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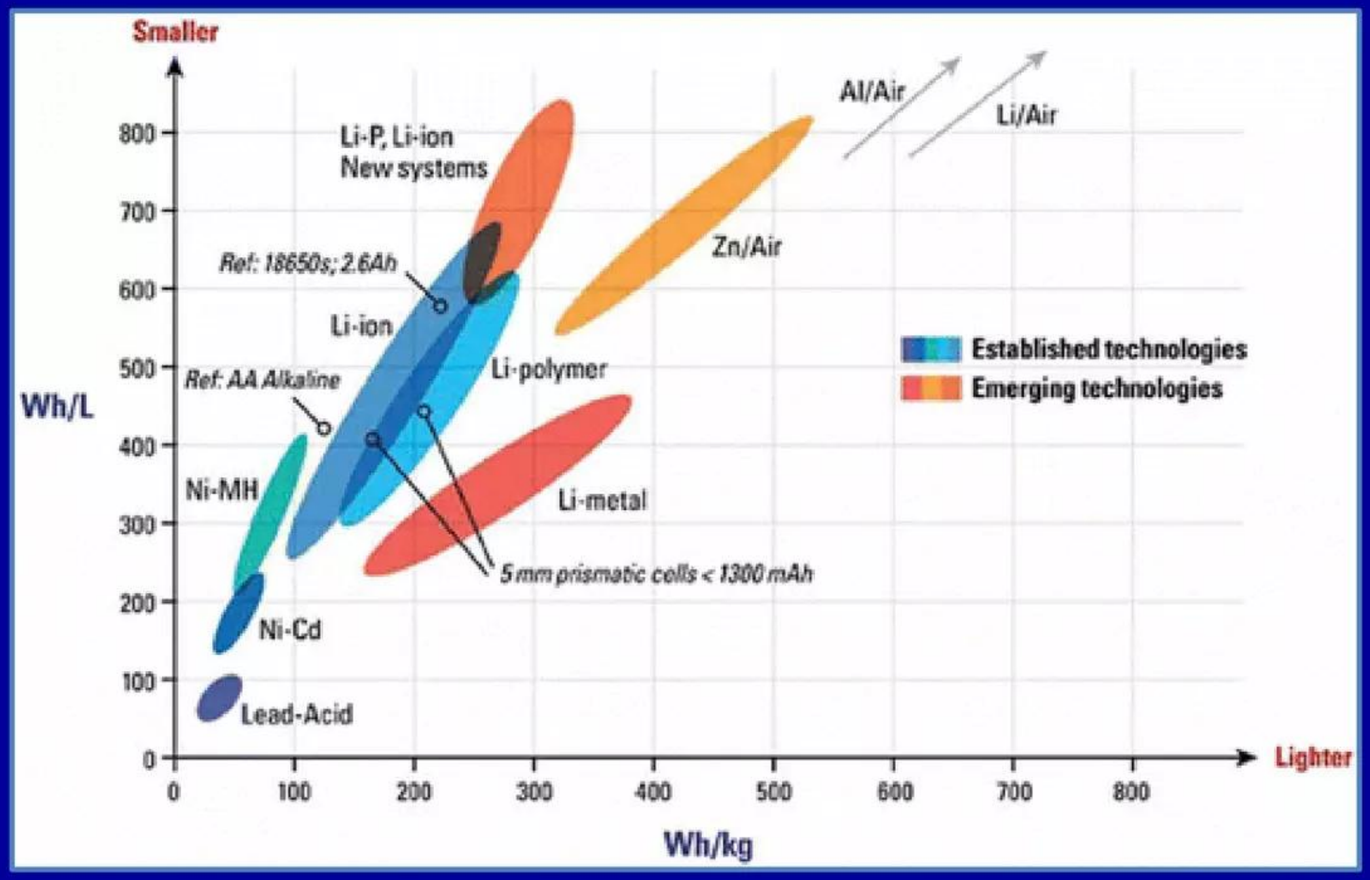
May 2014: in a surprising move both IBM and JCESR apparently slowed R&D to develop Lithium-air batteries

Maybe this is fortunate: we think thermal runaway risks might be higher



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Two major players in Lithium-air batteries tap the brakes

IBM and the Joint Center for Energy Storage Research (JCESR)

"Two big labs step back from the most promising next-generation battery"

QUARTZ Steve Levine in *Quartz* May 30, 2014

Source: http://qz.com/214969/two-big-labs-most-promising-next-generation-battery-electric-car/

"In a sign of more gloom in the struggle for a better battery, two major US labs have quietly downgraded research on a technology until now widely believed to be the most promising path to a competitive electric car."

