solid energy

>400Wh/kg is here

How SolidEnergy is transforming the future of transportation and connectivity

The battery literature is full of fake news and empty promises. Many claims often look great on paper, but cannot deliver real cells that demonstrate any of the claimed benefits. The world is confused and wondering when there would actually be a real transformation… Until now.

Today SolidEnergy designs and manufactures the lightest rechargeable cells in the world at >400Wh/kg on a commercial scale. This will transform the future of connectivity and transportation, both in air and on land.

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The world is entering a new era in transportation and connectivity

At 90,000ft near the edge of space, high altitude pseudo satellites are providing wi-fi and free access to internet and education to children in rural areas. From downtown to airport, a commute that would typically take 1 hour, now with autonomous electric shared vertical takeoff and landing flying taxis only takes 10 minutes. In music festivals, swarms of drones are lighting up the sky in beautifully choreographed light shows. Around the world, drones are working hard in mapping, surveillance, forest patrol, agriculture, delivery, power line and bridge inspection, emergency response, aerial filming and many more. In major cities, battery-powered electric cars are reducing pollution and enabling safer, smarter, more efficient and better connected transportation networks.

The conventional Li-ion technology that was first commercialized in the early 1990s for the brick phones simply doesn't belong in this new era. The world demands a new cell technology, it demands >400Wh/kg.

The world doesn't care if the cell is solid or liquid, ceramics or polymer, silicon or graphite, lithium or magnesium. What the world wants is a cell that has significantly higher energy density, longer cycle life, better safety, lower cost and more robust performance.

And all these benefits must be demonstrated in real cells, not materials, or coin cells, or computer simulations. Very often we hear exciting claims in the literature, but they cannot be reduced to real practical cells. This has caused a great deal of confusion and fake news in the industry. We must evaluate the merit of a technology not based on the fame of its author or claims on paper, but actual verifiable performances in real practical cells.

Must demonstrate step change in energy density

Throughout the history of rechargeable cell technology, from Lead-Acid, to Ni-Cd, to Ni-MH, to Li-ion with graphite anode, and to now Li-ion with silicon-based anode, despite the absence of a fundamental Moore's Law as there is in the semiconductor industry, we see a clear trend (Figure 1). A new technology replaces the old one because of step-change in energy density. It only gets lighter and smaller, never the other way around.

There are many options below 400Wh/kg and 1000Wh/L, all the conventional technologies, and even some emerging technologies fall in that region.

