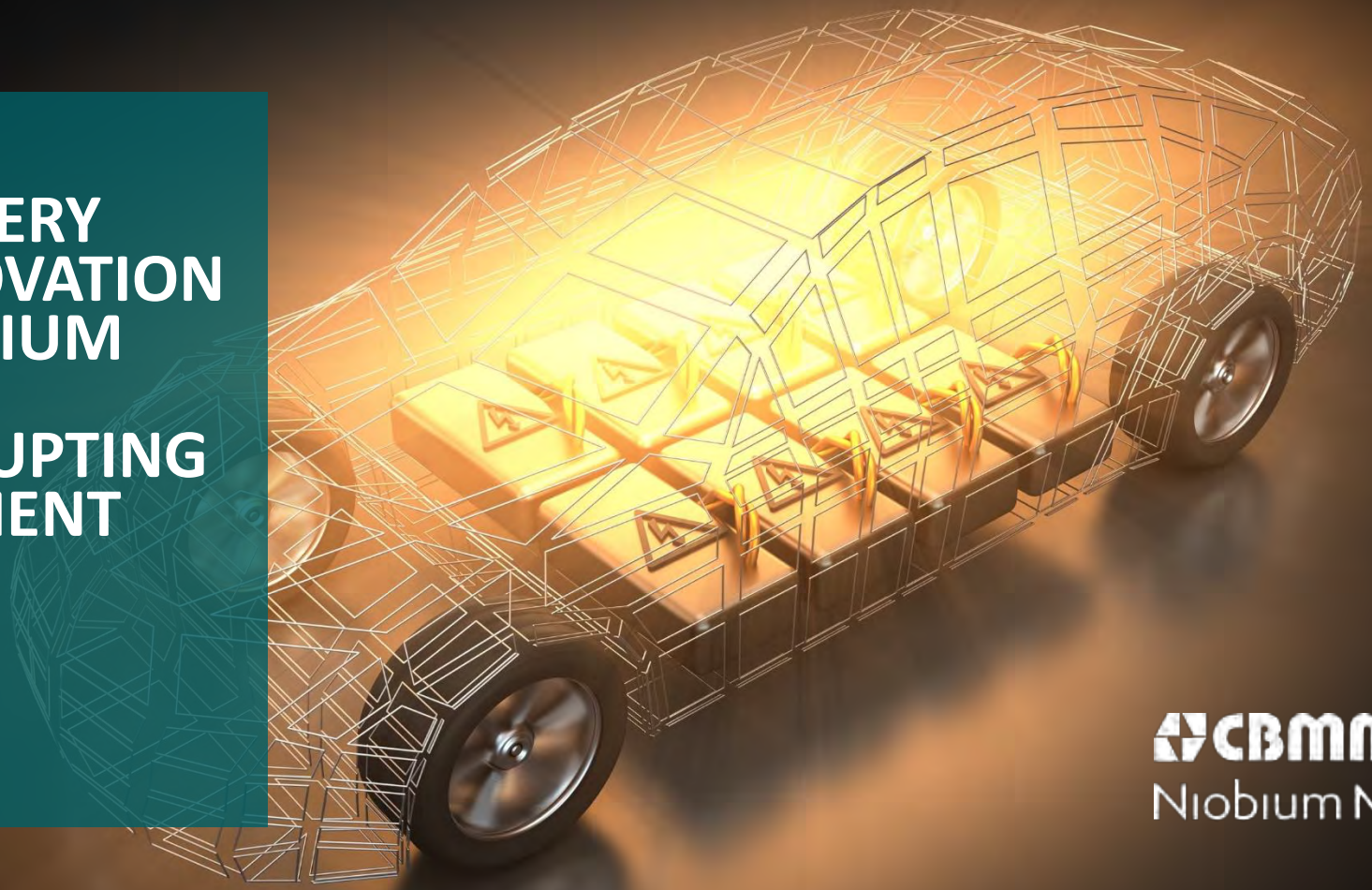
BATTERY INNOVATION NIOBIUM AS A DISRUPTING ELEMENT



CBMM
Niobium Nb

ENERGY CONVERSION AND STORAGE LANDSCAPE

"…TO RELIABLY SUPPLY THE ENERGY WE NEED AT AN AFFORDABLE COST"

Energy Sources → **Useful Energy** → **Saving Energy**

- Oil
- Natural Gas
- Coal

- Hydropower

- Nuclear

- Renewables
  (biomass, water)
- Intermittent
  (solar, wind)

Useful Energy

- Fuels
  (gasoline, diesel, hydrogen)
- **Electricity**
- Heat

conversion

storage

Saving Energy

Capacitor
Rechargeable Battery
Flow Battery

BATTERY TECHNOLOGY
WIDE RANGE OF APPLICATIONS

Increasing battery size and energy storage capacity

- Technology enabler
- Portability

Energy capacity
"small is beautiful"

- Reduction of CO_2 emissions
- Clear out ground level pollutants
- Fuel efficiency

Safety
"safety is king"

- Renewables utilization
- Offsetting intermittency
- Reduce need of power plants

Scalability and cost
"reliable and cheap supply rules"