"IBM and the US-funded Joint Center for Energy Storage Research (JCESR) have ratcheted down or outright abandoned their work on the lithium-air battery, a concept in which oxygen would react with lithium to create electricity."

"In a little-remarked-upon article in March, *Nature* magazine reported that IBM's Winfried Wilcke, director of the Battery 500 Project, had a 'change of heart' about lithium-air and had turned his favor to a technology featuring sodium. In an electric car, a sodium-air battery, he said, stood a better chance of meeting the economics needed to compete with conventional cars. It was a dramatic move, with the most bullish player in lithium-air --- Wilcke himself --- calling it a day."

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"Wilcke did not respond to emails. **An IBM spokesman told Quartz that the *Nature* report is accurate but said that the company is now working on both lithium-air and sodium.**"

"**About the same time, JCESR dropped its lithium-air project entirely. Like IBM, JCESR did not announce the decision publicly.** Kevin Gallagher, a JCESR manager, said it concluded that the challenges were too overwhelming to resolve any time soon. 'The penalty of using gaseous reactions overwhelmed any advantage,' he told *Quartz*."

"**Lithium-air is not being abandoned everywhere.** At Argonne, Michael Thackeray is directing work on a novel hybrid battery combining lithium-ion *and* lithium-air.The result is the potential for a battery with specific density of 500 watt hours per kilogram, two-and-a-half times greater than today's best commercial lithium-ion cell."

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Lithium-air widely touted as next great thing in batteries