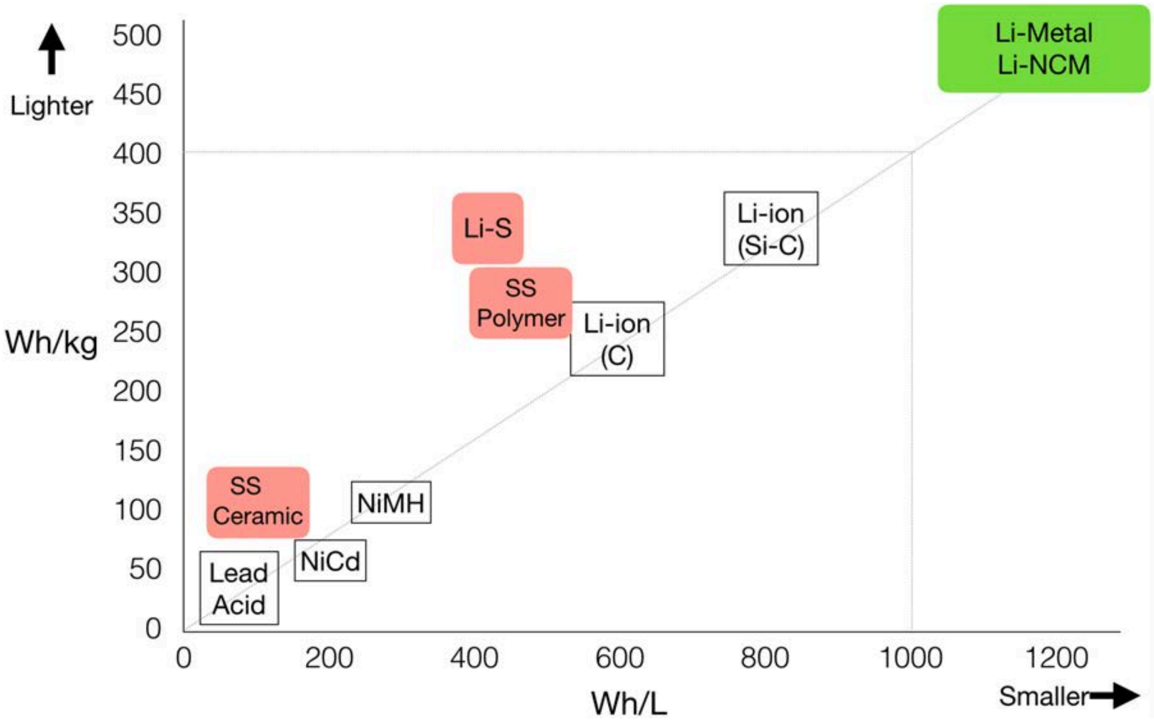

Figure 1 | History of battery technologies. A new technology replaces the old one because of significant improvement in energy density.

The state-of-the-art Li-ion with graphite-based anode has 250Wh/kg and 600Wh/L, and the state-of-the-art Li-ion with Si-based anode (either nanowire or silicon-graphite composite) has 350Wh/kg and 800Wh/L. These two are the industry standards, which all other technologies are being compared to.

Some of the "emerging" technologies such as Li-Sulfur and all Solid-State demonstrate interesting benefits, but have yet to achieve significant impact or scale despite having been around since the 1990s and continue to remain in the "emerging" state.

Li-Sulfur has demonstrated good gravimetric energy density around 360Wh/kg but suffers from poor volumetric energy density of 500Wh/L and cycle life (<100), overall it shows no clear practical advantage compared to state-of-the-art Li-ion with Si-based anode. All Solid-State Polymer has demonstrated great safety, but its gravimetric and volumetric energy density are comparable with Li-ion with graphite anode, and its performance is limited to elevated temperatures (>80°C), therefore overall it shows no clear practical advantage compared to state-of-the-art Li-ion with graphite anode.

All Solid-State Ceramics has also demonstrated great safety and wide temperature performance, but is extremely difficult to scale. The ceramics or glass-based electrolyte needs to be either vacuum deposited or annealed. While solid-state ceramics electrolyte can sometimes eliminate the need for a separator, it replaces it with a much thicker ceramics brick. As a result, it is limited to micro-sized batteries with capacities in the 10s of mAh and has almost no energy density (because of packaging), too small to power our future transportation demand.

These “emerging” technologies do not follow the trend. In order for new technology development to be meaningful, it must follow the trend, and must be significantly higher in both Wh/L and Wh/kg compared to state-of-the-art Li-ion with Si-based anode.

From its inception, SolidEnergy has focused on the uncharted territory of >400Wh/kg and >1000Wh/L. Today it has demonstrated 450Wh/kg and 1200Wh/L in real 3Ah cells capable of stable wide temperature performance using a lithium metal anode and high energy density NCM cathode, all independently tested and validated by third parties. It is on track to achieve >500Wh/kg by end of 2017.

While SolidEnergy’s goal is to design and manufacture the lightest practical rechargeable cells in the world and will use whatever material necessary and has no philosophical attachment to any particular materials, it is focused on lithium metal-based anode. This is due to its high specific capacity (3860mAh/g), low density (0.59g/cm^3) and low electronegativity (-3.04V vs. standard hydrogen electrode). Li-Metal is the next frontier.

Electrolyte development for Li-Metal

Rechargeable Li-Metal cells were first developed in the 1980s, but were plagued with the formation of mossy lithium during charging that can penetrate separators and lead to explosions, and were sidelined by the lithium-metal-free Li-ion batteries that offered significantly better safety (first graphite-based Li-ion in 1990 and then Si-based Li-ion in mid-2000s). With recent material breakthroughs and increasing demand for energy density, Li-Metal is making a strong comeback (Figure 2).