RECHARGEABLE BATTERY VARIETIES AND FORMATS

Coin cells

Pouch cells **Cylindrical cells**

Battery cell modules

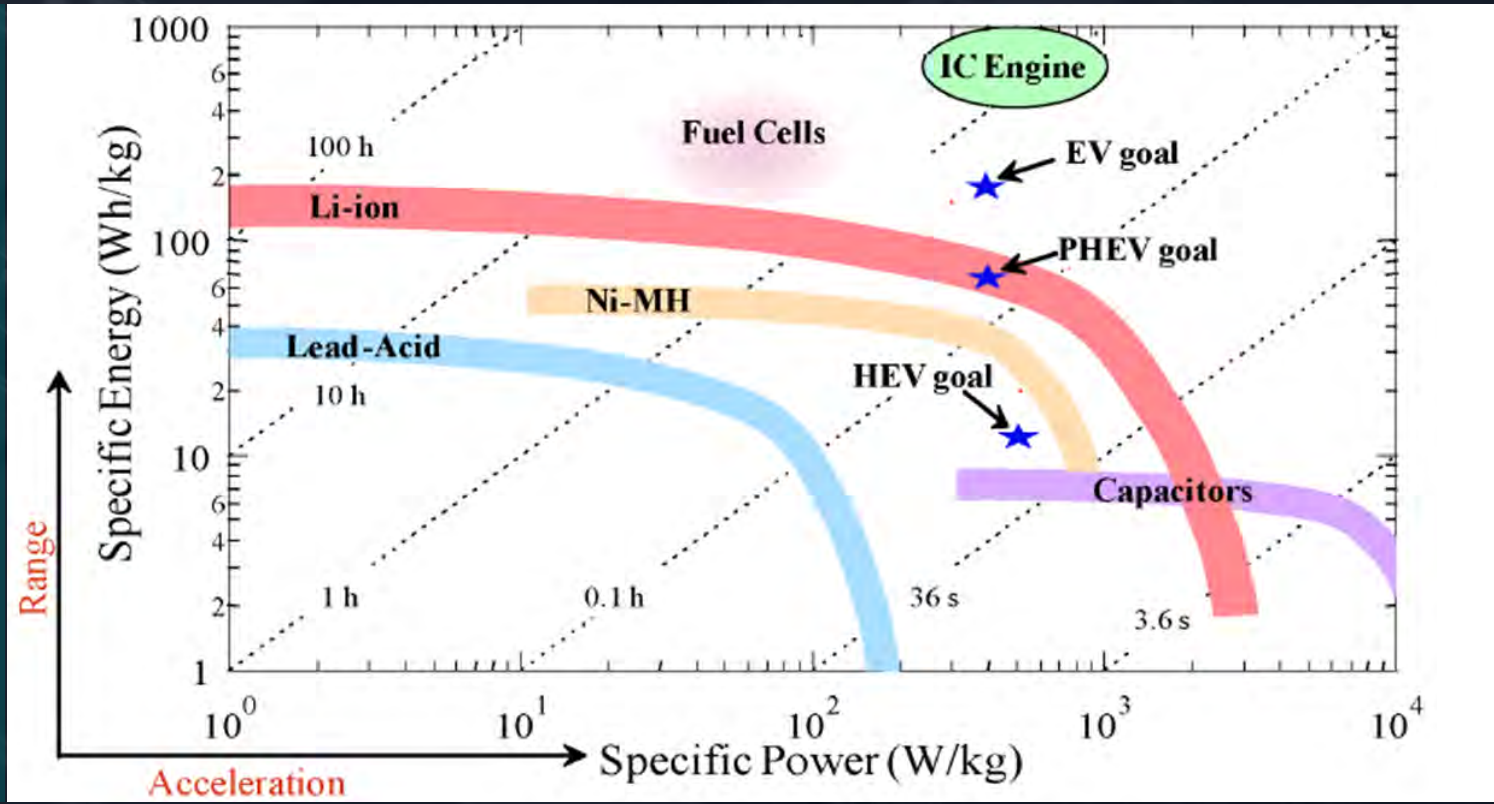
Battery pack (Tesla Model S – 16 modules)

540 kg | 7,104 lithium-ion cylindrical cells | 85 kWh

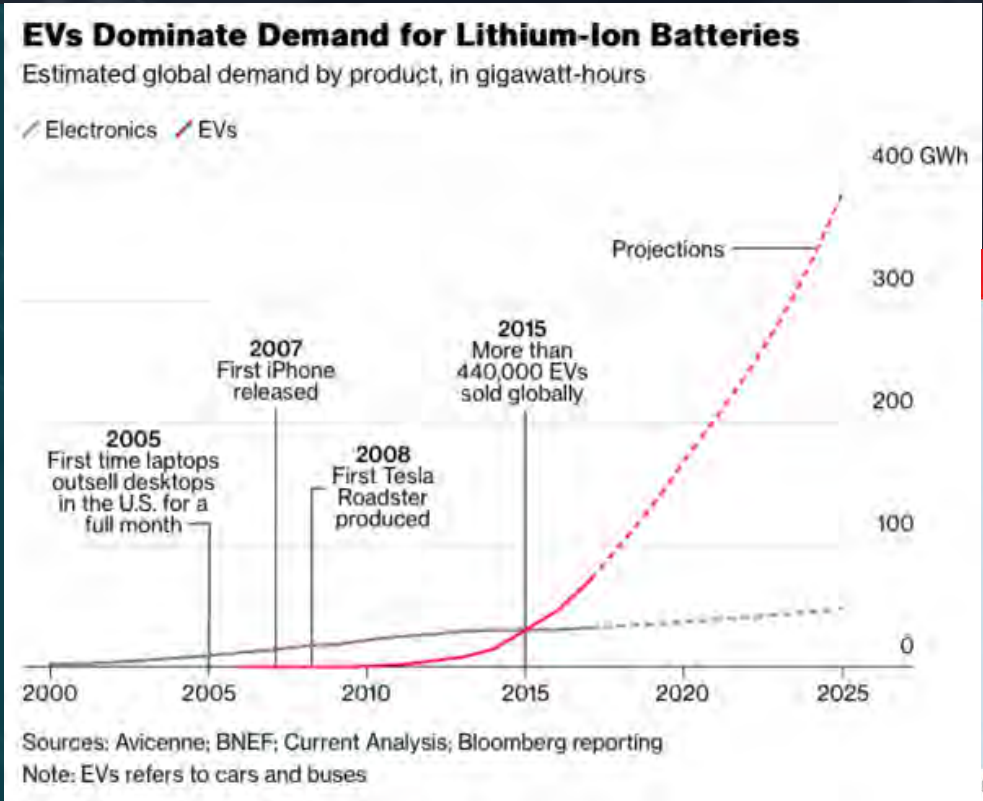
Tesla 50 MWh/25 MW ESS batteries installed at an existing 60 MW Gannawarra Solar Farm in Australia

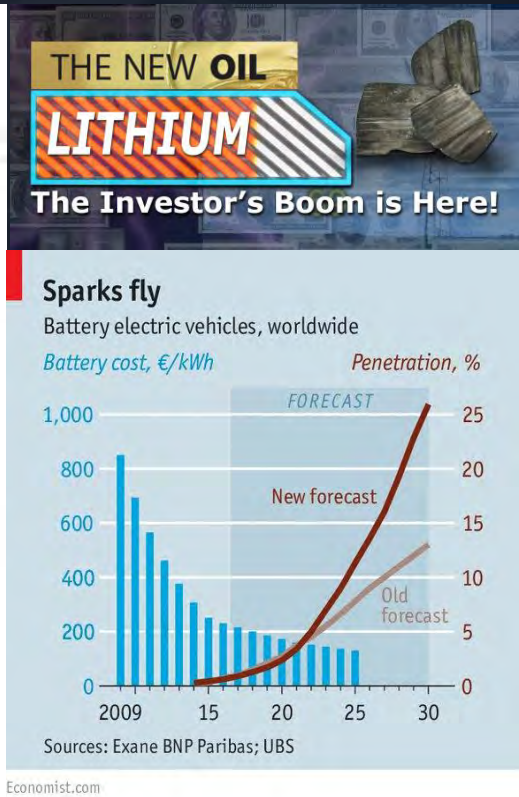
ESS – Energy Storage System

RECHARGEABLE BATTERIES…
WHY LI-ION?

