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THE BIG STORY / NOVEMBER 2017

For EV Batteries, FUTURE IS NOW

What's up next for electric-vehicle batteries? More of the same, and that means it's far from over for lithium-ion.

Although there's much hype around lower-cost, longer-range batteries to come, it's really just the dawn of the Li-ion era, and there remains considerable untapped potential yet in the technology as automakers seek to develop lower-cost, higher-range EVs.

BMW's i Vision Dynamics – one of many electric concepts featured at this year's Frankfurt auto show.

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Galyen: Just beginning for Li-ion batteries.

Battery makers only recently have begun to make big commitments to high-volume Li-ion production, with 12 new or expanded mega-factories reportedly set to come online worldwide by 2020. That includes 120 GWh of new cell capacity in China alone – enough battery power for another 1.5 million EVs annually.

With that level of new investment, the industry likely is chained to Li-ion technology – for better or worse – for most of the coming decade, or even beyond.

"We're just at the forefront, the beginning if you will, of Li-ion battery technologies," Bob Galyen, chief technology officer for China-based battery maker Contemporary Amperex Technology (CATL), says at the Battery Show Exhibition and Conference held in Novi, MI, in September.

That's not to say battery makers, upstarts and researchers aren't furiously experimenting with new chemistries and configurations in an effort to displace today's state-of-the-art technology. They are.

All are focused on making level-of-magnitude leaps in range, safety and durability with new concepts that use more widely available, less-costly materials; swap metals with air to cut weight; and replace the current volatile liquid electrolytes used with heat-resistant solids.

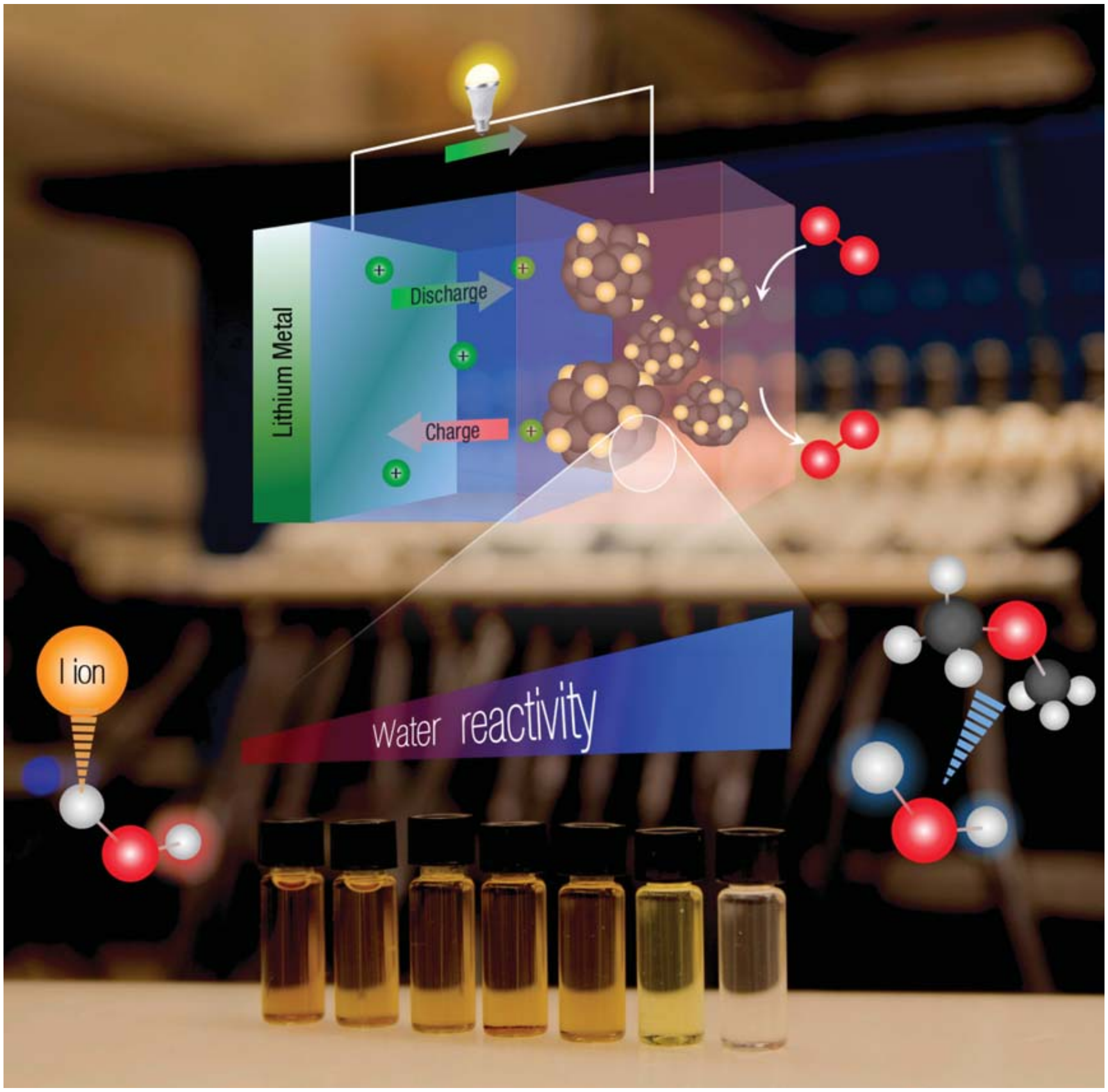
The U.S. Department of Energy has set a 2020 target to cut battery-pack size and weight in half and slash costs to $125/kWh, a price point seen igniting a market shift toward electrified vehicles.