Some have even made claims that it might rival gasoline energy density

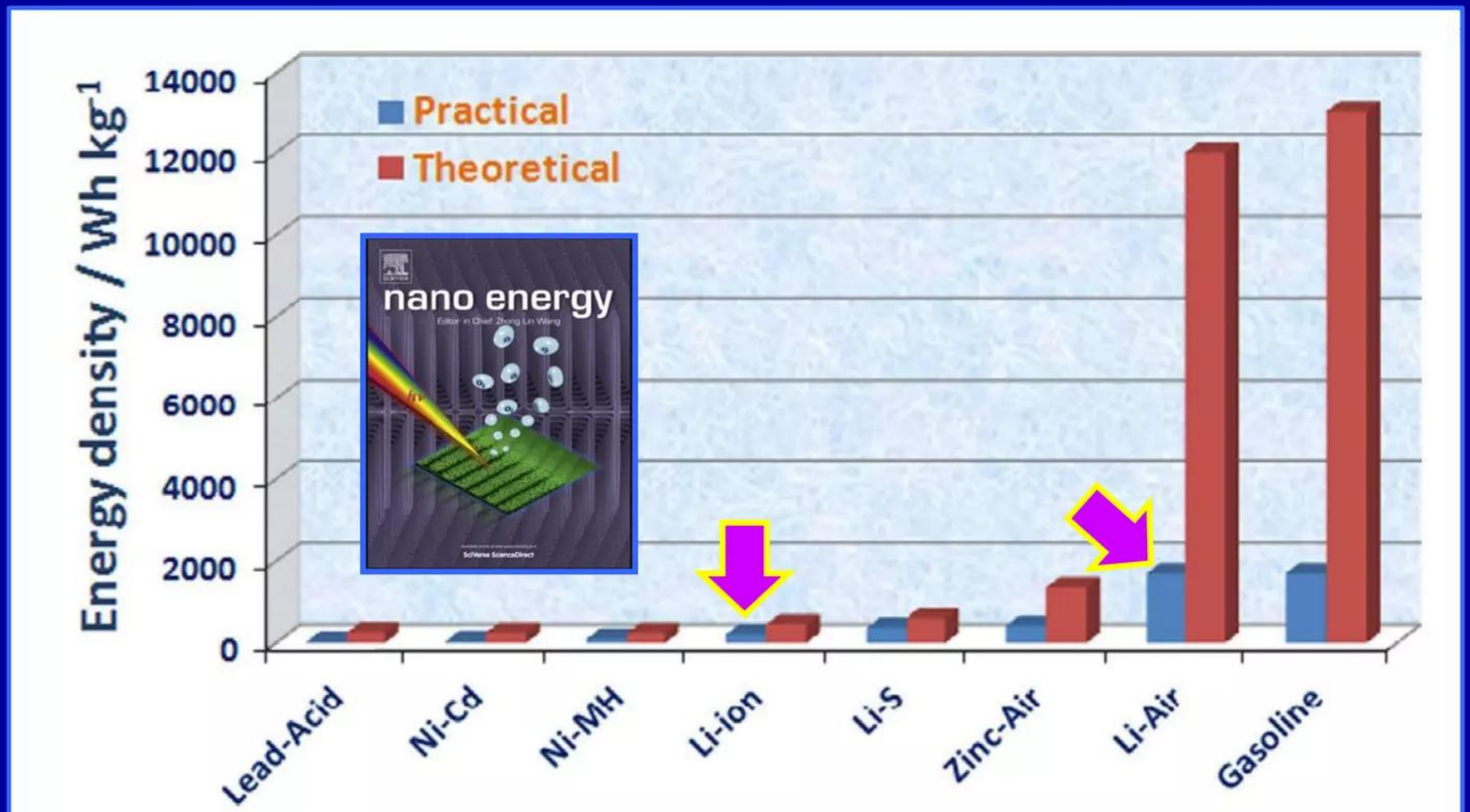

Figure 1 The gravimetric energy densities (Wh/kg) for various types of rechargeable batteries compared to gasoline.

Fig. 1 from: "Challenges and opportunities of nanostructured materials for aprotic rechargeable lithium-air batteries" J. Wang, Y. Li, and X. Sun, *Nano Energy* 2 pp. 443 - 467 (2013)

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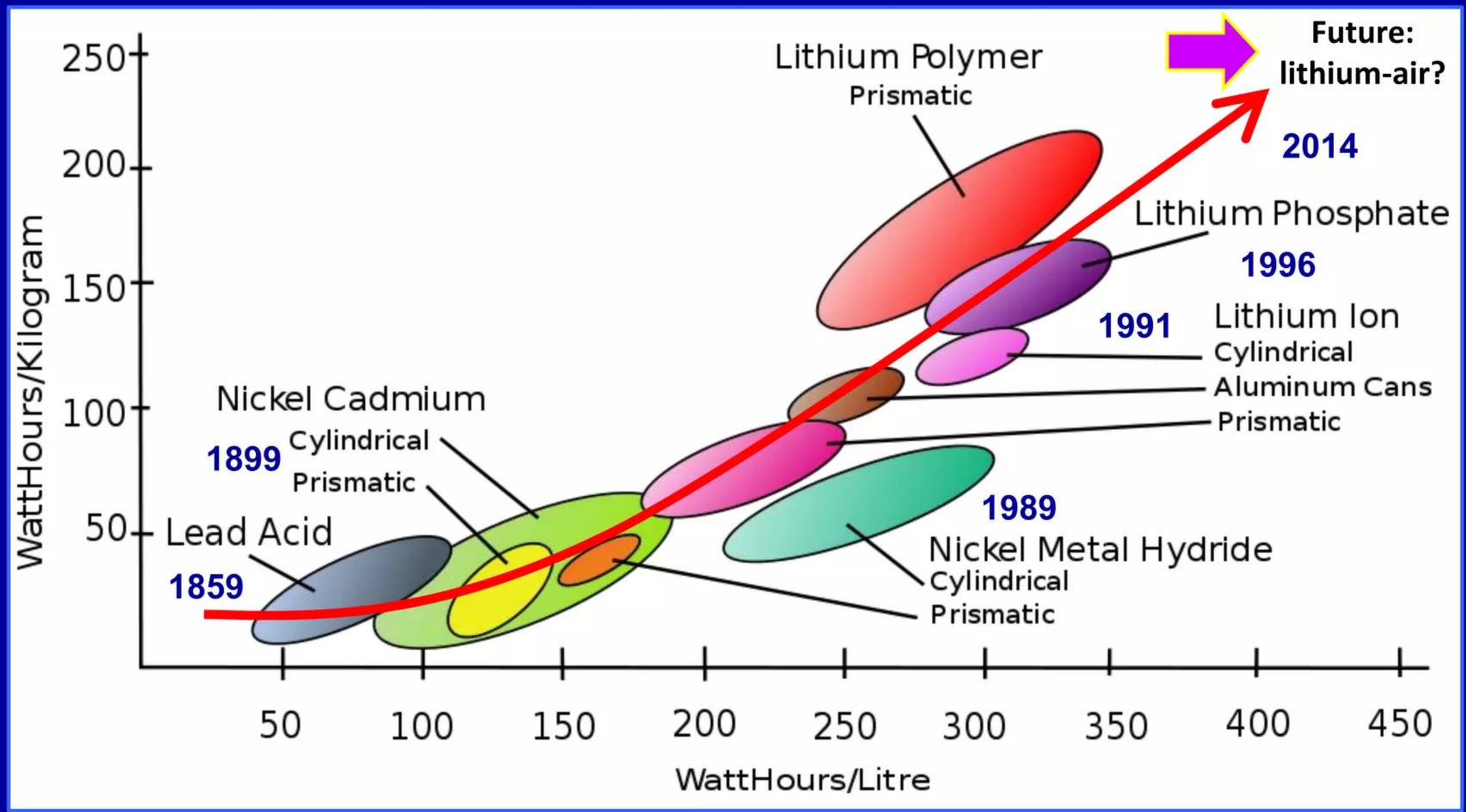
Battery energy densities increased greatly since 1859

