

# Pathways to Batteries with High Energy Density *and* High Power

Yet-Ming Chiang  
Materials Science and Engineering  
Massachusetts Institute of Technology

ASEB  
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# High energy batteries come from the top of the periodic table

# PERIODIC TABLE OF THE ELEMENTS

<http://www.ktf-split.hr/periodni/en/>

GROUP	1	2											13	14	15	16	17	18
PERIOD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1.0079 <b>H</b> HYDROGEN												5.012 <b>B</b> BORON	6.011 <b>C</b> CARBON	7.007 <b>N</b> NITROGEN	8.009 <b>O</b> OXYGEN	9.008 <b>F</b> FLUORINE	4.0026 <b>He</b> HELIUM
2	3.041 <b>Li</b> LITHIUM	9.0122 <b>Be</b> BERYLLIUM											10.811 <b>Al</b> ALUMINIUM	12.011 <b>Si</b> SILICON	14.007 <b>P</b> PHOSPHORUS	15.999 <b>S</b> SULPHUR	18.998 <b>Cl</b> CHLORINE	20.180 <b>Ne</b> NEON
3	11.009 <b>Na</b> SODIUM	24.305 <b>Mg</b> MAGNESIUM											26.982 <b>Al</b> ALUMINIUM	28.086 <b>Si</b> SILICON	30.974 <b>P</b> PHOSPHORUS	32.06 <b>S</b> SULPHUR	35.453 <b>Cl</b> CHLORINE	39.948 <b>Ar</b> ARGON
4	19.098 <b>K</b> POTASSIUM	40.078 <b>Ca</b> CALCIUM	44.956 <b>Sc</b> SCANDIUM	47.867 <b>Ti</b> TITANIUM	50.942 <b>V</b> VANADIUM	51.996 <b>Cr</b> CHROMIUM	54.938 <b>Mn</b> MANGANESE	55.845 <b>Fe</b> IRON	58.933 <b>Co</b> COBALT	58.933 <b>Ni</b> NICKEL	63.546 <b>Cu</b> COPPER	65.39 <b>Zn</b> ZINC	69.723 <b>Ga</b> GALLIUM	72.64 <b>Ge</b> GERMANIUM	74.922 <b>As</b> ARSENIC	78.96 <b>Se</b> SELENIUM	79.904 <b>Br</b> BROMINE	83.80 <b>Kr</b> KRYPTON
5	37.85468 <b>Rb</b> RUBIDIUM	87.62 <b>Sr</b> STRONTIUM	88.906 <b>Y</b> YTTRIUM	91.224 <b>Zr</b> ZIRCONIUM	92.906 <b>Nb</b> NIOBIUM	95.94 <b>Mo</b> MOLYBDENUM	(98) <b>Tc</b> TECHNETIUM	101.07 <b>Ru</b> RUTHENIUM	102.91 <b>Rh</b> RHODIUM	106.42 <b>Pd</b> PALLADIUM	107.87 <b>Ag</b> SILVER	112.41 <b>Cd</b> CADMIUM	114.82 <b>In</b> INDIUM	118.71 <b>Sn</b> TIN	121.76 <b>Sb</b> ANTIMONY	127.60 <b>Te</b> TELLURIUM	126.90 <b>I</b> IODINE	131.29 <b>Xe</b> XENON
6	132.91 <b>Cs</b> CAESIUM	137.33 <b>Ba</b> BARIUM	138.91 <b>La-Lu</b> Lanthanide	178.49 <b>Hf</b> HAFNIUM	180.95 <b>Ta</b> TANTALUM	183.84 <b>W</b> TUNGSTEN	186.21 <b>Re</b> RHENIUM	190.23 <b>Os</b> OSMIUM	192.22 <b>Ir</b> IRIDIUM	195.08 <b>Pt</b> PLATINUM	196.97 <b>Au</b> GOLD	200.59 <b>Hg</b> MERCURY	204.38 <b>Tl</b> THALLIUM	207.2 <b>Pb</b> LEAD	208.98 <b>Bi</b> BISMUTH	(209) <b>Po</b> POLONIUM	(210) <b>At</b> ASTATINE	(222) <b>Rn</b> RADON
7	(223) <b>Fr</b> FRANCIUM	(226) <b>Ra</b> RADIUM	89-103 <b>Ac-Lr</b> Actinide	(261) <b>Rf</b> RUTHERFORDIUM	(262) <b>Db</b> DUBNIUM	(266) <b>Sg</b> SEABORGIUM	(264) <b>Bh</b> BOHRNIUM	(277) <b>Hs</b> HASSIUM	(268) <b>Mt</b> MEITNERIUM	(281) <b>Uun</b> UNUNNIUM	(272) <b>Uuu</b> UNUNUNIUM	(285) <b>Uub</b> UNUNBIUM		(289) <b>Uuq</b> UNUNQUADIUM				