One of the concerns with today's Li-ion batteries is the restricted availability of lithium and cobalt, a problem that only will grow as EV models proliferate and production ramps up.

WardsAuto data indicates automakers have penciled in no fewer than 85 new battery-powered models by 2025, with everyone from Aston Martin to Volvo announcing aggressive EV plans. Even commercial-truck makers are eyeing electrically powered big rigs for the future.

That has Transparency Market Research projecting the Li-ion

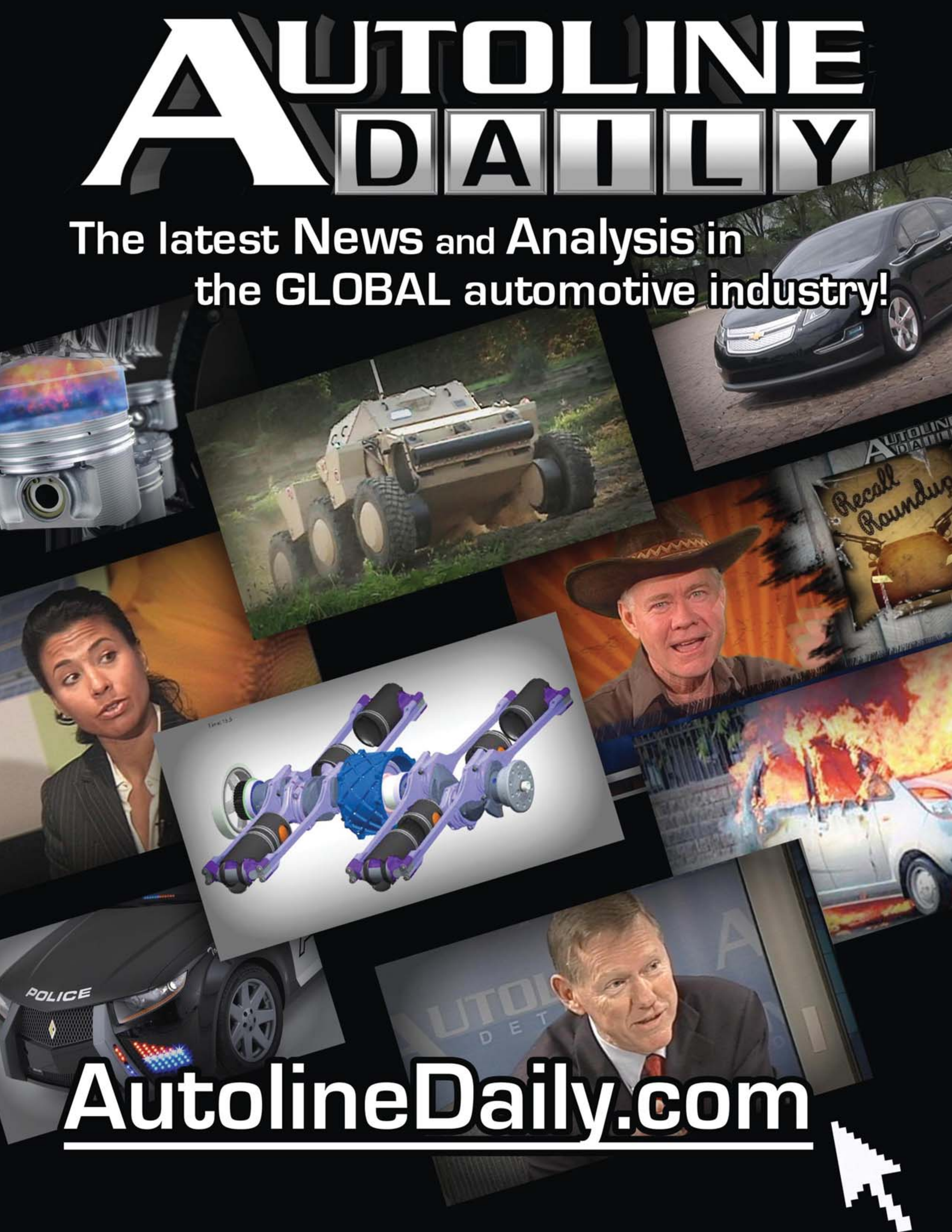
Still more improvements to come for today's Li-ion battery technology.



battery market will grow to $77.4 billion worldwide by 2024, from $29.7 billion in 2015, an escalation likely to ramp up pressure on the supply chain.

Demand for cobalt, becoming the go-to material for the cathode in Li-ion batteries, already is expected to outstrip supply this year by 900 tons, commodity consultancy CRU estimates.