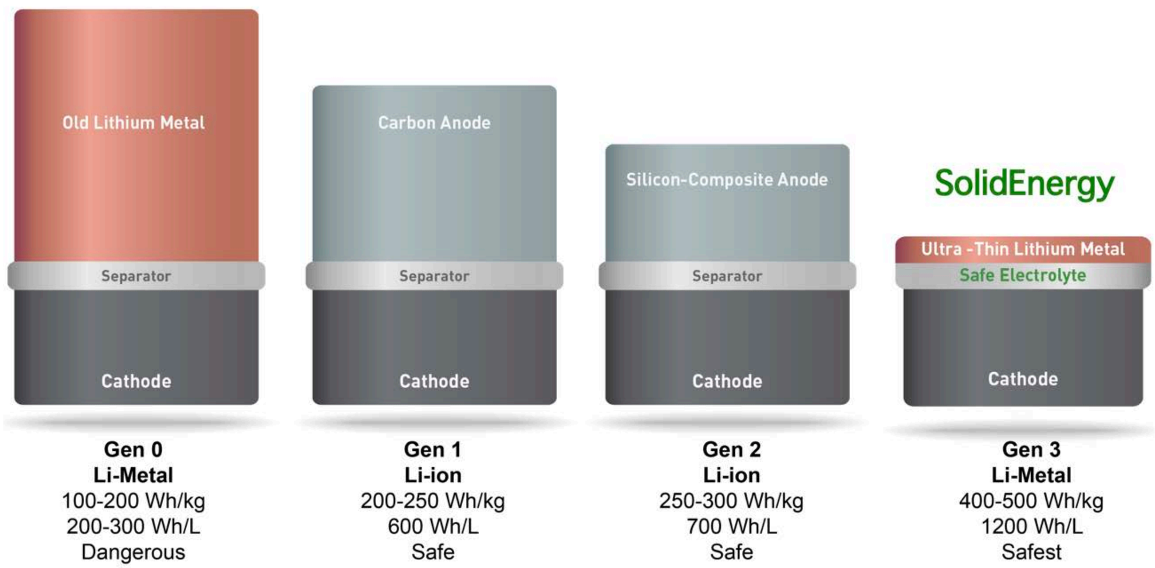

Figure 2 | History of Lithium Batteries from an Anode Perspective.

Li-Metal can be divided into three main categories: Li/intercalant cathode, Li/sulfur, and Li/air. Li/air has a potential for >10,000Wh/kg in gravimetric energy density (approaching that of gasoline), but remains a long way from commercialization because of fundamental science issues. Li/sulfur has demonstrated nearly 400Wh/kg in commercial cells and has been used in aerospace applications, where lightness is paramount. But its volumetric energy density (Wh/L) is low and has hindered its application in consumer electronics and electric vehicles. Li/intercalant cathode (such as high energy density NCM cathode) can increase energy density (both Wh/kg and Wh/L) by 100% compared to graphite anodes and 50% compared to silicon-based anodes. Whether the cathode is air, sulfur, or high voltage intercalant, the key ingredient to enabling a rechargeable Li-Metal battery is the electrolyte.

However, the field of electrolyte development for Li-Metal batteries is fragmented and narrowly-focused, currently there are three main categories, all aimed at controlling lithium plating morphology during charging.

1) *Solid state: increasing electrolyte conductivity*
Recently researchers at Toyota and Tokyo Institute of Technology developed superionic conductors $Li_{9.54}Si_{1.74}P_{1.44}S_{11.7}Cl_{0.3}$ and $Li_{10}GeP_2S_{12}$ that have very high conductivity at room temperature (10^{-2}S/cm). But they suffer from poor lithium metal stability, and difficulty in making thin electrolyte film, reducing the energy density at the cell level[1,2]. Researchers at Berkeley and Grenoble INP developed single-ion conducting polymer electrolytes that have high mechanical strength and electrochemical stability and excellent electrolyte-anode interface adhesion,

but suffer from low conductivity, limiting the cells to high temperature applications[3,4].

2) *New liquid: increasing lithium plating and stripping Coulombic efficiency and retarding mossy lithium growth*
Researchers at Pacific Northwest National Lab developed high concentration electrolyte (4 Molar solvent-in-salt approach) and demonstrated high Coulombic efficiency of over 99% and fundamentally smoother and denser lithium plating morphology. This enables high rate performance and robust manufacturing, but suffers from poor stability at high voltage cathode and the volatility of the solvent used, limiting the cells to low voltage and low capacity cathodes[5,6].