(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)

Relative atomic mass is shown with five significant figures. For elements having no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.

However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.

Editor: Aditya Vardhan (adivar@netlinx.com)

## LANTHANIDE

57 138.91 <b>La</b> LANTHANUM	58 140.12 <b>Ce</b> CERIUM	59 140.91 <b>Pr</b> PRASEODYMIUM	60 144.24 <b>Nd</b> NEODYMIUM	61 (145) <b>Pm</b> PROMETHIUM	62 150.36 <b>Sm</b> SAMARIUM	63 151.96 <b>Eu</b> EUROPIUM	64 157.25 <b>Gd</b> GADOLINIUM	65 158.93 <b>Tb</b> TERBIUM	66 162.50 <b>Dy</b> DYSPROSIUM	67 164.93 <b>Ho</b> HOLMIUM	68 167.26 <b>Er</b> ERBIUM	69 168.93 <b>Tm</b> THULIUM	70 173.04 <b>Yb</b> YTTERBIUM	71 174.97 <b>Lu</b> LUTETIUM
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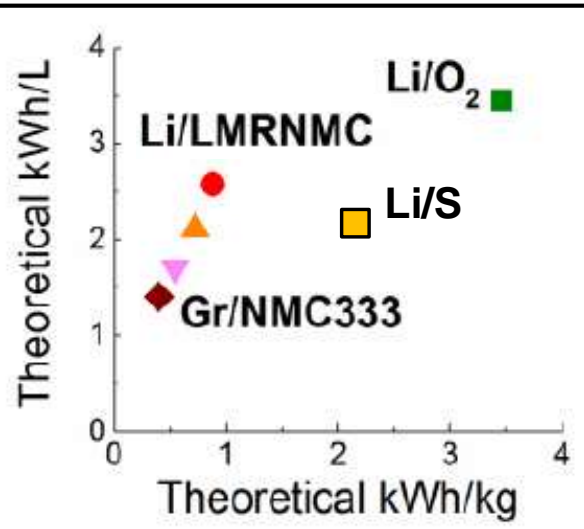
## ACTINIDE