Lithium supply may be even more problematic. Two-thirds of proven reserves are located in the "Lithium Triangle," a small area of South America where Argentina, Bolivia and Chile intersect. That has cell producers in China, the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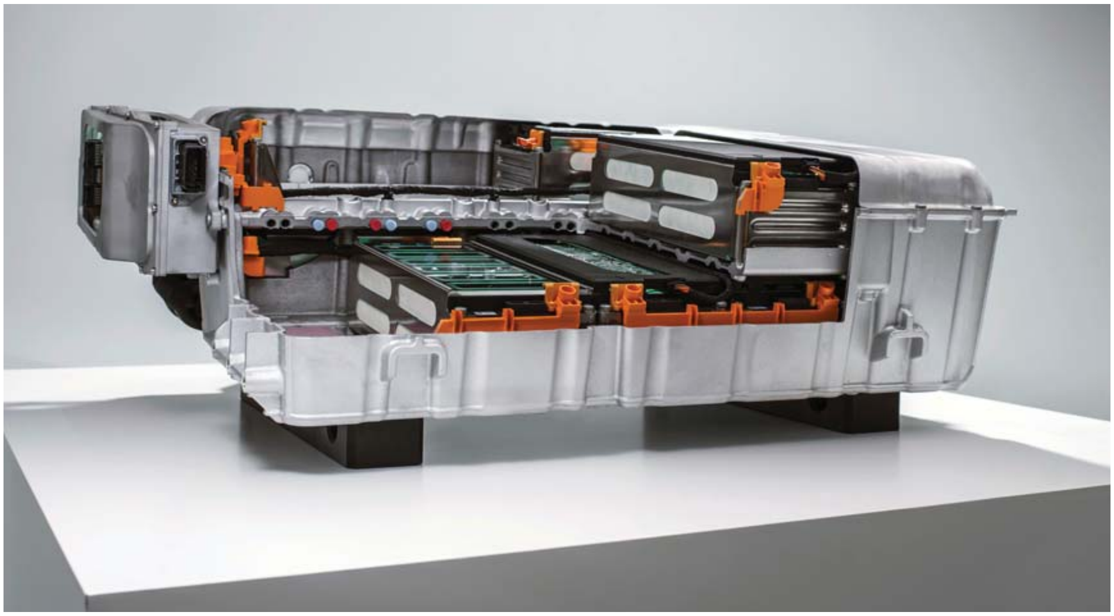


Because of potential volatility, today's Li-ion battery packs must be bulletproof to survive rigors of automotive use.

fourth-largest source of lithium, locking up stakes in Chilean and Argentinian mining companies to corner the market on the material and further tighten their grip on the emerging EV-battery sector.

Prices reportedly have been skyrocketing.

"We're starting to see some headwinds coming in from raw materials," Joern Tinnemeyer, chief technology officer for EnerSys, notes during a Battery Show panel discussion. "This may have some impact on EV adoption, because the price point will not drop as much as we need it to."

But moving past some of these constraints with new technology won't come easily. Commercializing a new battery is hard – and it's twice as difficult to make one that is viable for automotive use. Not only does the battery cell have to work, it also has to be capable of mass production and assembly into a single package. It also must survive repeated charge/discharge cycles in extreme environments and be absolutely bulletproof on the road for at least 10 years and 100,000 miles (162,000 km).

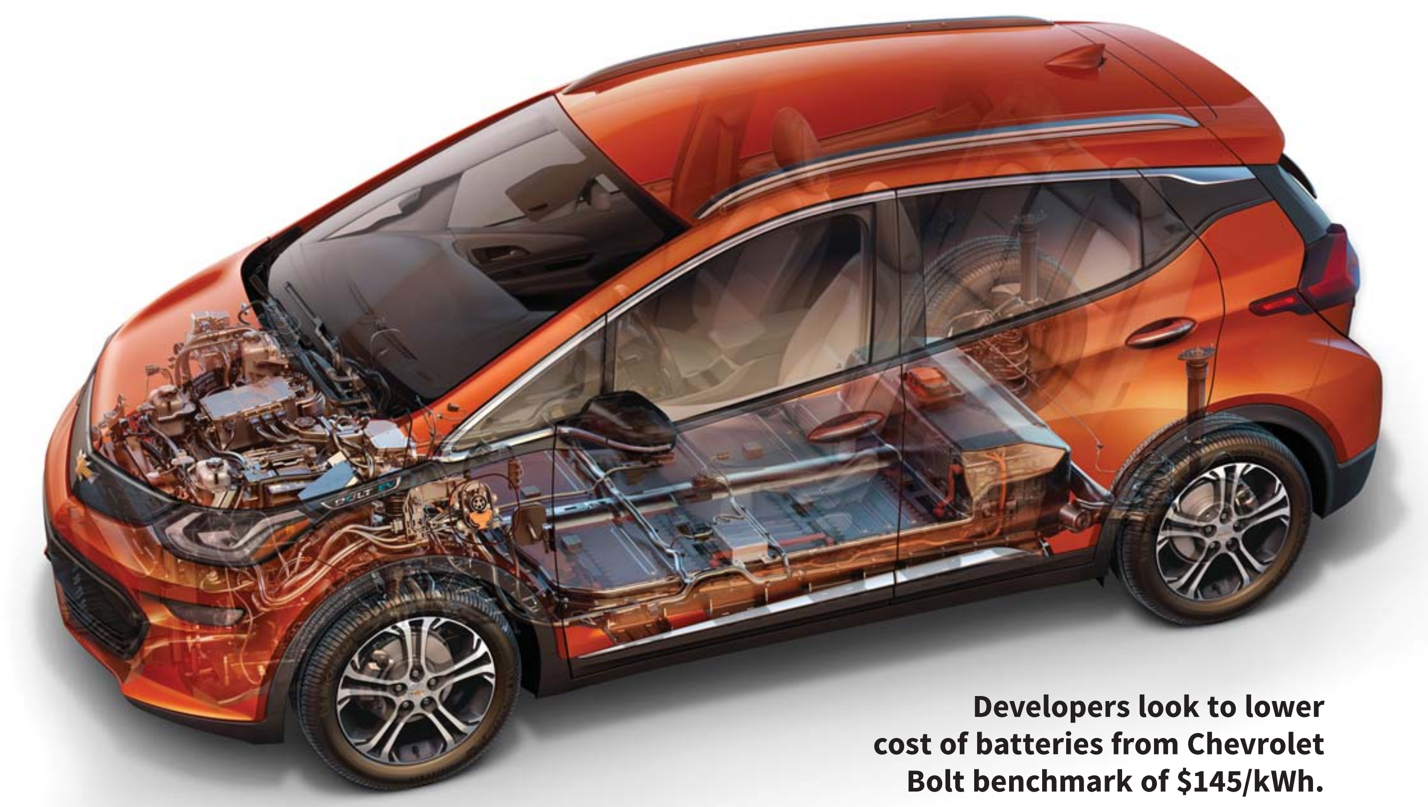
Every Li-ion alternative being explored today still has a number of hurdles to overcome. So even if development proves brisk, it's going to take time – a considerable amount – to get these concepts out of the lab and into the chassis of future EVs.