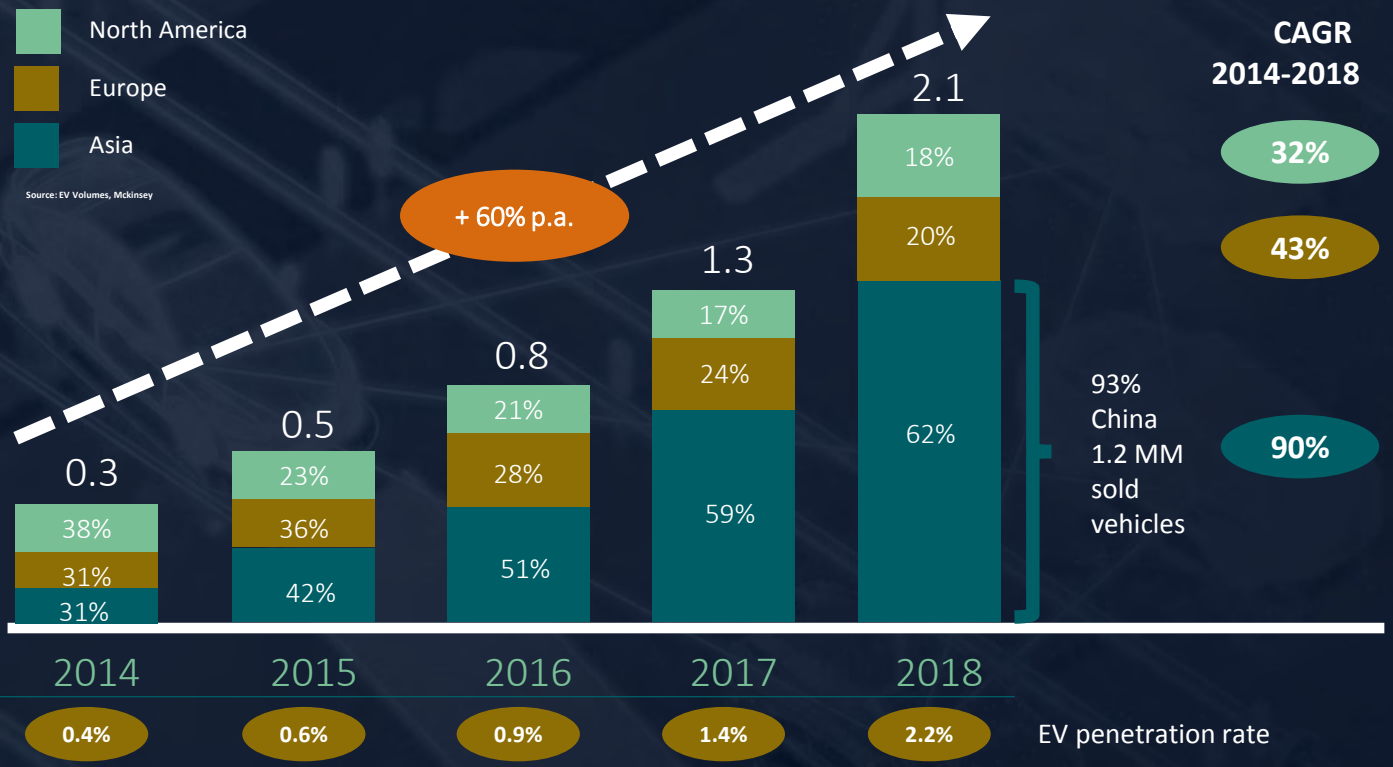


LI-ION BATTERIES
THE NEW "OIL"?





GLOBAL EV MARKET SALES BY REGION



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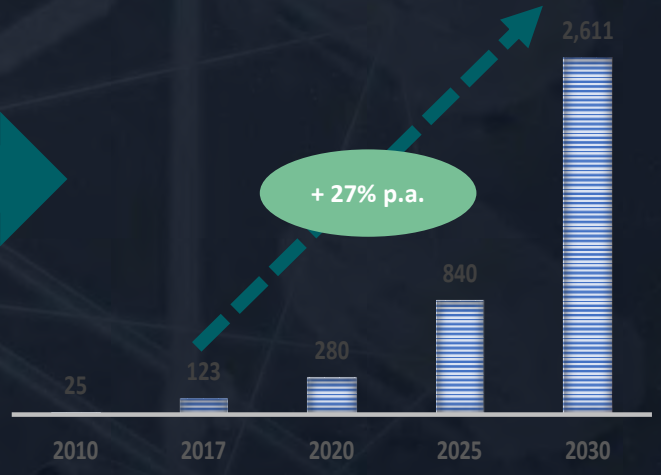
BATTERY FALLING PRICES WILL BOOST HIGHER DEMAND

Li-ion battery pack prices, USD/kWh

Base: 40 kWh, NMC 622, Prismatic Design

Total battery demand, GWh



Source: BNEF and Mckinsey

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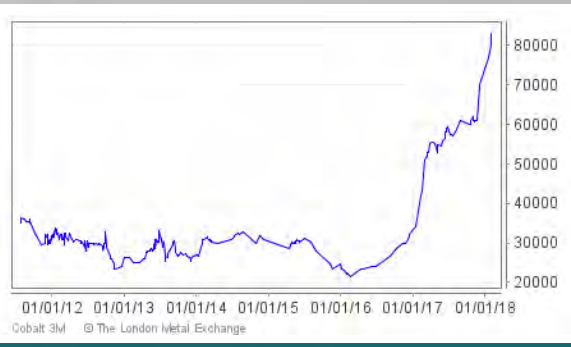
BATTERY CELL MANUFACTURING CAPACITY – 2025 (~726 GWH)

Source: BNEF and Mckinsey

MATERIALS CHEMISTRY IS KEY ON BATTERY TECHNOLOGY

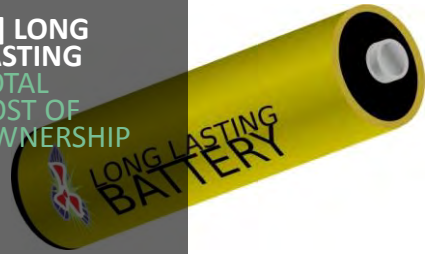
[1] SAFETY
#1 CONCERN OF THE INDUSTRY

[2] HIGH ENERGY
EXTENDING DRIVING RANGE AND LIGHTWEIGHT



[3] HIGH POWER
FAST CHARGING

[4] LONG LASTING
TOTAL COST OF OWNERSHIP



[5] RAW MATERIALS PRICE STABILITY?
AFFORDABILITY FOR MASS COMMERCIALIZATION

BATTERY TECHNOLOGY
MATERIALS CHEMISTRY

CARBON GRAPHITE

Lithium Titanium Oxide
($Li_4Ti_5O_{12}$ – LTO)