89 (227) <b>Ac</b> ACTINIUM	90 232.04 <b>Th</b> THORIUM	91 231.04 <b>Pa</b> PROTACTINIUM	92 238.03 <b>U</b> URANIUM	93 (237) <b>Np</b> NEPTUNIUM	94 (244) <b>Pu</b> PLUTONIUM	95 (243) <b>Am</b> AMERICIUM	96 (247) <b>Cm</b> CURIUM	97 (247) <b>Bk</b> BERKELIUM	98 (251) <b>Cf</b> CALIFORNIUM	99 (252) <b>Es</b> EINSTEINIUM	100 (257) <b>Fm</b> FERMIUM	101 (258) <b>Md</b> MENDELEVIUM	102 (259) <b>No</b> NOBELIUM	103 (262) <b>Lr</b> LAWRENCIUM
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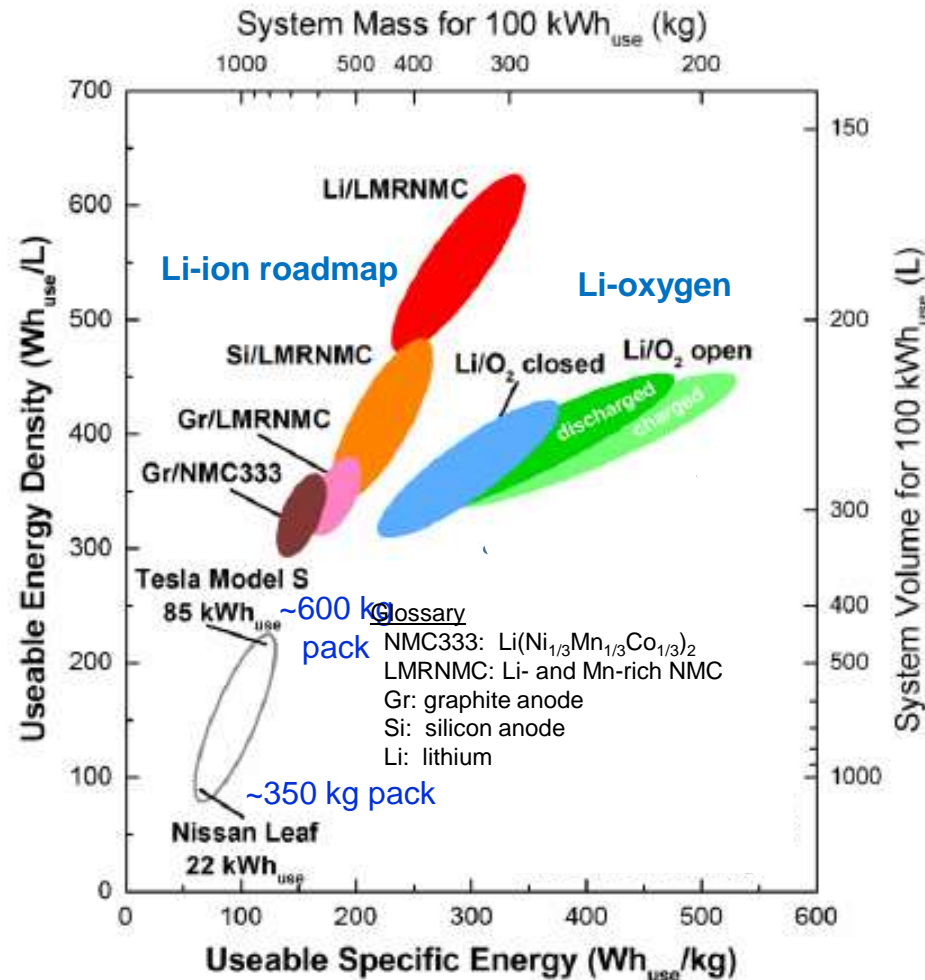
# Theoretical vs Usable Energy Densities