"It's a slow march towards progress," admits Graham Leverick, a graduate student who is part of an advanced-battery research team at the Massachusetts Institute of Technology.

Still, there is some interesting work going on. While it's difficult to handicap which technologies have the best shot of seeing commercial application and when, here's a short-list of concepts and some of the research under way that could provide the big bang needed to shift the EV market into a higher gear.

Nickel-3D Zinc

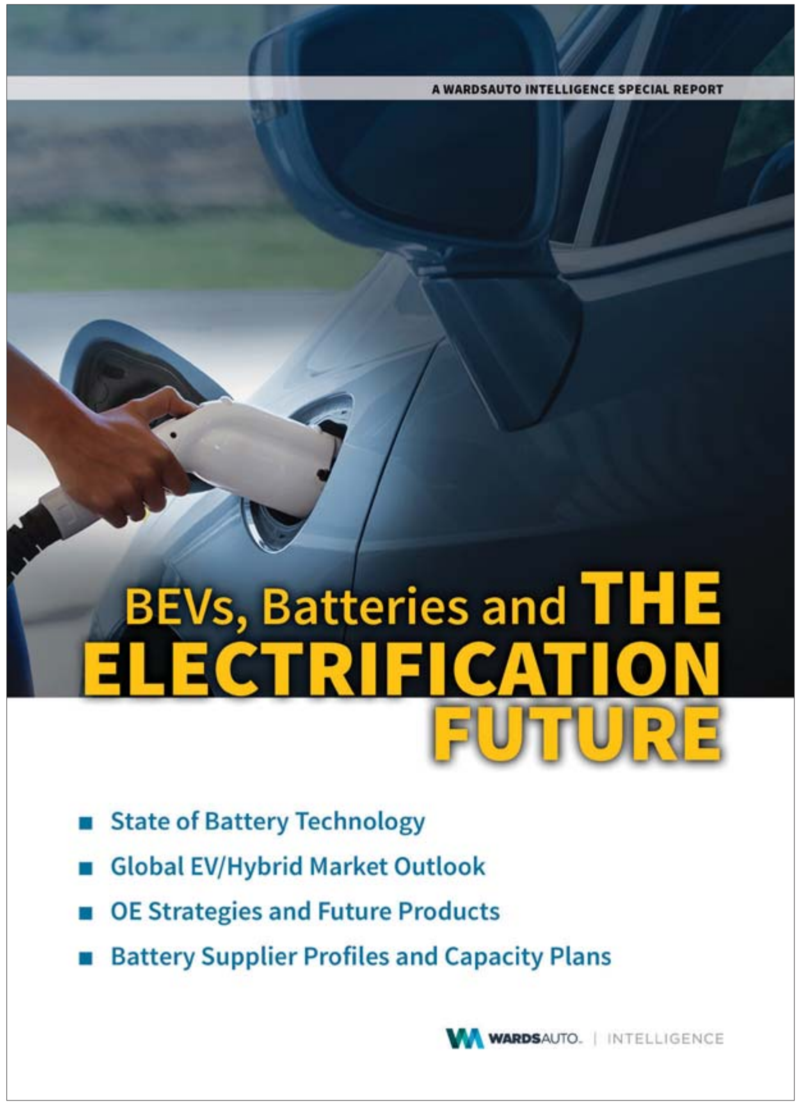
Under development at Maryland-based EnZinc in collaboration with the U.S. Naval Research Lab, nickel-3D zinc technology may sit on the low rung of the battery-development ladder, but it has some compelling advantages that could make it a



Developers look to lower cost of batteries from Chevrolet Bolt benchmark of $145/kWh.

REPORT: The Future of the Electric-Vehicle Market

A comprehensive look at automaker EV activity, future plans and emerging battery technology



WardsAuto takes an in-depth look at the future of the electric-vehicle market, how automaker EV plans are progressing, where battery technology is headed and how battery suppliers are positioning themselves for near-term growth.