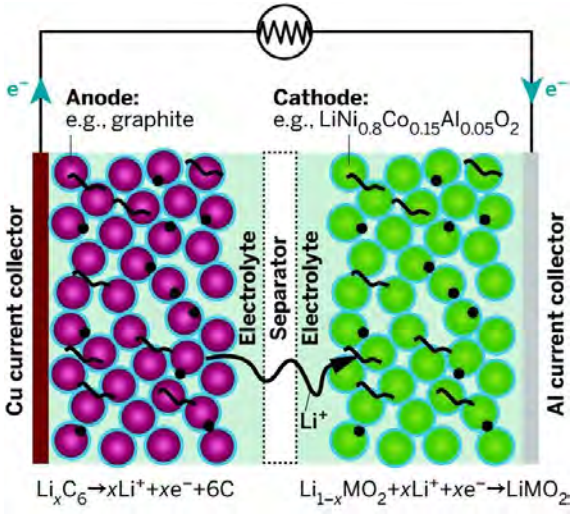
Niobium Titanium Oxide
(Nb_2TiO_7 – NTO)

Silicon

Silicon-Graphite Composites

Li metal

CHEMICAL ENERGY INTO ELECTRICITY



Lithium Cobalt Oxide
($LiCoO_2$ – LCO)

Lithium Manganese Oxide
($LiMn_2O_4$ – LMO)

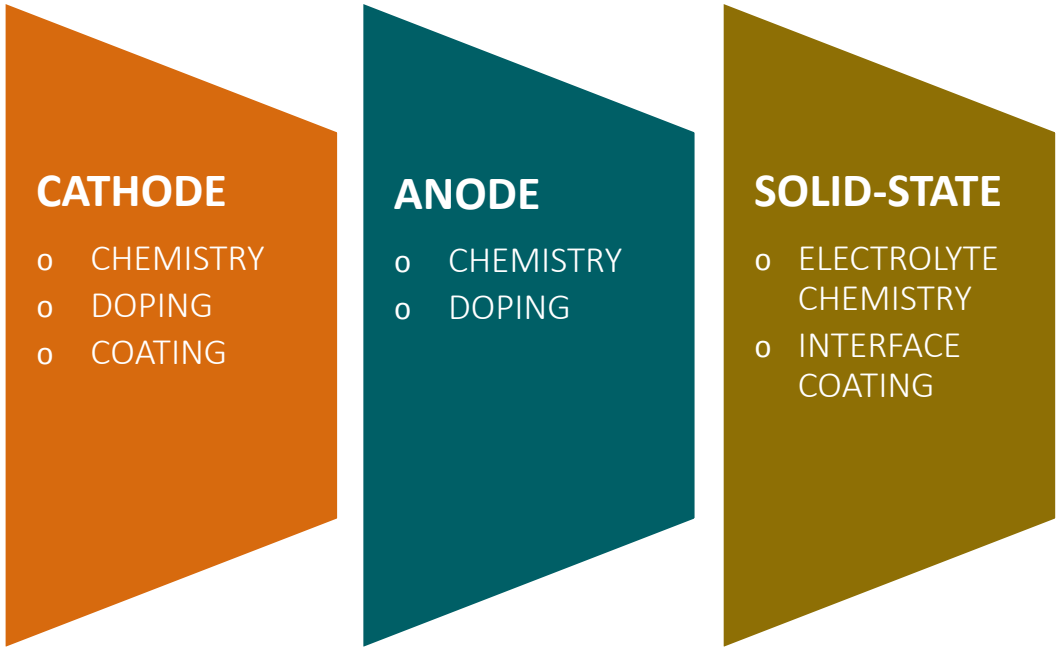
Lithium Iron Phosphate
($LiFePO_4$ - LFP)

Lithium Nickel Manganese Cobalt Oxide
($LiNiMnCoO_2$ – NMC)

Lithium Nickel Cobalt Aluminium Oxide
($LiNiMnAlO_2$ – NCA)

NIOBIUM FOR LITHIUM-ION BATTERIES

NIOBIUM IS ADDRESSING THE **MAJOR CHALLENGES IN MATERIALS CHEMISTRY** TO MEET DEMANDS OF **HIGHER PERFORMANCE, LONGER-LIFE AND SAFER BATTERIES**



NIOBIUM BENEFITS FOR LITHIUM-ION BATTERIES

CATHODES

Niobium is being used to develop cobalt-reduced or -free, lithium-rich and manganese-based new cathode materials with higher energy density and longer-term stability

ANODES

Fast charging, safer and higher energy capacity batteries are being possible by the use of Niobium in the formulation of new anode materials under current industrial trials

SOLID STATE

Niobium is becoming an essential element to further the development of all solid-state batteries, the ultimate solution on battery technology

NIOBIUM BENEFITS FOR LITHIUM-ION BATTERIES

NTO - Niobium Titanium Oxides

NWO - Niobium Tungsten Oxides

DR - Niobium *Disordered* Rock-Salt

LNO - Lithium Niobates

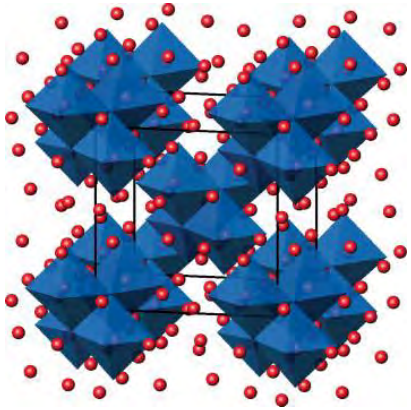
CATHODE CHEMISTRY
INCREASING ENERGY DENSITY

Further Li content induces the formation of ***cation-disordered rock-salt structure (DR)***:

Novel redox mechanism – combining TM and oxide ions oxidation (**Mn^{+3}/Mn^{+4} and O^{2-}/O^{-}**);

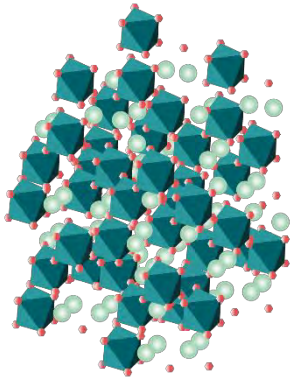
Nb^{+5} ions stabilizes effectively the solid-state novel redox mechanism
(charge compensation).