Theoretical energy densities are all very high



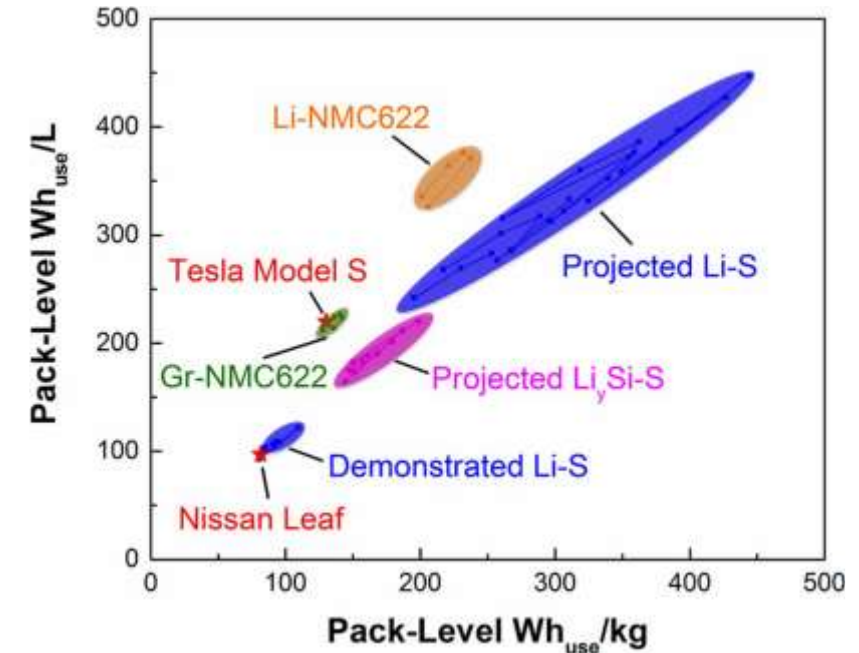
Highest Energy Density Batteries All Use Li Metal

Lithium-oxygen vs. Li-ion Roadmap



K.G. Gallagher et al., "Quantifying the promise of lithium-air batteries for electric vehicles," *Energy Environ. Sci.*, 7, 1555 (2014)