The report includes:

- **Forecast:** WardsAuto/AFS global market outlook
- **OEM Report Card:** Which automakers will be best positioned for the EV future state?
- **Product plans:** Automakers' emerging EV model plans
- **The state of EV battery technology:**
  - Detailed data on cost breakdowns for today's Li-ion battery packs, xEV sales in key markets, lithium-ion battery production and demand by segment, EV sales incentives in top markets
  - Close-up look at key battery suppliers and their new Li-ion capacity initiatives
- **Verbatim interviews** with select battery executives, market analysts and developers
- **Exclusive industry survey results:** What will drive the EV market? What technology is likely to be the battery game-changer? Are widespread internal-combustion-engine bans by 2030 realistic?

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Burz foresees initial applications of nickel-3D zinc in scooters, 48V mild hybrids.

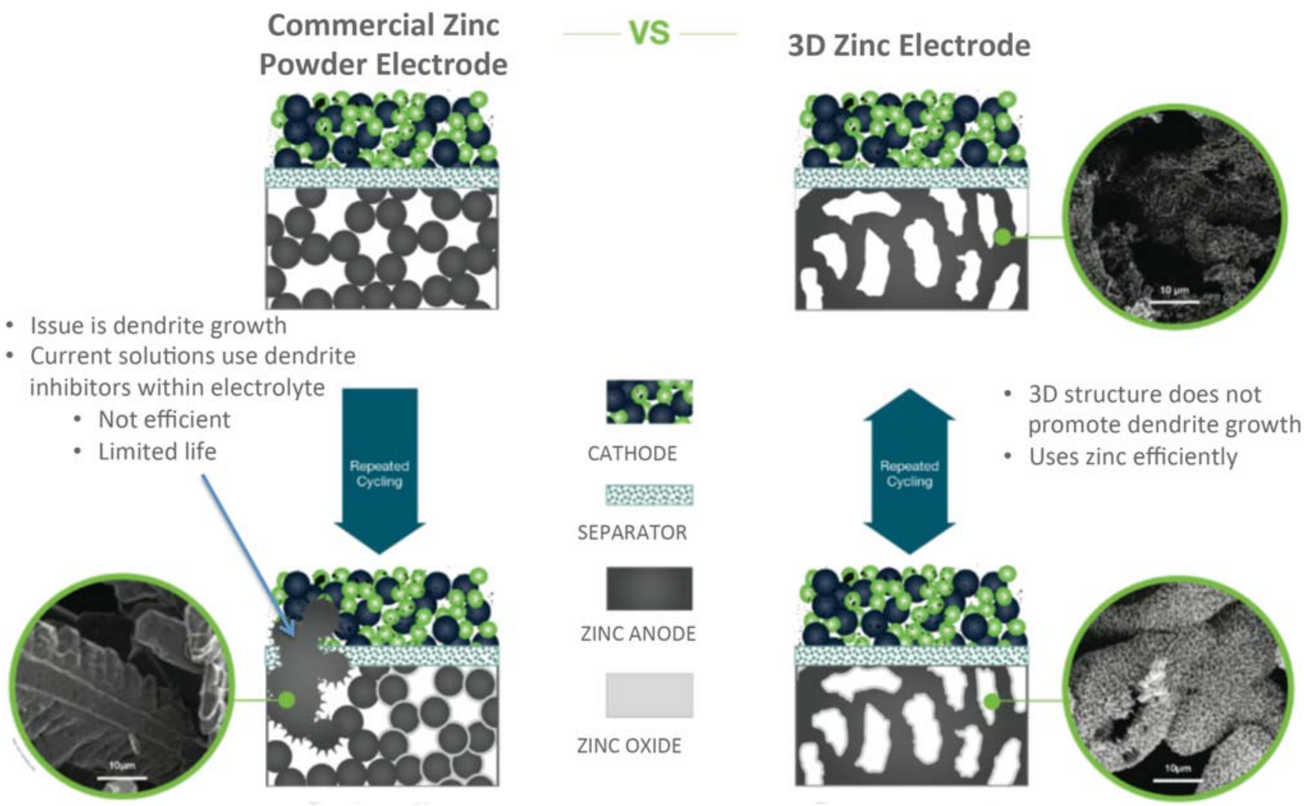
nearer-term competitor to today's Li-ion in some vehicle applications, as well as a bridge-builder to what comes next.

Chief among them is low volatility, meaning there's no danger of a faulty nickel-3D zinc cell bursting into flames. That's not the case with Li-ion, which requires automakers to design robust cell-management and pack cooling systems to prevent thermal-runaway incidents such as the one Samsung experienced last year with its self-immolating Galaxy S7 smartphones.

"You can just puncture this sucker all day and the only thing you're going to do is lose voltage," EnZinc President Michael Burz says of the nickel-3D zinc battery.

Zinc, relatively inexpensive and widely available, has been eyed as potential electrode material as far back as 1901. But the metal has been prone to corrosion and failure after only a limited number of charge-discharge cycles.

That's where the 3D designation comes in. By making the zinc electrode 3-dimensional – a sort of sponge structure, rather than a powder-bed composite, electrons can flow more freely. Corrosion coats only the outside of the sponge, leaving the zinc in its



Comparison of conventional zinc powder electrode with EnZinc sponge-like design.

inner core undamaged, allowing it to continue carrying the current.