Succession of much improved battery chemistries began with Lead Acid



Adapted from source: http://liteplusbattery.com/lifepo4-energy-density/

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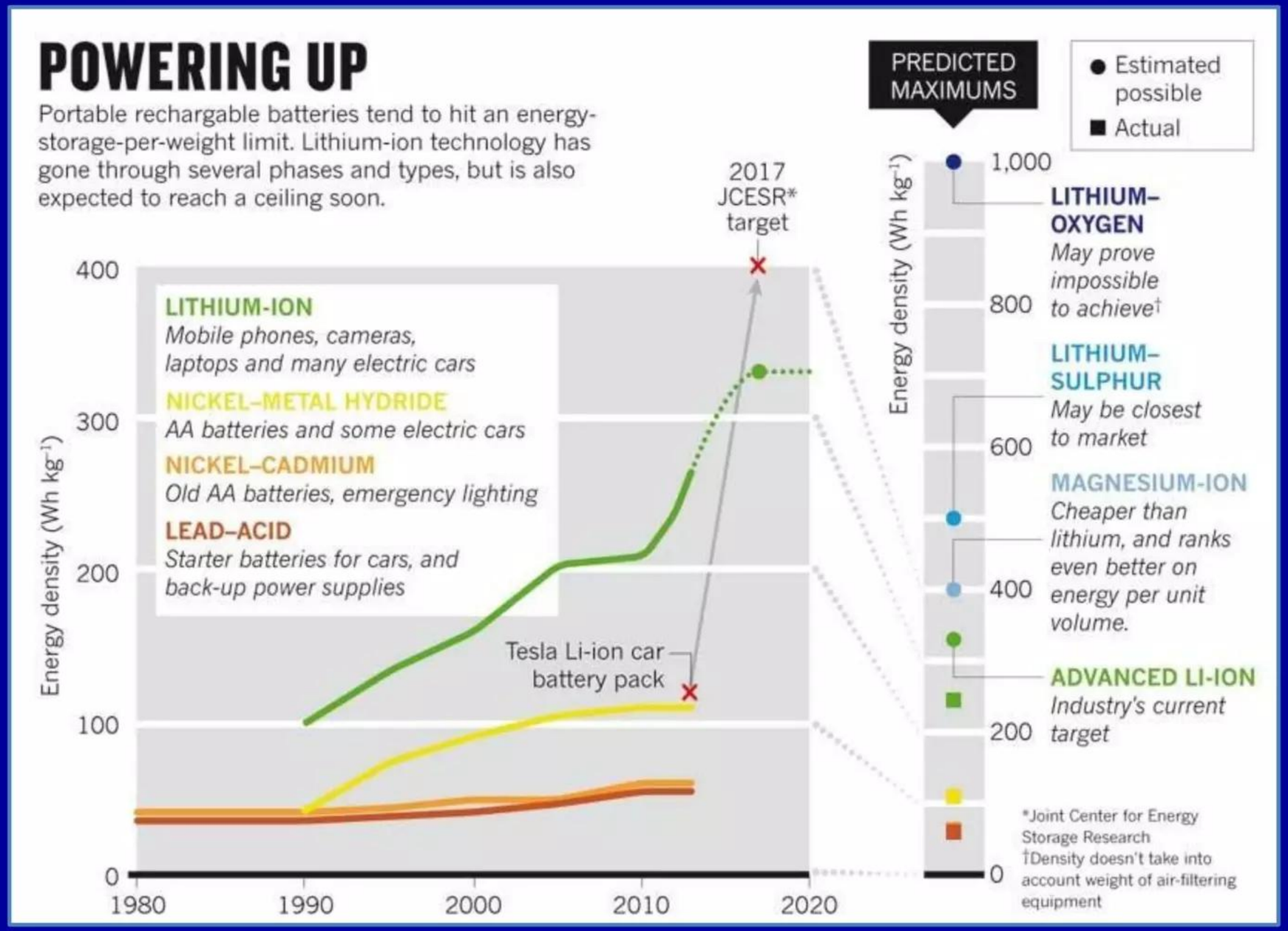
Lithium-air widely touted as next great thing in batteries

Lithium-ion technology nearing energy-density limits for that chemistry



Source: C. Zu & H. Li, *Energy & Environmental Science* 4 pp. 2614 - 2624 (2011)

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Two major players in Lithium-air batteries tap the brakes

IBM and the Joint Center for Energy Storage Research (JCESR)

"The rechargeable revolution: A better battery

Chemists are reinventing rechargeable cells to drive down costs and boost capacity."

nature International weekly journal of science

Richard Van Noorden in *Nature* 507 pp. 26 - 28 March 5, 2014

Source: http://www.nature.com/polopoly_fs/1.14815!/menu/main/topColumns/topLeftColumn/pdf/507026a.pdf

"Modern Li-ion batteries hold more than twice as much energy by weight as the first commercial versions sold by Sony in 1991 --- and are ten times cheaper. But they are nearing their limit. Most researchers think that improvements to Li-ion cells can squeeze in at most 30% more energy by weight (see 'Powering up')."