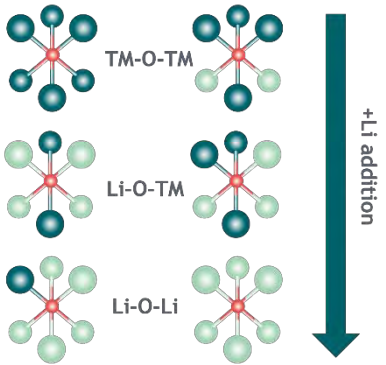
Cobalt-free Li_3NbO_4 ordered rock-salt structure (NbO_6 octahedra units)
Li atoms in red



$Li_{1.3}Nb_{0.30}Me^{3+}_{0.40}O_2$
- (Mn^{+3} and Fe^{3+})
> 300 mAh g^{-1}

Increased Li in disordered structure
$Li_{1.3}Nb_{0.3}Mn_{0.4}O_2$





= Lithium = Nb and Mn = Oxygen

- WALTON et al, Dalton Trans 39 (26) (2010) 6031
- YABUUCHI et al, PNAS 112 (25) (2015) 7650

CATHODE CHEMISTRY
INCREASING ENERGY DENSITY

COMPETITIVE LANDSCAPE WITH COMMERCIAL CATHODES

CATHODE CHEMISTRY	SPECIFIC CAPACITY – mAh g^{-1}	VOLTAGE - V	SAFETY
Li_3NbO_4-based Host Structure (DR)	> 300	3.2	0
NMC 622	221	4.5	0
NMC 111	189	4.3	- -
NCA	167	3.8	- -
LCO	160	4.0	- -
LFP	155	3.4	++
LNM	130	4.6	+ +

CATHODE CHEMISTRY
INCREASING ENERGY DENSITY

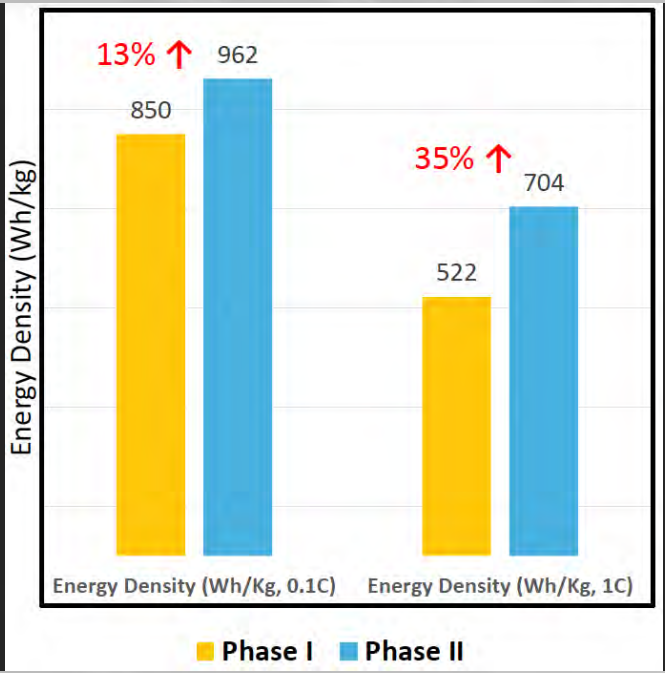
Wildcat Discovery Technologies

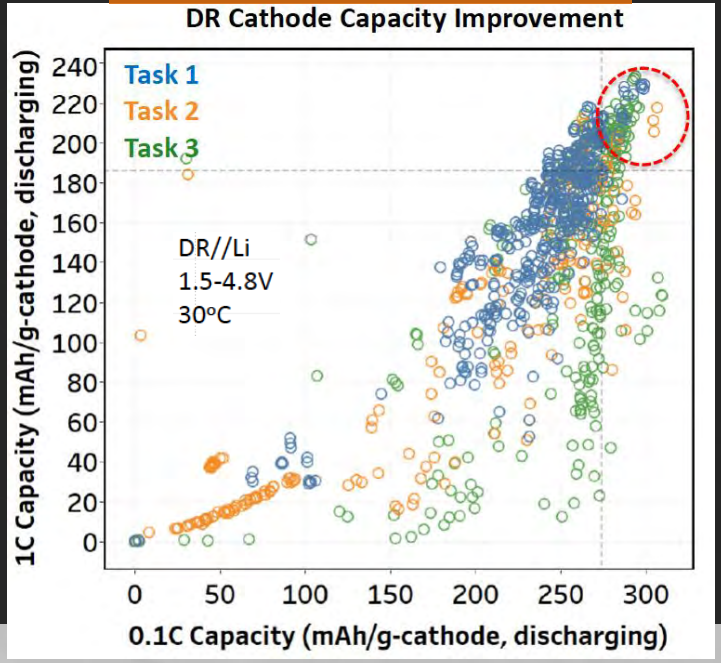
HIGH-THROUGHPUT SCREENING
- Compositional space
- Synthesis process
- Carbon coating
- Electrolyte
- Testing protocol

DR Cathode
Mn-rich Chemistry
Development

$Li_{1.4}Nb_{0.1}Mn_{0.43}M_xO_yX$
$Li_{1.35}Nb_{0.1}Mn_{0.40}M_xO_yX$

Challenges:
- **Cycle Life**
- **Electronic Conductivity**





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CATHODE CHEMISTRY
IMPROVING CAPACITY RETENTION

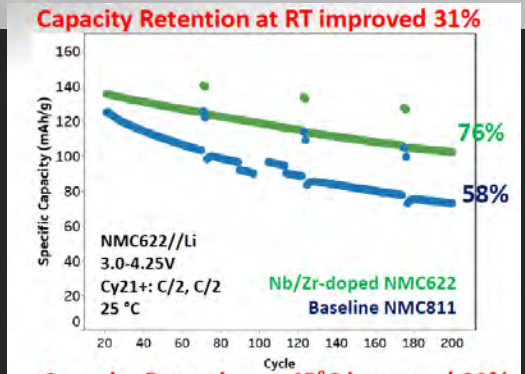
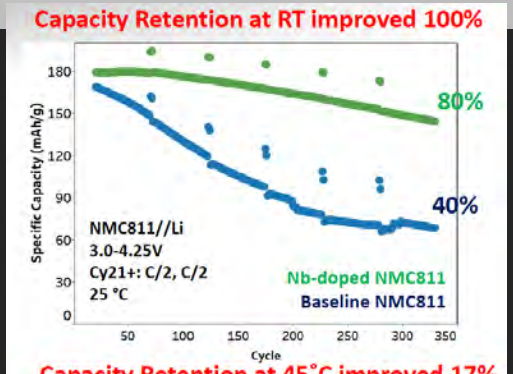
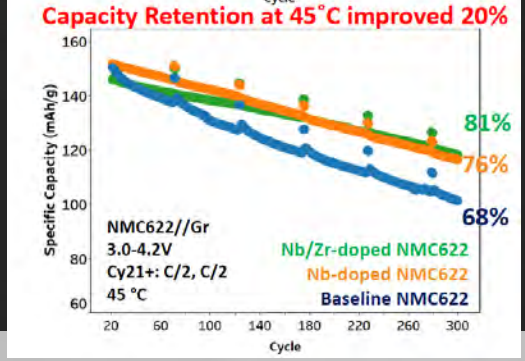
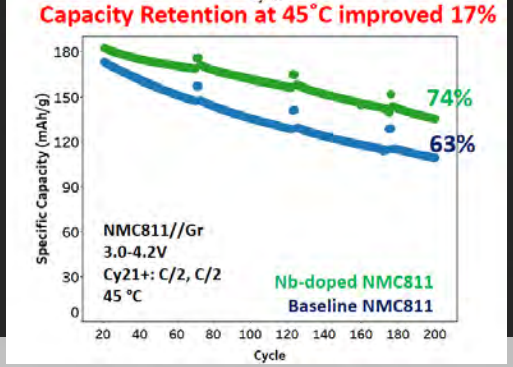
Wildcat Discovery Technologies