3) *Surface modification: 3D scaffold structure on lithium surface*
Researchers at Stanford impregnated lithium metal with 3D scaffold structures, forcing lithium plating into the porous matrix, effectively reducing current density and minimizing volume change during cycling. But the scalability of the technique is questionable, the large empty volume needed to accommodate plated lithium reduces volumetric energy density, and the high surface area also accelerates electrode and electrolyte consumption due to SEI formation[7,8].

SolidEnergy's integrated approach

It is one thing to develop a new material and maybe even demonstrate some interesting properties, especially under benign academic conditions such as small plating capacity (<1mAh/cm^2), low voltage window (low voltage cathodes or symmetric cells), thick electrolyte (>50μm), and excess lithium anode (>1X plating capacity). But the question is how does it fit into a larger cohesive vision? How does it enhance the user experience, whether it's communicating with love ones on a smart phone or driving with family in an electric car or flying a drone at the edge of space broadcasting wi-fi?

SolidEnergy does not start with a specific material; it starts with the final user experience and works backwards. If Li-Metal cannot deliver far superior energy density than Li-ion, then it has no reason to exist. At the same time, high temperature and micro-capacity limitations from earlier versions of Li-Metal are not desirable and must be avoided. SolidEnergy has also disciplinarily adopted a rigorous testing platform, high plating capacity (>3mAh/cm^2), high voltage cathode (>4.3V), thin electrolyte (<12μm), ultra-thin lithium anode (<1X plating capacity), and all in a real 2Ah pouch cell, allowing it to efficiently identify meaningful progress from misleading ones.

SolidEnergy introduces and integrates three new products (Figure 3): 1) A breakthrough solid protective coating (anode-lyte) consisting of polymer and inorganic materials that is applied directly onto a surface-treated lithium metal anode to suppress the growth of mossy lithium. It has high Li^+ conductivity but is immiscible with liquid electrolyte, and its mechanical rigidity and elasticity can withstand the stress of >3mAh/cm^2 (>15μm) of lithium plating and stripping for hundreds of cycles; 2) A revolutionary liquid electrolyte (cathode-lyte) that has high lithium plating and stripping efficiency, high oxidation stability at high voltage cathode, and reduced solvent volatility; 3) An innovative cell assembly process that maximizes cell level energy density, addresses volume expansion during cycling and enables Li-Metal to be manufactured at scale using existing Li-ion infrastructure.