"Five years ago, Wilcke, who heads IBM's nanoscience and technology division in San Jose, California, launched a project to develop a car battery with an 800-kilometre range. At the start, he focused on the theoretical ultimate in energy-dense electrochemical storage: the oxidation of lithium with oxygen drawn from the air. Such 'breathing' batteries have a huge weight advantage over other types, because they do not have to carry around one of their main ingredients. A lithium-oxygen (Li-O) battery can, in theory, store energy as densely as a petrol engine --- more than ten times better than today's car battery packs."

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"But after driving more than 22,000 kilometres in his [Tesla] electric roadster, Wilcke is happy with the 400-kilometre range that its battery already provides. The real problem, he says, is money: battery packs for electric cars cost more than \$500 kWh^{-1}. 'What's holding back the mass acceptance of electric cars is really the price rather than the energy density,' he says. So Wilcke now favours a cheaper breathing battery based on sodium. Theory predicts that sodium-oxygen (Na-O) batteries could provide only half the energy density of Li-O, but that is still five times better than Li-ion batteries. And sodium is cheaper than lithium, so Na-O might, Wilcke hopes, get closer to the \$100-kWh^{-1}goal that the JCESR and others have set for affordability."

"Wilcke's change of heart was undoubtedly influenced by the fact that many have given up hope on Li-O … 'The bottom line is that Li-O has zero chance for vehicles," says Stanley Whittingham … who invented the concept of Li-ion batteries in the 1970s …"

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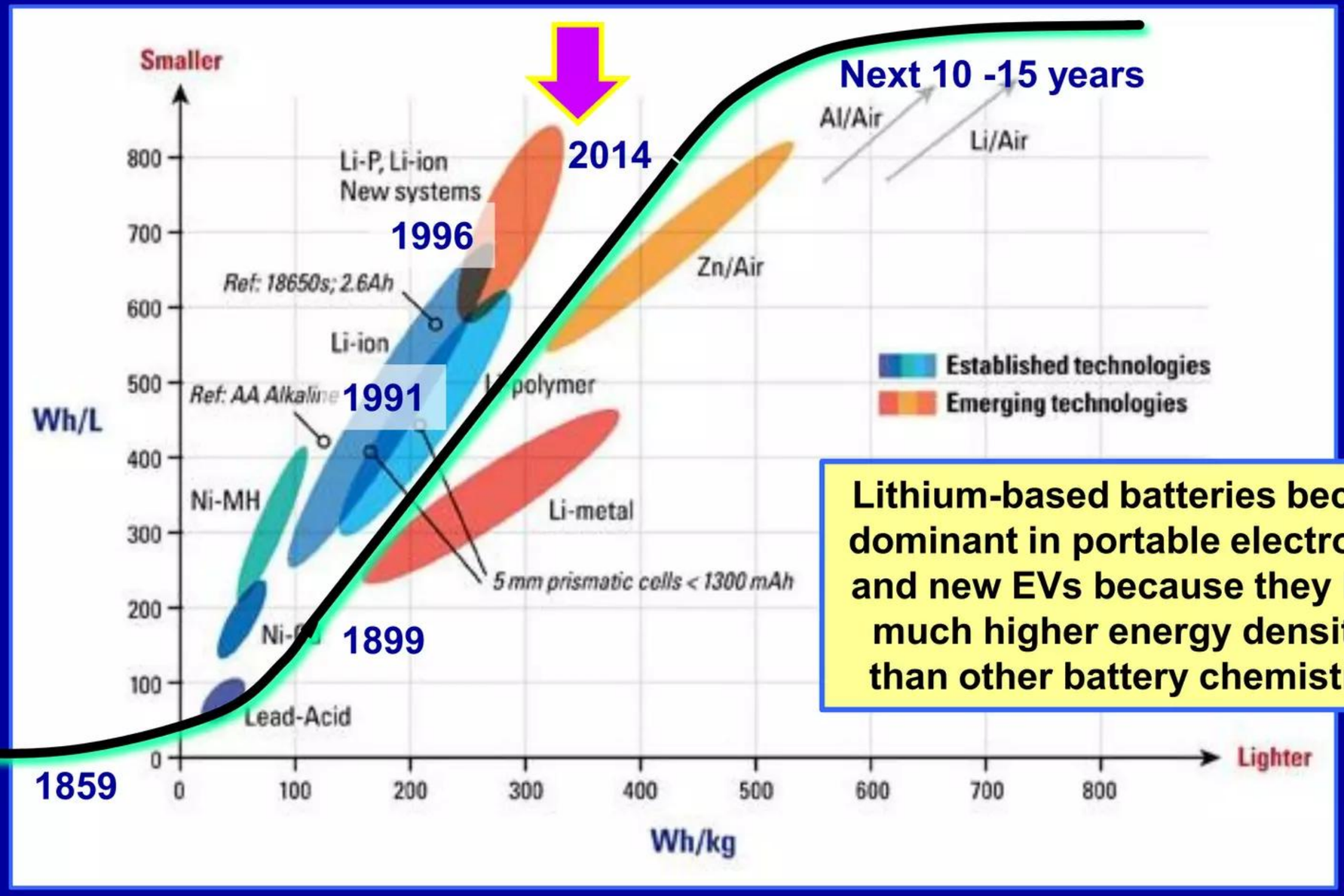
Batteries maturing and approaching technological limits