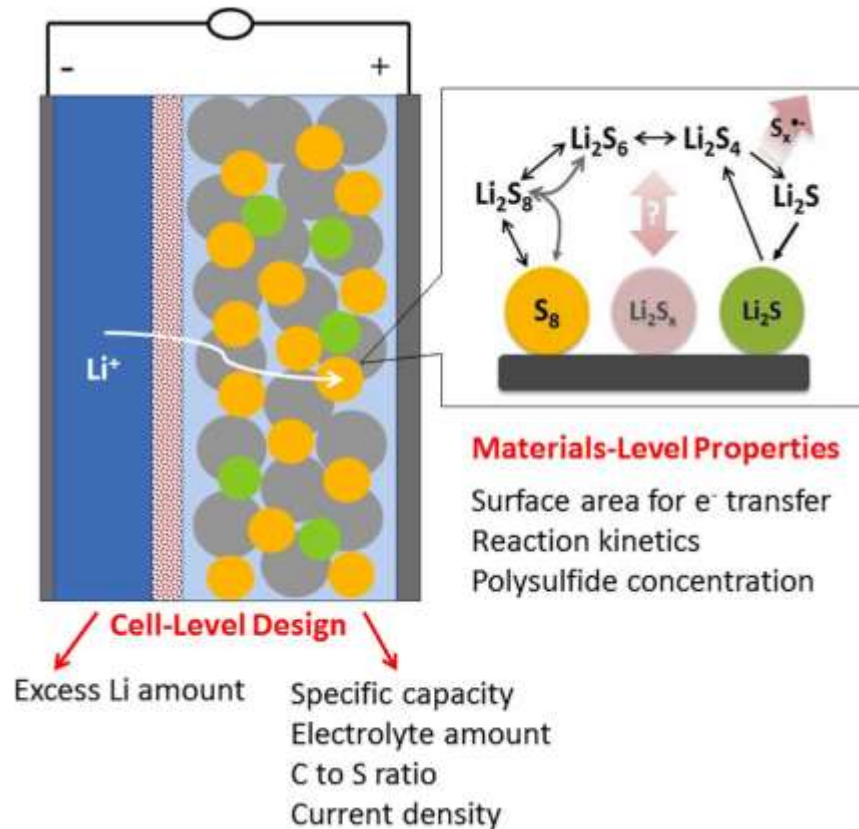
Lithium-sulfur vs. Li-ion Roadmap



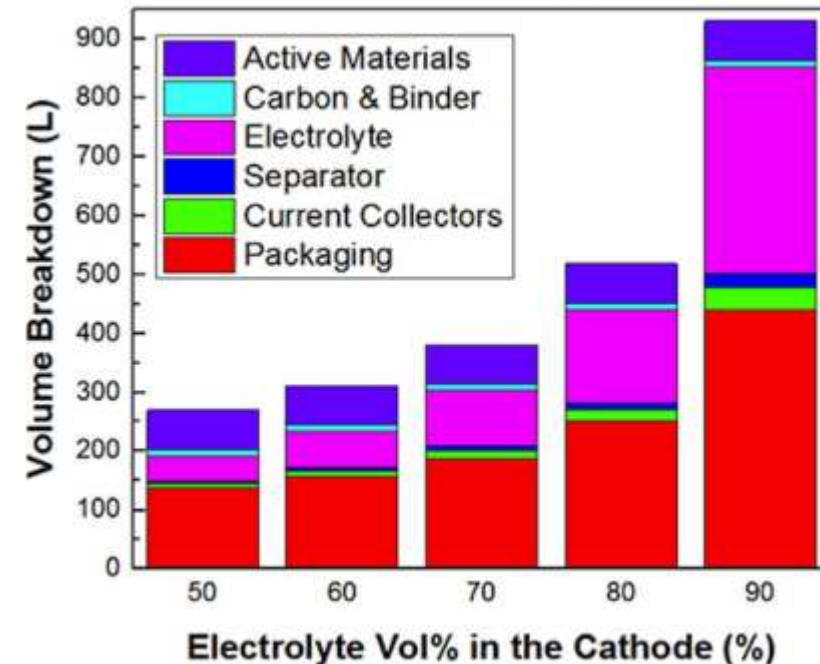
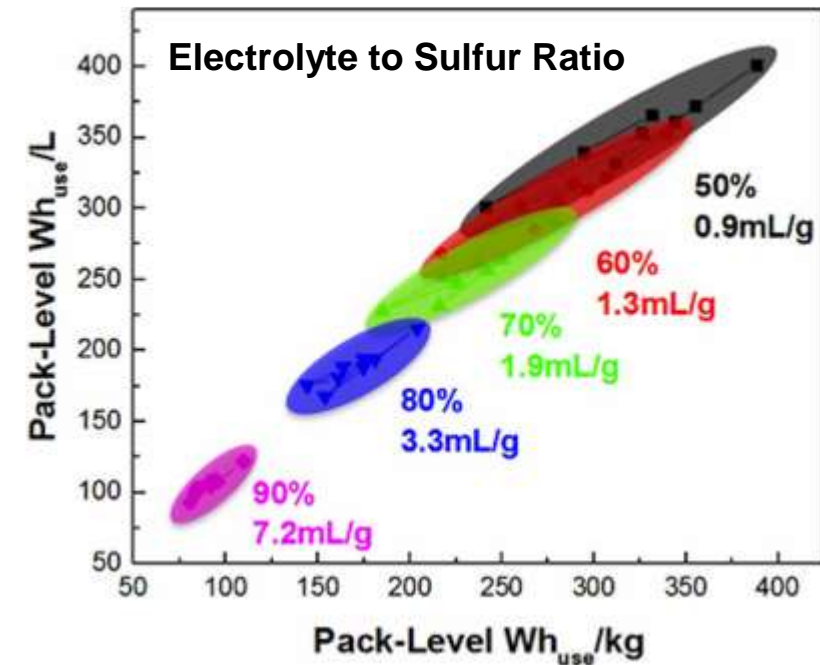
D. Eroglu et al., *J. Electrochem. Soc.*, 162, A982 (2015)