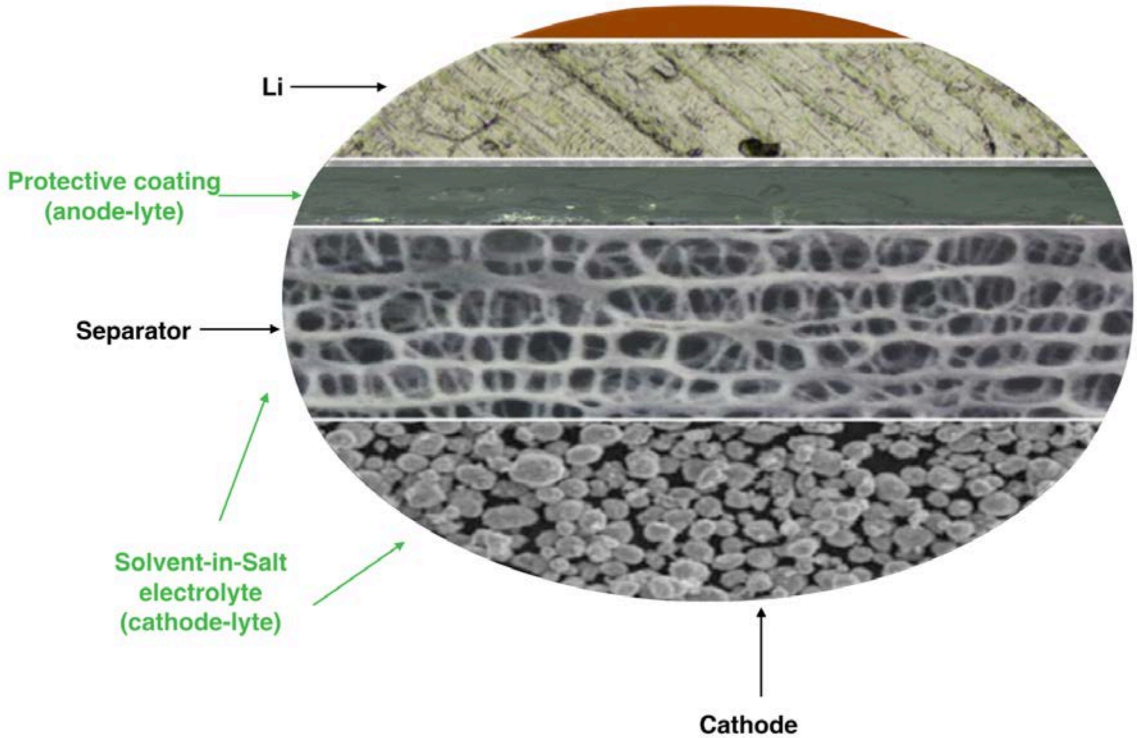

Figure 3 | SolidEnergy's Semi-Solid Li-Metal Cell Design. A hybrid approach

The final product is a Semi-Solid Li-Metal cell and the results are magical. SolidEnergy has successfully demonstrated in real 3Ah cells (not based on simulation results) 450Wh/kg and 1200Wh/L, twice the energy density of state-of-the-art Li-ion, and capable of cycling at high current density at room temperature, all independently verified by third parties. Figure 4 shows a SolidEnergy 3Ah cell next to an iPhone 6+ cell which is also 3Ah.

This hybrid approach technology is versatile for a wide spectrum of high energy density cathode chemistries including LCO, NCM, NCA, Li-Mn rich operating at >4.4V, allowing it to ride the wave of innovation in cathodes. Such high energy density battery can also be discharged up to 10C at room temperature, making it suitable for power applications such as drones and electric vehicles.

Figure 4 | Half the size and half the weight. A SolidEnergy 3Ah cell (left) in comparison with an iPhone 6 Plus 3Ah cell (right).

The story of SolidEnergy

SolidEnergy started in 2012 as a Harvard/MIT student team that won prestigious business plan competitions including MIT $100K, MIT Clean Energy Prize, US Department of Energy Clean Energy Prize, and runner-up at the first ever US National Clean Energy Business Plan Competition. That autumn, in one of the worst meltdowns in the history of the lithium battery industry, several large Li-ion battery companies filed for bankruptcy after having raised tens of billions of dollars, including another Massachusetts-based company A123. Investors that were initially excited about SolidEnergy couldn't run away faster.

On a serendipitous day that winter, SolidEnergy visited A123 on a "dumpster hunting" trip out of desperation, and found lots of idling equipment and employees, and asked them if they could help build some batteries. Initially they laughed, but then they showed the whole process and before long SolidEnergy was going there every weekend and evening building batteries.

In an interesting turn of event, A123 was acquired and emerged from bankruptcy in spring of 2013. SolidEnergy officially formed a partnership to leverage A123's infrastructure, and investors were impressed by its prototypes and ability to get things done even with limited resources, it received its first investment. Almost all student teams dissolved after competitions, but SolidEnergy went on to become a real company.

Fast forward to 2017, the young fledging company that was born to adversity has risen out of the ashes. SolidEnergy moved out of the A123 incubator and built a brand new state-of-the-art pilot production facility. Its new facility is big enough to house the wings of a Boeing 747. It can produce 5,000 cells per month, and these are not ordinary cells, these are the lightest practical rechargeable cells in the world, all >400Wh/kg.

The integrated approach that SolidEnergy developed is now at the heart of the current worldwide renaissance in Li-Metal batteries.

SolidEnergy is now supplying Li-Metal cells under the name Hermes™ (High Energy Rechargeable Metal cElls for Space) to customers in aeronautics, space and consumer drones, and enabling exciting applications such as high altitude pseudo satellites to provide free and open access to internet and education to children in rural areas, autonomous electric flying taxis to dramatically reduce pollution and traffic during our daily commutes, and beautifully choreographed drones light shows that capture our imagination.

Figure 5 | Designed to Unlimit Human Imagination. SolidEnergy's state-of-the-art pilot production facility.

Today, pioneers with 2018 ideas are *limited* by 1990 battery technology. They are the creative genius, but often they are ridiculed for having outlandish ideas. SolidEnergy wants to help those people by bringing them an entirely new source of energy, and *unlimit* human imagination.

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