Energy density increases and related cost reductions are slowing down



Source: http://www.estquality.com/technology

Note: superimposed S-curve and dates added by Lattice

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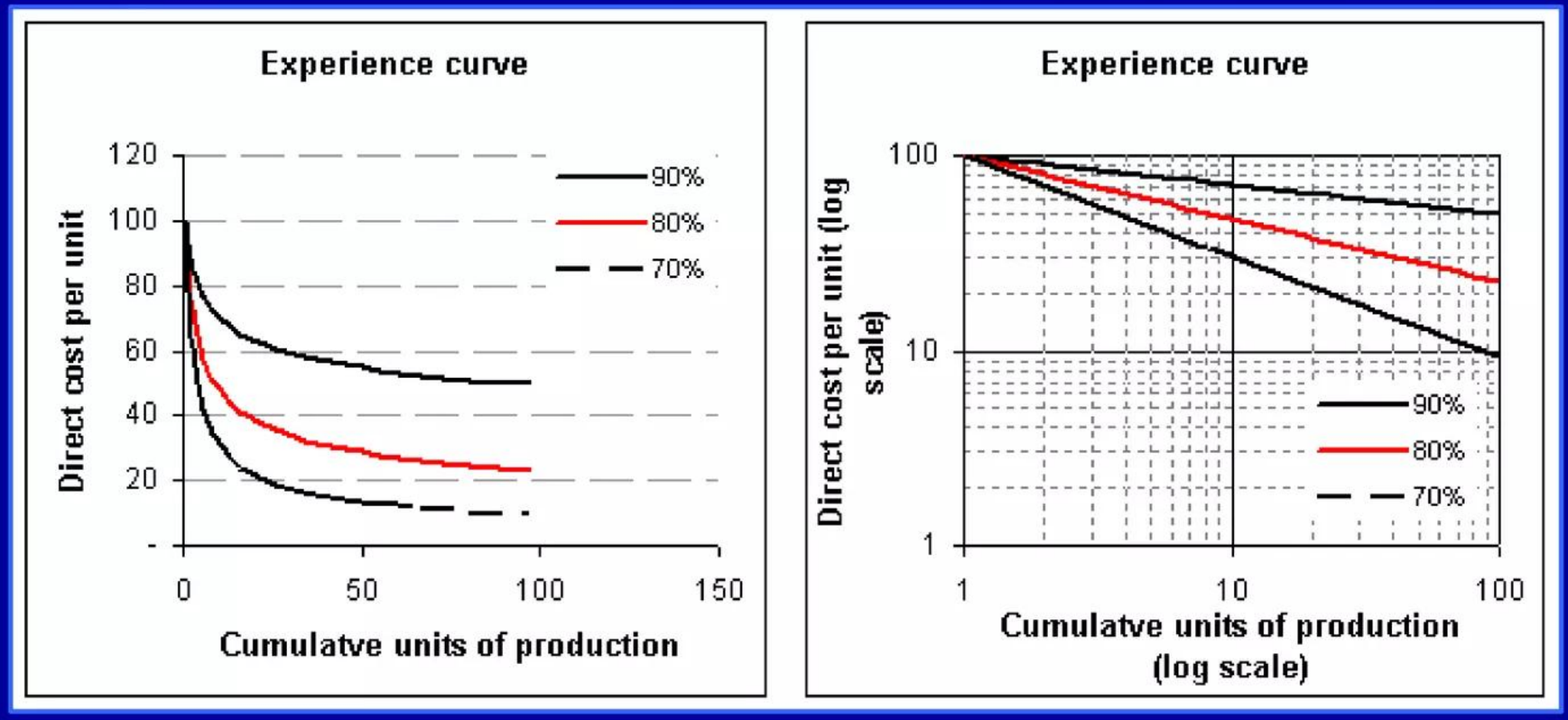
Experience curve cuts cost of producing/storing electricity

