batteries has been increasing at about a rate of 8-9 Wh/kg per year. Among all electrochemical batteries, lithium batteries have the highest energy density. Up to now, the highest reported energy densities for full cells is the 711 Wh/kg pouch-type rechargeable lithium metal battery. While a 360 Wh/kg quasi-solid-state battery developed by IOP and Welion is the highest value for the mass production and practical application. In the foreseeable future, the energy density of batteries will continue to increase, and application scenarios will continue to expand, such as electric aviation and humanoid robots. For electric aviation batteries, usable specific energy and safe rather than cost is the major constraint. Energy density plays the main role in the iteration of practical batteries. The path to higher energy density requires a comprehensive and sustained effort involving scientists, engineers, and other talents from all industries.

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DECLARATION OF INTERESTS

The authors declare no competing interests.