NIOBIUM DOPING

NMC622
NMC811

Primary doping
Nb (0.5 wt.%)

Secondary doping
Nb/Zr (0.5 wt.%/0.5 wt.%)

	NMC622	NMC811
HALF CELL @RT		
FULL CELL @45°C		

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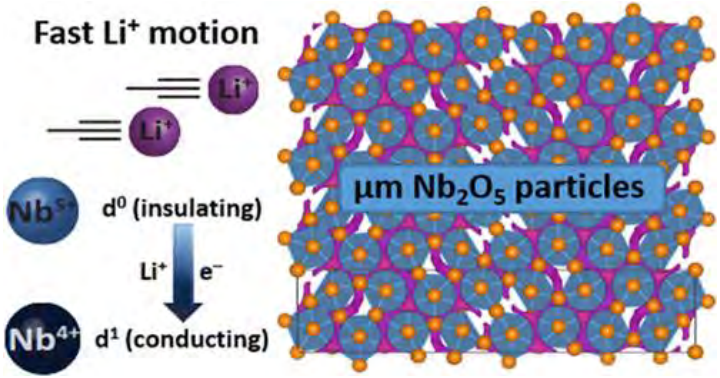
ANODE CHEMISTRY
HIGH POWER & FAST CHARGING

$Nb_2O_5 + xLi^+ + xe^- \leftrightarrow Li_xNb_2O_5$

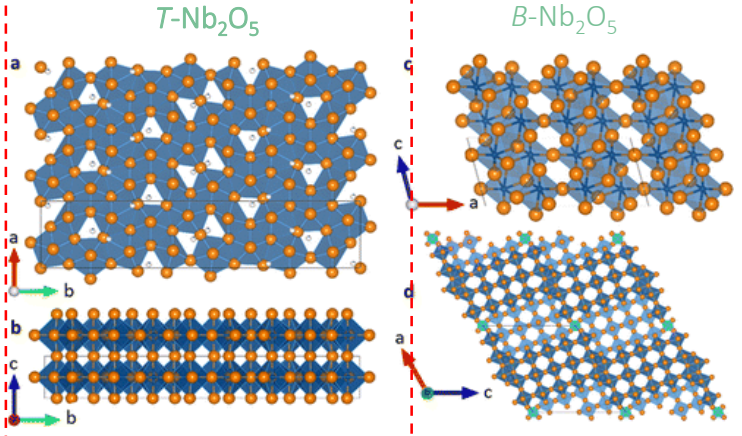
…Li^+ intercalation on T-Nb_2O_5



NIOBIUM (V) OXIDES

- Potential Window
  ca. +1.0 to +2.0 V vs. Li^+/Li
- 0.8 to 2.0 Li per Nb^{+5}/Nb^{+4} redox pair
- High Rate
- High Capacity

Niobium (V) Oxides Polymorphs



Discharge rates:

- 150 $mAh.g^{-1}$ at 5C
- 125 $mAh.g^{-1}$ at 10C

GREY et al, **JACS 138** (2016) 8888

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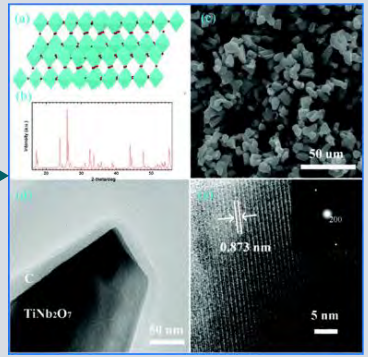
ANODE CHEMISTRY
HIGH POWER & FAST CHARGING

Titanium Niobium Oxides - TNO
new class of anode materials

Ternary Family

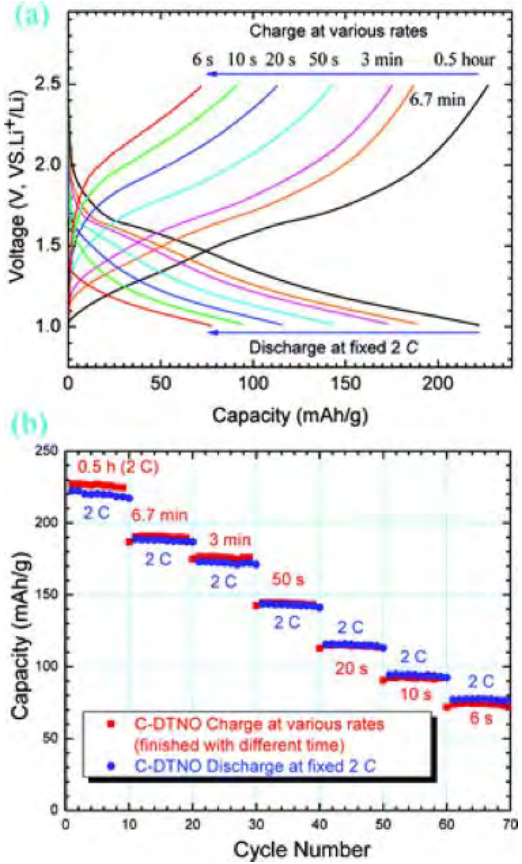
Ti-Nb-O Ternary Family

- $TiNb_2O_7$ ($TiO_2.Nb_2O_5$)
- $Ti_2Nb_{10}O_{29}$ ($2TiO_2.5Nb_2O_5$)
- $TiNb_{24}O_{62}$ ($TiO_2.12Nb_2O_5$)



- Theoretical Energy Density: 387.9 mAh.g^{-1}
- Ti^{+4}/Ti^{+3} and Nb^{+5}/Nb^{+4}; Nb^{+4}/Nb^{+3} redox couples (~5 Li per formula unit)