Lithium battery chemistry has ridden experience curve for 20+ years

Batteries now moving toward new chemistries to increase energy density

An experience curve, which differs somewhat from a so-called "learning curve," is a graphical representation of a price phenomenon that was developed and widely publicized as a corporate strategy tool by Bruce Henderson, founder of the Boston Consulting Group. Concept refers to effect that manufacturers learn from doing, which means that the higher the cumulative volume of production, the lower the direct cost per new unit of produced product. Thus, experience curves are innately convex and have downward slopes, as shown in two graphs below:

Idealized relationship between direct cost/unit and total cumulative unit production



Source: Wikipedia - http://en.wikipedia.org/wiki/Experience_curve_effects

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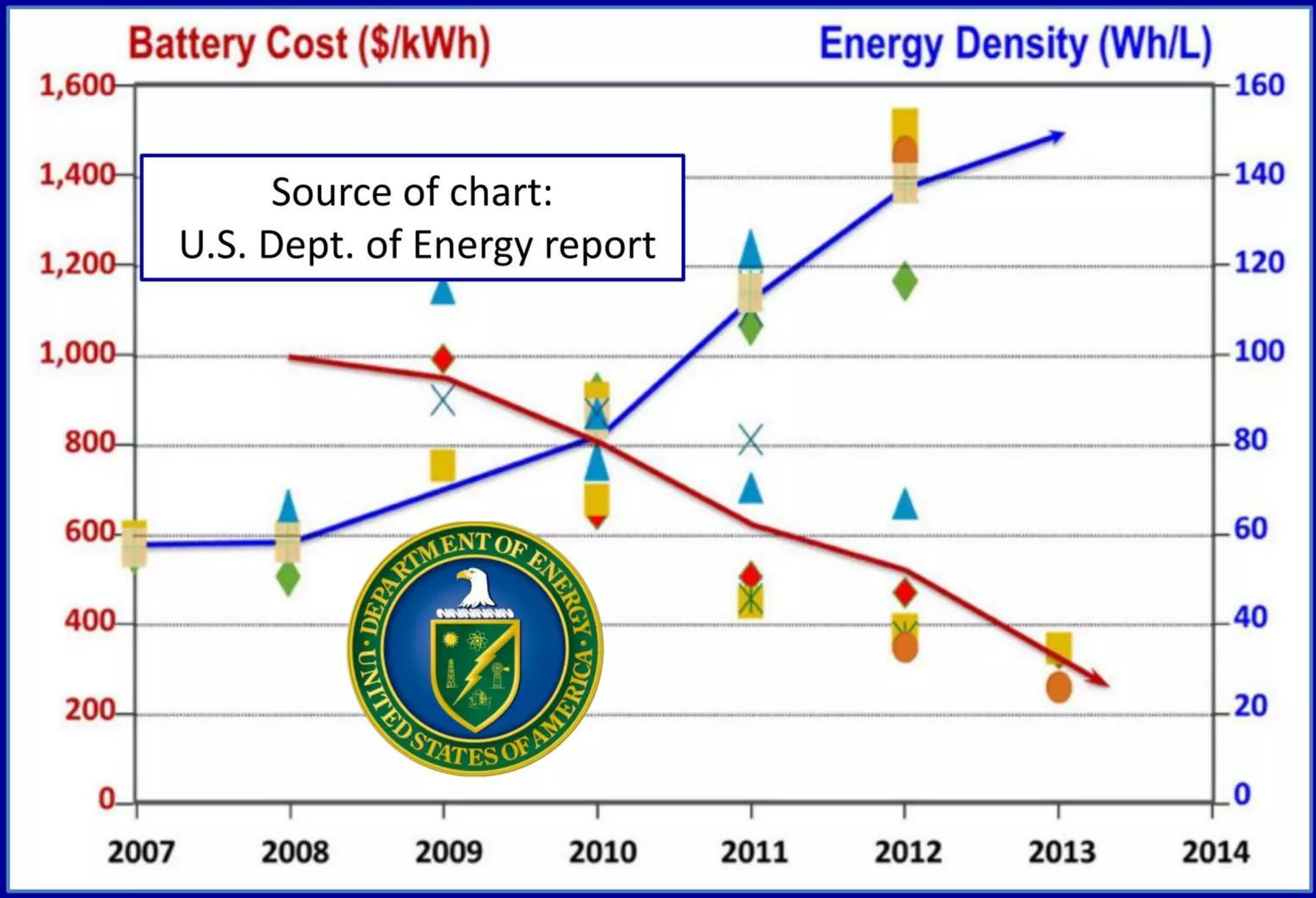
Battery cost reduction tied to increases in energy density