EnZinc is aiming for a battery that costs about the same as lead-acid but matches the performance of a Li-ion pack.

Automakers such as Tesla and General Motors pay about $145 per kWh for their Li-ions. But when including the price of sophisticated battery-management controls; a heavy-duty, armor-like casing to protect the cells in a crash; and advanced cooling system, costs escalate to $300-$350 per kWh, Burz contends.

"We're starting at $90-$100 per kWh," he says, noting the EnZinc battery, which uses a non-flammable water-based electrolyte, doesn't need an elaborate management or cooling system.

The Nickel-3D Zinc doesn't pack as much energy as Li-ion, but because of weight savings derived from the less-robust package, the gap can be filled by increasing the number of cells. Pound for pound, automakers would get the same effective power from a nickel-3D zinc pack as a Li-ion at about half the cost, EnZinc believes.

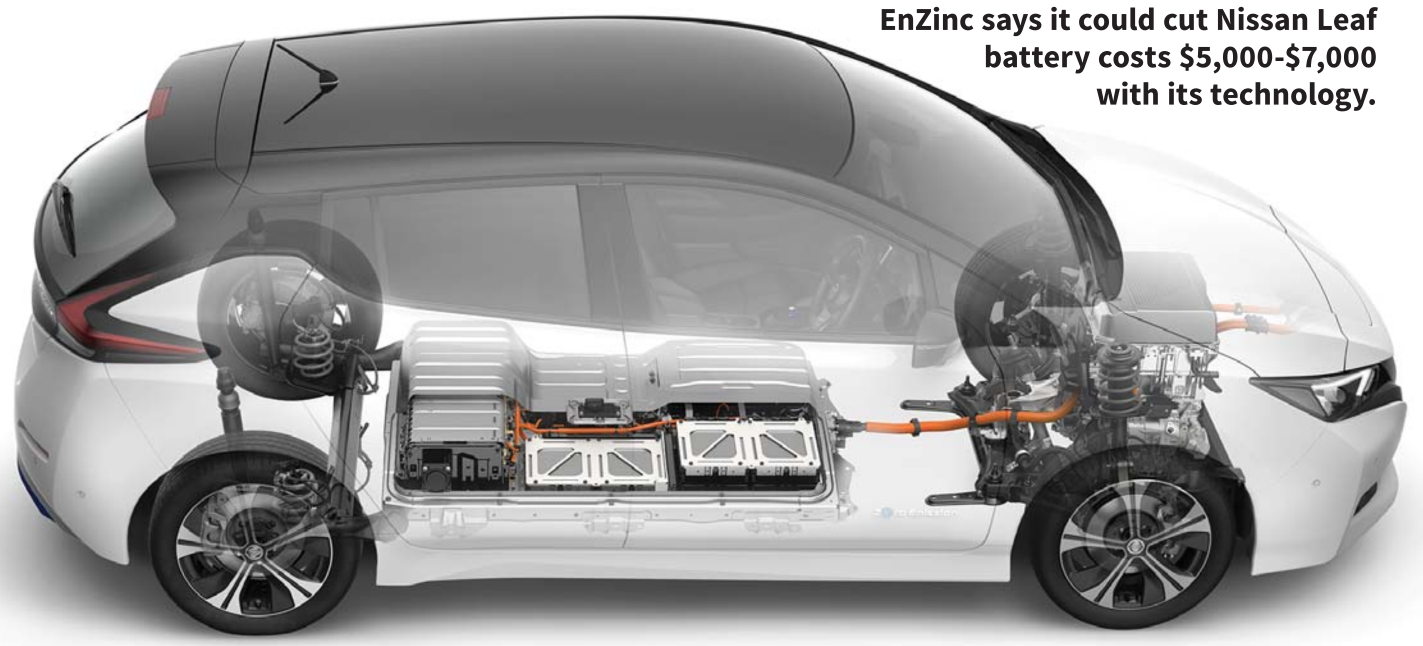
"I could take a Nissan Leaf and knock $5,000-$7,000 off the car just on the battery pack alone," Burz says.

Another plus is the widespread availability of zinc. China by far has the most abundant reserves, but the U.S., Australia and Canada are among those next in line, Burz points out, limiting any potential geopolitical hurdles for the supply chain.