# Lithium-Sulfur Batteries today require too much electrolyte, which limits the practical energy density

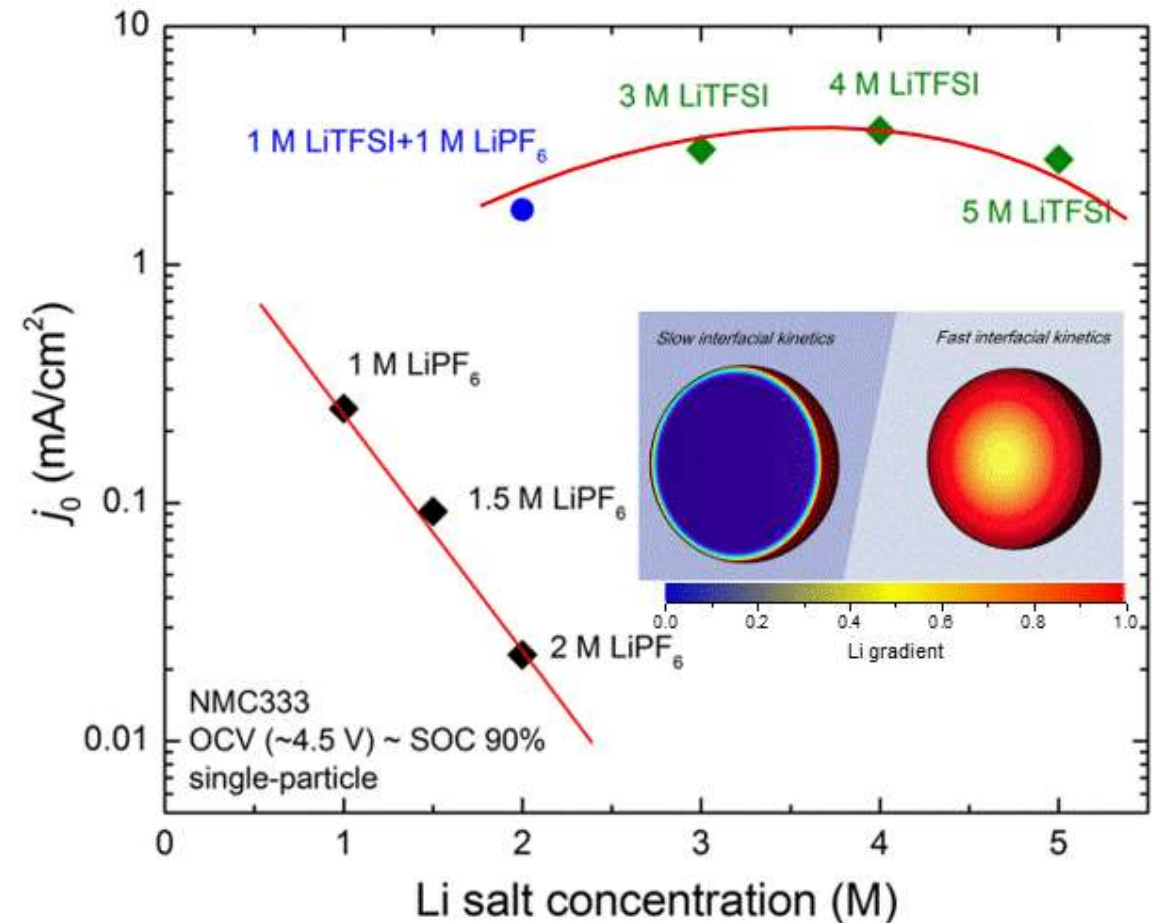