Source: http://theenergycollective.com/onclimatechangepolicy/347491/making-low-carbon-future-better-well-cheaper

Lattice Energy LLC

Sept. 2013: Lattice cautioned about Li-air runaway risks

LENR issues might occur more often at higher battery energy densities

"Large increases in battery energy densities drive convergence between energetic materials, LENRs and batteries"

Lewis Larsen, Lattice Energy LLC, September 6, 2013 [110 MS-PowerPoint slides]

Source: http://www.slideshare.net/lewisglarsen/lattice-energy-llc-increased-energy-densities-drive-convergence-of-batteries-and-lenrssept-6-2013

Slide #37: "Conditions conducive to initiation of LENRs occur in microscopic, micron-scale regions in random scattered locations on dendrites and other types of growing nanostructures and nanoparticles inside lithium-based batteries and electrolytic cells … Although radiation-free, LENRs involving neutron captures on stable lithium isotopes are extremely energetic nuclear processes … Microscopic 100 micron LENR hotspots can release 5^{+} Watts of heat in less than 400 nanoseconds; nuclear processes raise local hotspot temps to 4,000 - 6,000^{o} C"

Slide #83: "Recognizing that many key technical details of Li-air batteries have yet to be worked-out, but given what has happened so far with lithium-based battery chemistries, there is no reason to believe *a priori* that such batteries would be immune to the risk of thermal runaways. Given much greater energy densities, one could argue that LENRs might be more likely in Li-air"

Lattice Energy LLC

World needs a new source of dense CO_2-free energy

Low energy neutron reactions (LENRs) are truly green nuclear power

- ✓ While solar PV and wind are decidedly CO_2-free and reasonably biosafe, their intrinsic energy densities are much lower than today's fossil fuels and they are intermittent --- not continuous --- sources of electrical and thermal power
- ✓ Renewable primary energy sources such as combustion of biomass are not the answer because they only have moderate energy densities and emit much CO_2
- ✓ Nuclear fission power has high energy densities, does not produce CO_2 and operates continuously; but emits copious quantities of very dangerous neutron and gamma radiation during operation and produces very long-lived radwastes
- ✓ Nuclear fusion power, while better than fission in terms of producing much smaller quantities of radwaste, still emits very dangerous neutron and gamma radiation during operation; also, there is still no sign of it being commercialized after 60 years of huge effort and hundreds of billions of R&D $ spent worldwide
- ✓ Low energy neutron reactions (LENRs) are only new energy technology on the foreseeable horizon that can potentially provide the world with dense green power, help mitigate climate change, and enable sustainable economic growth

Lattice Energy LLC

World needs a new source of dense CO_2-free energy

Low energy neutron reactions (LENRs) are truly green nuclear power

- ✓ No emission of deadly MeV-energy hard gamma radiation
- ✓ No dangerous external emissions of energetic neutrons
- ✓ Insignificant production of hazardous radioactive wastes
- ✓ Revolutionary, disruptive, CO_2-free and environmentally safe
- ✓ Vast reduction in system cost versus fission or fusion
- ✓ **Intrinsically scalable system-level thermal outputs go from portable battery-like devices up to megawatt-scale powerplants**

Lattice Energy LLC

Nuclear energy density surpasses chemical technology

LENR-based power generation could have vast competitive advantage

LENRs Versus Chemical Energy Sources: Batteries, Fuel Cells, and Microgenerators

Source of Energy	Approximate Energy Density (Watt*hours/kg)
Alkaline Battery	164
Lithium Battery	329
Zinc-Air Battery	460
Direct Methanol Fuel Cell (35% efficient)	1,680
Gas Burning Microgenerator (20% efficient)	2,300
100% Efficient Combustion of Pure Methanol	5,930
100% Efficient Combustion of Pure Gasoline	11,500
LENRs (based on an assumption of an average of 0.5 MeV per nuclear reaction in an LENR system)	**57,500,000** (maximum theoretical energy density – only a fraction would be achievable in practice)

~2,000 Wh/kg might be practical with lithium-air

~11,680 Wh/kg is theoretical maximum with lithium-air

Chemical

LENRs

Lattice Energy LLC

LENRs offer a technology beyond batteries

Convergence and change trigger revolution