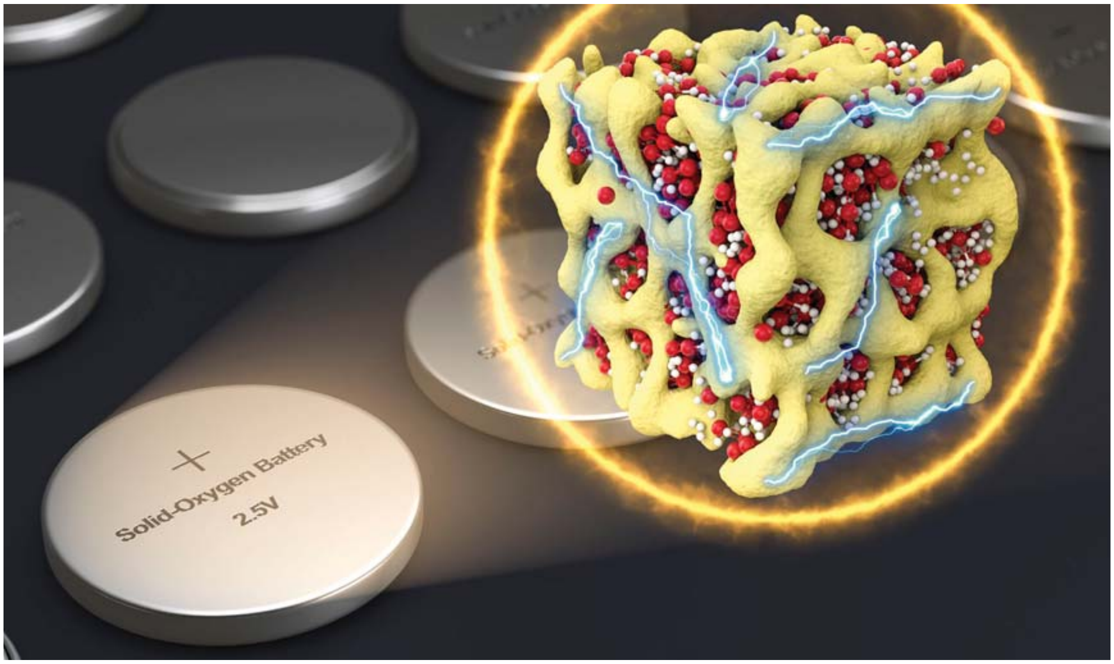
"We don't need to worry about sources outside of North America," he says, adding EnZinc could provide batteries for all EVs and internal-combustion-engine vehicles in the U.S. from a single zinc mine it operates in Alaska. Most of the nickel needed could come from Canada.

There's no potential roadblock with manufacturing either. Unlike Li-ion production, nickel-3D zinc batteries don't require clean-room-like, environmentally controlled plants.

EnZinc says it could cut Nissan Leaf battery costs $5,000-$7,000 with its technology.



Lithium-air batteries in use today in watches and other electronics, but making them rechargeable a challenge.



"It's more like building a lead-acid battery," Burz says. "I could go to a lead-acid battery maker... and they would recognize the way in which the battery was assembled."

Automotive applications are at least three years away at best, however. Besides the holy grail of full-EV applications, EnZinc envisions its battery replacing less-durable lead-acids in 48V stop/start systems and on scooters and 3-wheeled vehicles. Its work with the Navy signals potential applications on ships and submarines, where flammable Li-ion is prohibited.

Zinc Air

Another step along the performance paradigm is zinc-air.

Already used in watches and small electronics, these batteries, work by oxidizing zinc with oxygen. Because air is used for the cathode rather than metal, zinc-air batteries weigh less, offering a higher specific energy-to-weight ratio than current EV batteries.

"Whereas (today's) Li-ion is 140 Wh/kg, the zinc-air battery will be 250-300 Wh/kg – that's effective, installed in the car," says Burz, whose company is working on the technology as a logical followup to its nickel-3D zinc battery. "(First) you have to get the zinc to work. The second challenge is to get the air cathode to work."

The concept is six to eight years away from commercial viability in EV applications, he says, with EnZinc researchers about three to four years from having a working battery and another three to four years away from engineering a complete vehicle system.

"It won't be quite as cheap as a nickel-3D zinc battery, because it will require the ancillary systems for the air management," he says. "But the overall cost of the system (will be less than Li-ion), because it (consists of) zinc and carbon, and that's basically it."

Lithium-Air

Similar to zinc air but using lithium, this technology promises to take EV batteries to yet another level, but there's some debate whether repeated failures in the lab already have doomed its future.

The big sticking points: efficiency and an ability to withstand recharging.

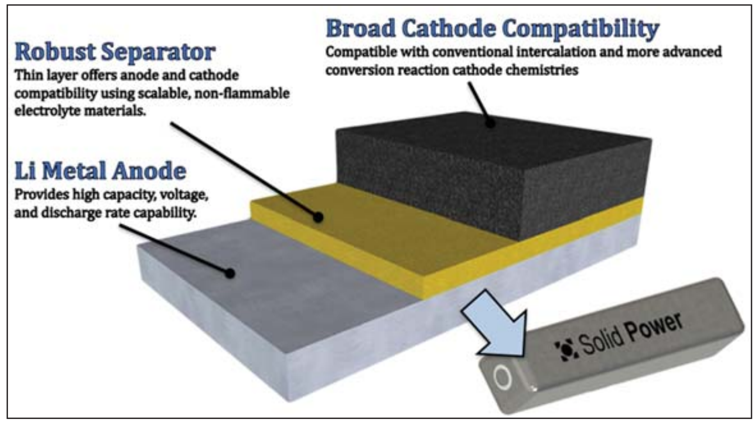
"We can make really good primary batteries – batteries you just discharge once," says MIT's Leverick. "But we struggle a lot to charge the battery successfully. (And) you inject a lot more energy into your battery during charge than what you're able to extract during discharge."

Doug Campbell, CEO of solid-state battery developer Solid Power, believes the window is closing on lithium-air.

"(Lithium-air) was very sexy several years ago, but researchers have uncovered major, major… technical roadblocks," he says. "Multiple industry entities have terminated their lithium-air research and really doubled down on solid state. Solid state right now appears to be the most viable candidate for being that 'beyond-lithium-ion' technology in the future."

Leverick isn't giving up but admits "solid state feels closer than lithium-air right now. Maybe 10 years from now we would start to make lithium-air batteries (for automotive)."