GOODENOUGH et al, *Chem Mater* **138** (2016) 8888



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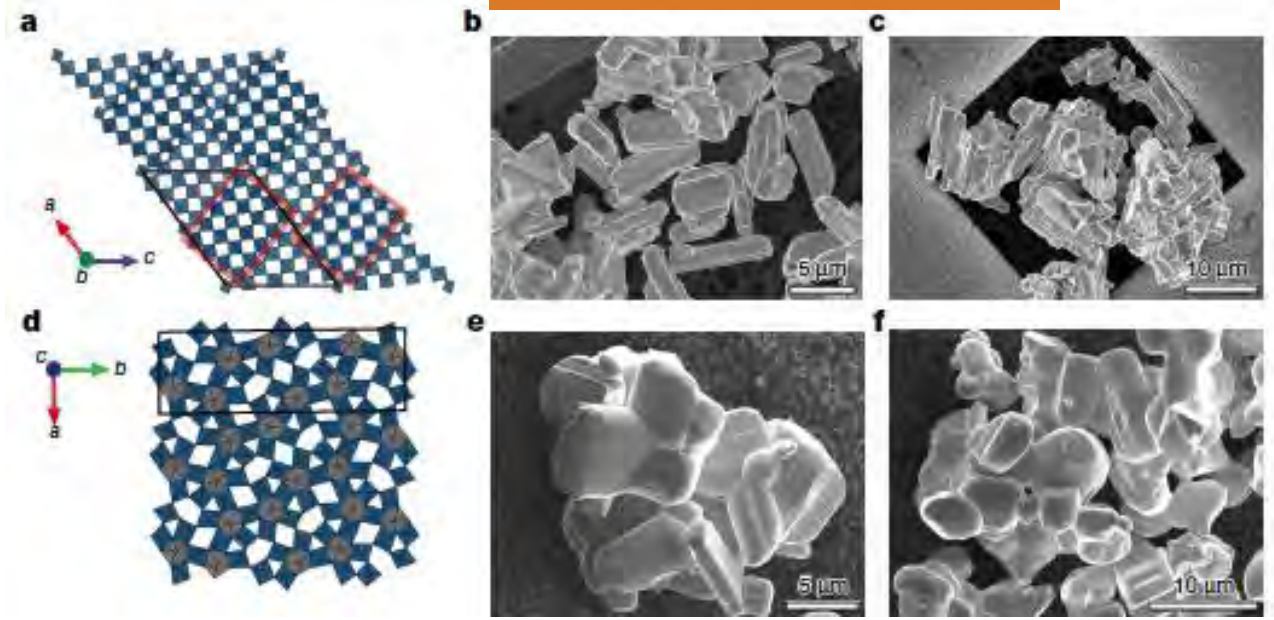
Mater **138** (2016) 8888

CBMM Niobium

ANODE CHEMISTRY
HIGH POWER & FAST CHARGING

NIOBIUM TUNGSTEN OXIDES- NWO
NEW CLASS OF Nb_2O_5-WO_3
MATERIALS AT MICRO-SIZED SCALE

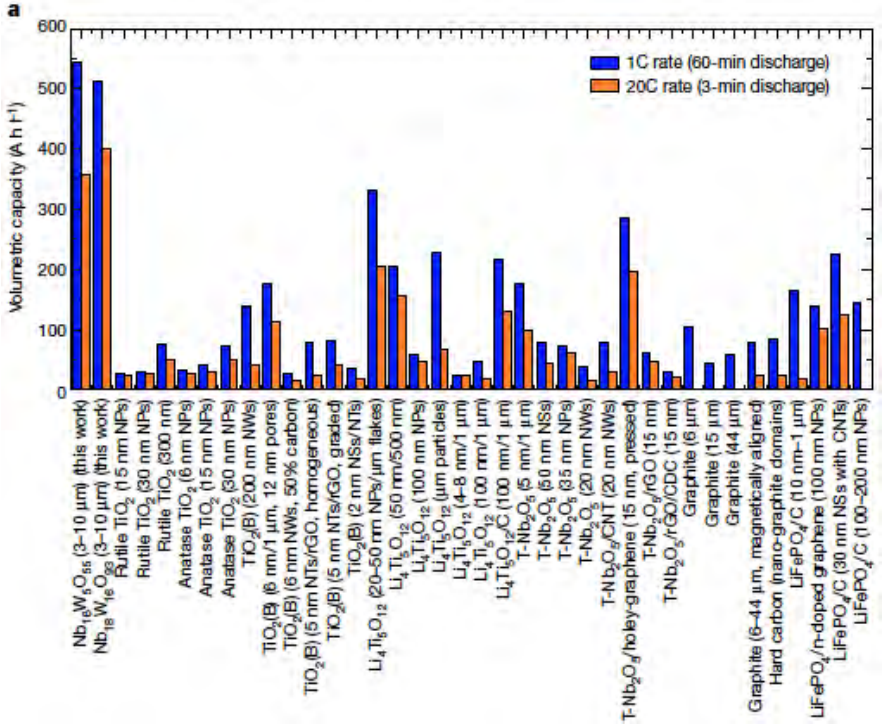
- **$Nb_{16}W_5O_{55}$**
  Monoclinic, crystallographic shear ReO_3-like structure
- **$Nb_{18}W_{16}O_{93}$**
  Orthorhombic, tetragonal tungsten bronze superstructure