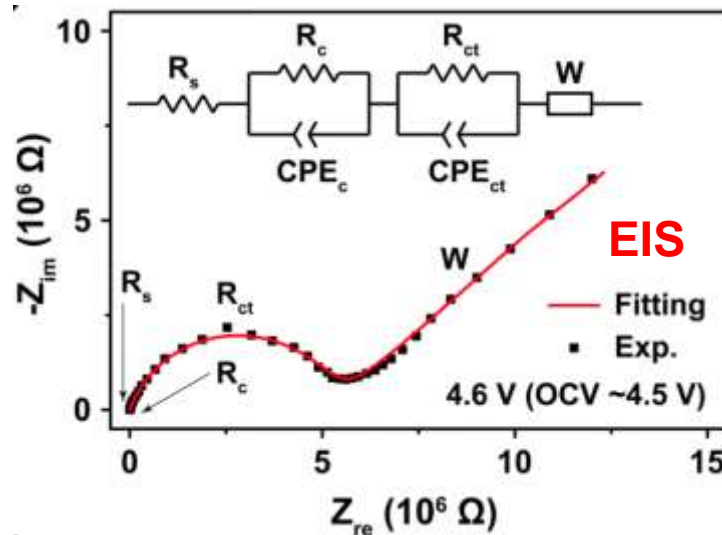
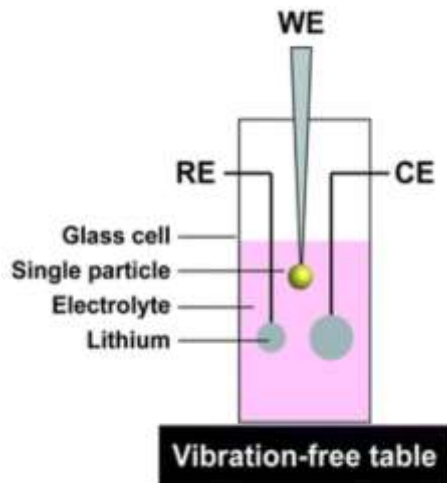
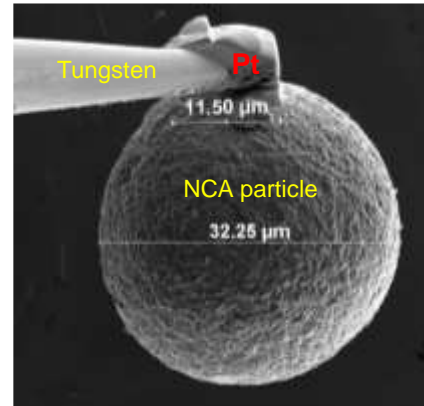
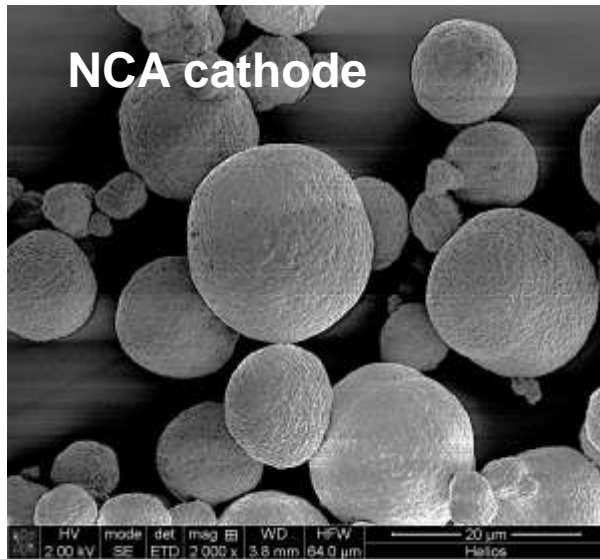