Solid State



Schematic of Solid Power's solid-state battery.

That leaves solid state as the odds-on favorite to be the EV-market game-changer, if there is one. Several developers are working on perfecting the technology, and more than a few automakers have expressed interest in the concept. The list includes Toyota, which is promising to market an EV with a solid-state battery by the early 2020s, as well as global EV leader Nissan.

In a solid-state battery, the conventional liquid electrolyte is replaced with an ion-conducting solid, typically a ceramic-like inorganic material. The switch results in a high-energy battery that no longer is flammable. Much like nickel-3D zinc, there would be no need for sophisticated battery-management and thermal-control systems for the solid-state pack.

The technology's potential appears huge. Because the solid electrolyte prevents the formation of dendrites that can short out the battery and cause fires, cells can be packed more closely together, increasing energy capacity and boosting EV range.

"We have shown through abuse testing – nail penetration, overcharge, over-discharge, that while the cells fail, it is a very benign, boring sort of event," says Campbell, whose start-up company was spun off from solid-state battery research conducted at the University of Colorado.

The solid-state cells also can handle higher currents, meaning they'll charge faster than today's Li-ion – another key part of the equation that must be solved if EVs are to win over consumers in bigger numbers.

Solid Power's battery can function at operating temperatures as high as 302º F (150º C), about three times the capability of today's Li-ion.

Campbell: Commercializing new energy-source technology not trivial.

The anode is made of lithium metal – not possible in today's rechargeable Li-ion batteries because it would corrode in contact with a liquid electrolyte. It is paired with a now-common nickel-manganese-cobalt (NMC) cathode to take specific energy to about 350-400 Wh/kg, Campbell says, compared with about 270 Wh/kg in the best of today's Li-ion battery packs.

Packaging also becomes easier when the electrolyte is a solid.

"There's a whole ton of mass and volume efficiency…because you've eliminated the need to contain that liquid electrolyte," Campbell says.

Production isn't a huge hurdle for the Solid Power battery either, he says, because it is designed to be made with existing Li-ion manufacturing processes.

"Let's face it, commercializing a new energy-source technology is not trivial, because there's just a tremendous amount of infrastructure and investment into the incumbent solution, which in this case is Li-ion," Campbell says. "So, the only way for this to be viable is…to impart as little changes on the manufacturing infrastructure as possible."

One roadblock is cost, and the concept continues to rely on lithium and cobalt. Although designed to be made with existing tooling and processes, no one has proven the batteries can be produced in volume.

"Manufacturing technology – the speed and the cost – is the big problem with solid-state right now," CATL's Galyen says.

It will be at least two years before Solid Power's concept reaches commercialization, likely beginning with niche industrial applications. It will take another two to five years before the battery shows up in the military and aerospace sectors. Automotive applications might be possible in five to 10 years, Campbell says.

"We absolutely have to meet the exact same performance targets as Li-ion and, of course, in addition to that have some other value offering," the Solid Power CEO says, pointing to the potential for longer cycle life with solid state. "Otherwise, what's the point?"

Li-ion Still Future for Now

The growing infrastructure around Li-ion battery production and the high performance bar the technology has set is what makes it the biggest barrier to something new.

"Li-ion is a well-engineered system, so from a performance standpoint, everyone knows what you can get," Campbell says, noting the dramatic reductions in Li-ion battery costs over the past few years. "If you're a new technology that's going to come into the marketplace in three, four, five years from today, you're not looking at $140/kWh. You're looking at $120, $110, less than $100, because that's the trajectory the cost for Li-ion is on. The market is making no compromises."

The bottom line is Li-ion still has a lot of bandwidth left to explore.

Case in point was Toshiba's October announcement of a next-generation Li-ion due for commercialization in fiscal 2019 that uses titanium-niobium-oxide for its anode and is said to double the storage capacity of more conventional graphite-based-anode Li-ions. It also charges faster. Toshiba claims a 6-minute rapid charge can yield 198 miles (320 km) of range in a compact-vehicle application.

Others are experimenting with vanadium-based chemistries or inexpensive (and abundant) silicon some researchers claim would take battery cost down to one-tenth that of current Li-ions.

"Our largest battery work is actually related to just improving current lithium-ion batteries," says MIT's Leverick. "We're still trying to understand exactly what (the) limitation is."

More clear is the seemingly unstoppable drive toward electrification, although forecasters don't all agree on the pace or breadth of adoption. Governments in several countries, including France, the U.K., Germany, India and China, are threatening to outlaw internal-combustion vehicles as early as 2030. That's one way to drive demand, but some industry insiders believe as more EVs enter the market, consumers will discover the benefits of electric driving and more naturally gravitate to battery-powered cars.

"It looks like the tipping point is going to come fairly soon, by the early 2020s to the mid-2020s for mainstream BEVs," says Mike Tinskey, global director-emerging services for Ford and a panelist at the recent Battery Show in Novi. Reaching parity with gasoline-powered models will require on-par costs and range, as well as a widespread fast-charging network to facilitate longer trips, he adds. "You get all that right… plus some other incentives or enhancements, and I think you have the recipe for a tipping point."

Developers are working on it, but patience is required.

"Typically the timeline (to) adoption of new technology… it's a long term," sums up CATL's Galyen. **WA**

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