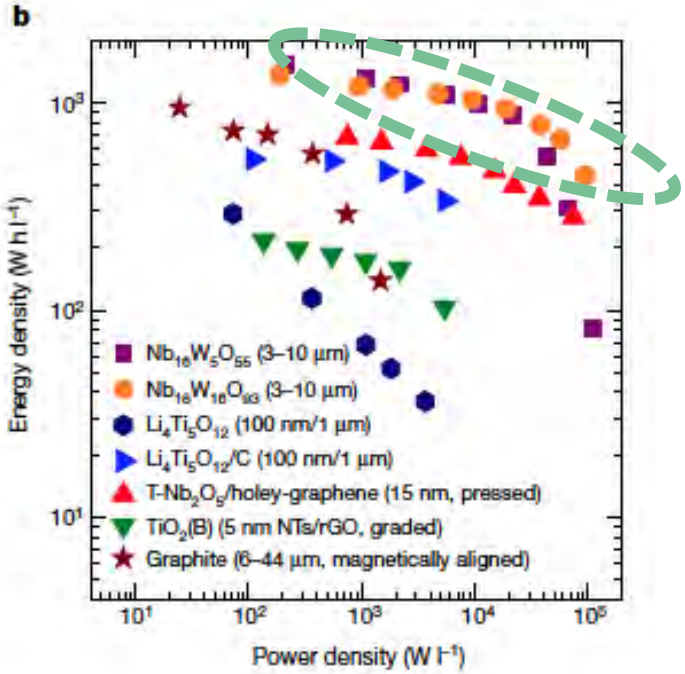


- Kent J. Griffith et al., Nature 559 (2018) 556

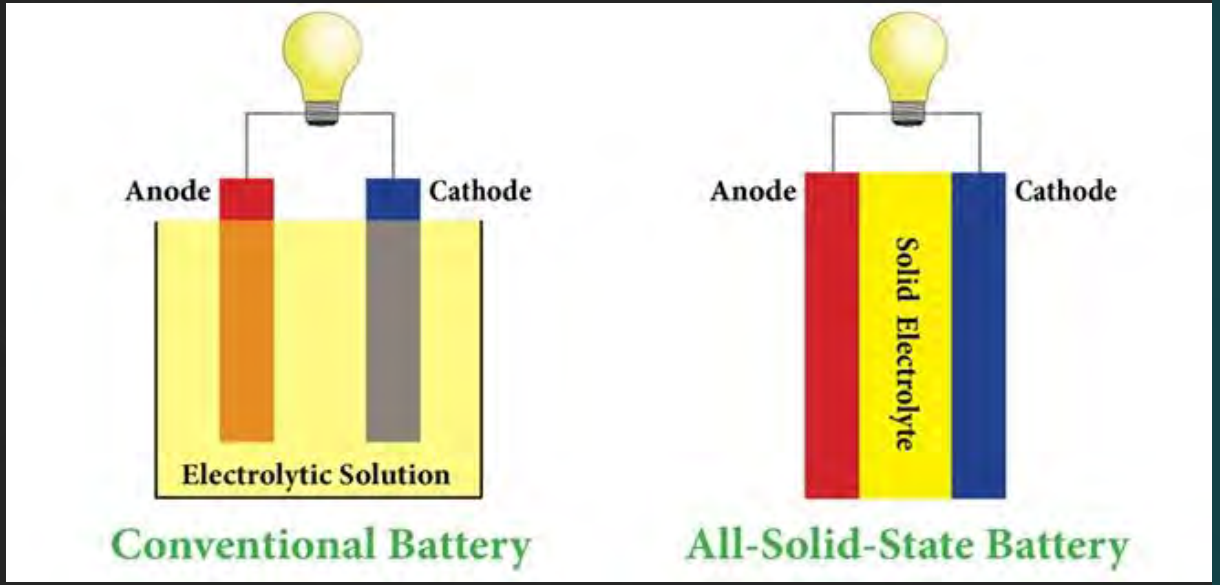
ANODE CHEMISTRY
HIGH POWER & FAST CHARGING

NWO > LTO > LTO/C > *T*-Nb_2O_5/Graphene > TiO_2 NPs > Graphite





ALL SOLID STATE BATTERIES



- FLAMMABLE ELECTROLYTE
- SEI FORMATION
- HEAVIER (STEEL CASE)
- LOW TEMPERATURE OPERATION
- BMS COMPLEX

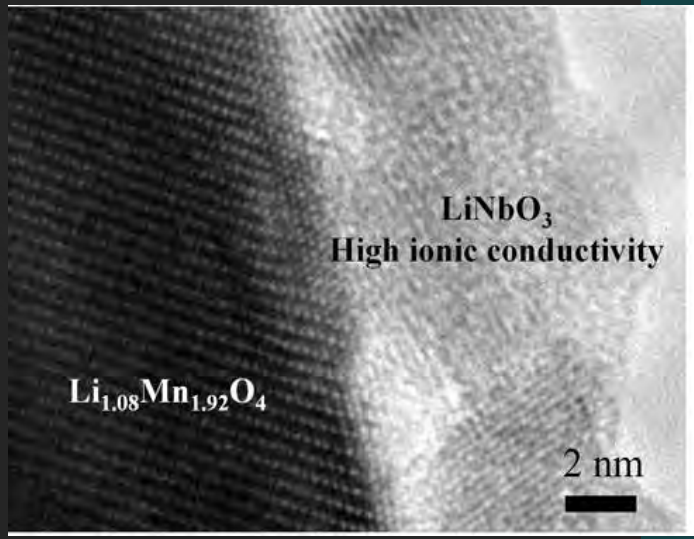
- NON- FLAMMABLE ELECTROLYTE
- NO SEI FORMATION
- LIGHTER AND SMALLER
- ALLOW HIGH TEMPERATURE OPERATION
- BMS SIMPLER

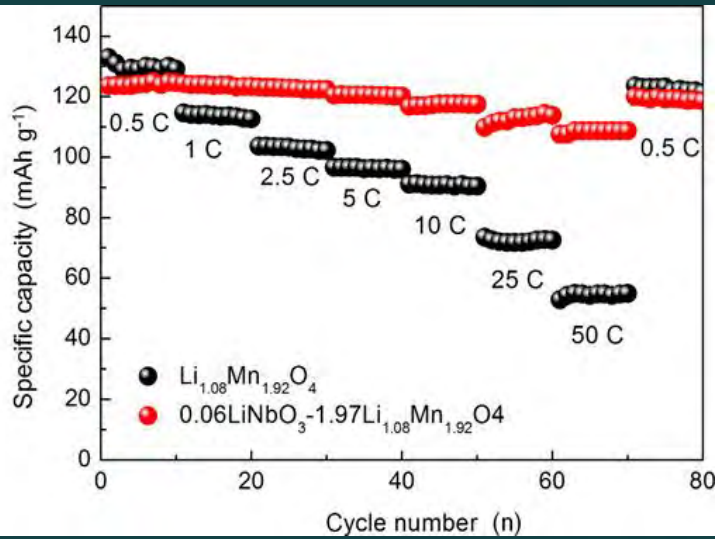
OTHER BENEFITS:

- Higher cycling stability;
- Manganese dissolution prevention;
- Lower charge-transfer resistance.

NIOBIUM INCREASES RATE CAPABILITY / IONIC CONDUCTIVITY

LITHIUM NIOBATE (LN) COATING ON SPINEL-LIKE LMO CATHODE





$0.06LiNbO_3$-1.97 $Li_{1.08}Mn_{1.92}$ O_4

ZHANG et al, **ACS Appl Mater Interfaces** 6 (2014) 22155

NIOBIUM LIFE CYCLE ON BATTERY MATERIALS

1st life

xEVs, e-Buses, e-Bikes, Consumer Electronics

Niobium recycling

2nd life

Energy Storage Systems (ESS)

Home Energy Storage

Niobium based batteries are projected to well over 10,000 charge-discharge cycles with 80% capacity retention

Niobium is a sustainable and safe metal with no harmful and toxic properties

FINAL WORDS

Niobium is poised to be a DISRUPTIVE element for advanced lithium-ion battery materials:

- ✓ Cobalt-free, high-energy, disordered rock-salt (DR) structures for cathodes;
- ✓ Doping to improve capacity retention upon cycling;
- ✓ High power and fast charging Nb-based mixed oxides for anodes;
- ✓ Coating for improving rate capability and ionic conductivity;
- ✓ Improved safety and long battery life.

…