D. Eroglu *et al.*, "Critical Link between Materials Chemistry and Cell-Level Design for High Energy Density and Low Cost Transportation Battery," *J. Electrochem. Soc.*, 162, A982 (2015)



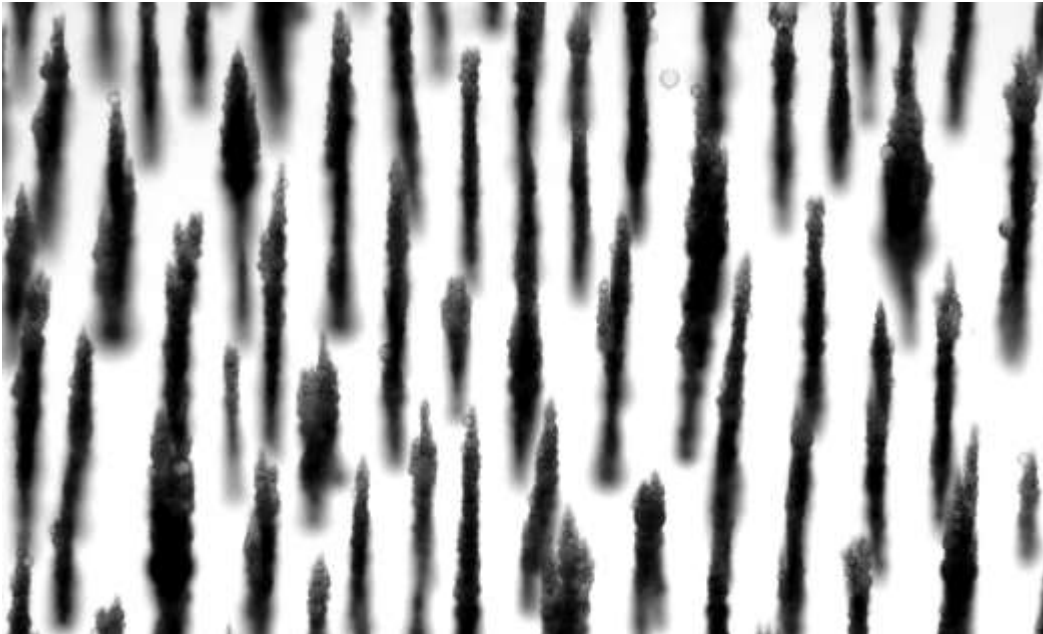
# Ion Transport Constraints Limit Discharge Power

Electrolyte innovations needed to increase conductivity, interfacial transport rates



# Ion Transport Constraints Limit Discharge Power

At electrode scale, novel low-tortuosity structures needed



Magnetic field alignment of low tortuosity electrodes

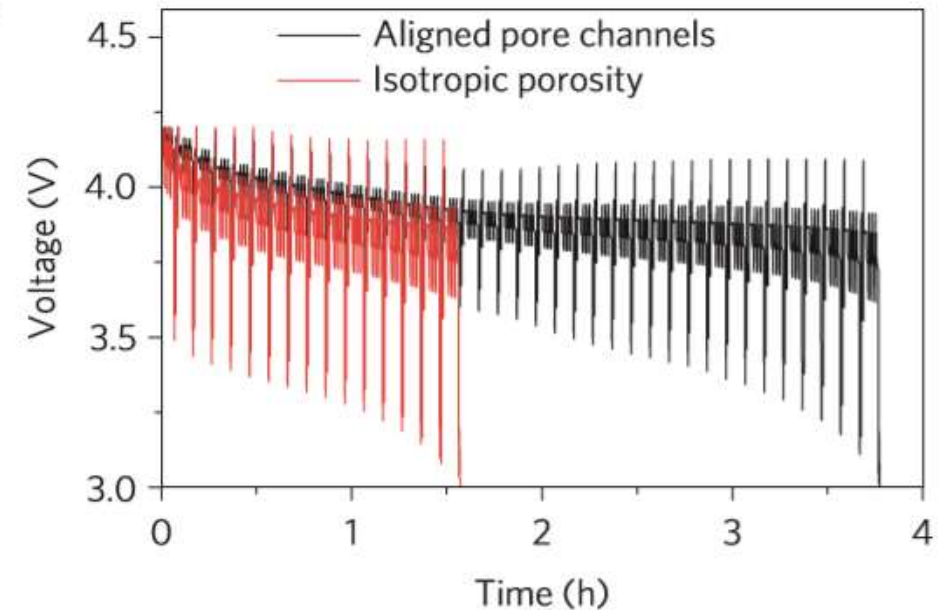
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Sustainable Energy

**A powerful new battery could give us electric planes that don't pollute**



Thank you