UNIVERSITY OF CAMBRIDGE

A Brief Sprint Through Battery Science

10th Cleanpower Smart Grids 2019, 1-2 July Cambridge, UK

www.cir-strategy.com/events

R Vasant KUMAR

Department of Materials Science

University of Cambridge

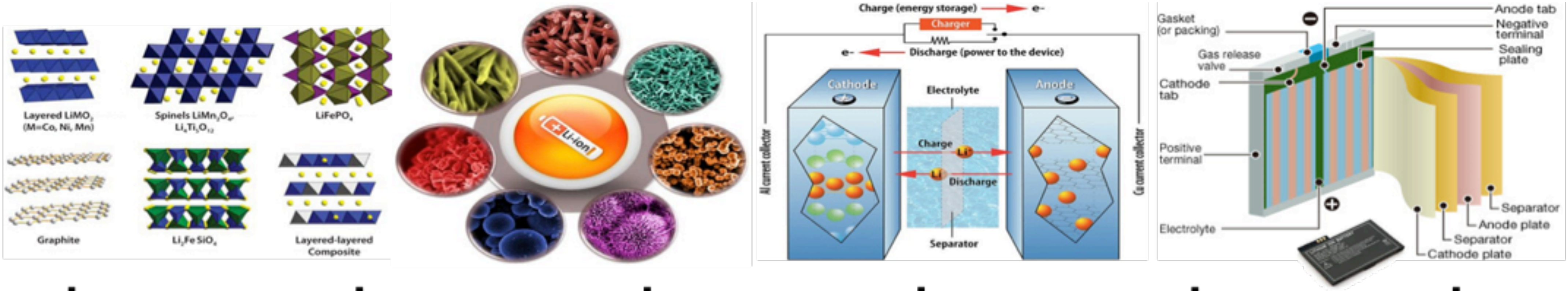
rvk10@cam.ac.uk

High Performance Electrochemical Energy Storage Devices – portable devices, back-up storage, storage with renewables, storage with grid, electrical vehicles

Requirements & Resolution

→ Energy and power are originated from electrode material

+ Performance Cost!! Safety!! for Practical Use

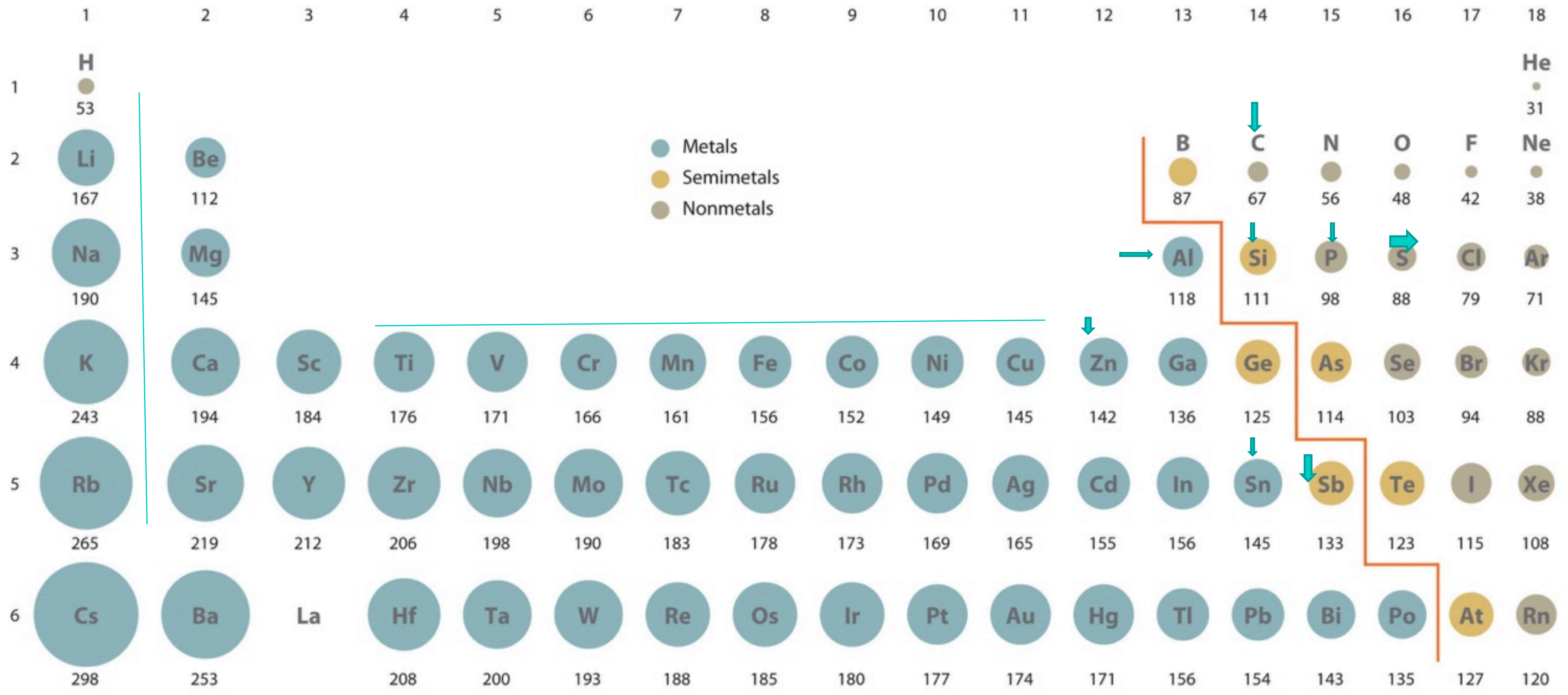


10^{-10} — 10^{-8} — 10^{-6} — 10^{-4} — 10^{-2} — 10^{0} (m)

Design of Materials	Design of Electrode	Design of Electrodes Pairing & Electrolyte	Design of Current and Heat Transport
Voltage Capacitance Lattice stability Kinetic barrier Transport property	Ion supply Electric conductivity Surface area Porosity Structural stability	Electrode selection Electrolyte Charge balance Loading thickness	Electric & thermal Connection Dimension Form factor

----By HK Kim et al

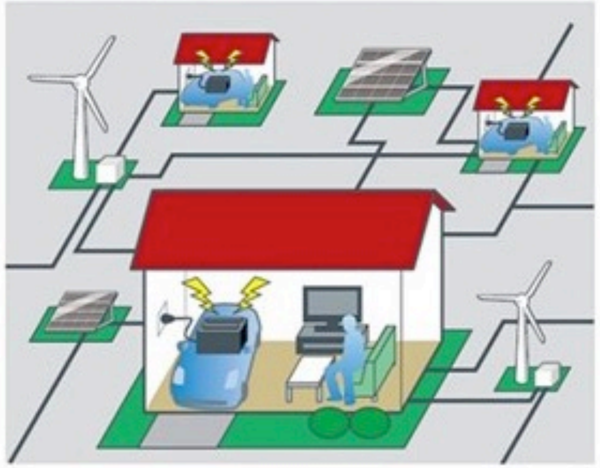
Atomic Radii in Picometres



Batteries are a Key Technology which will Enable the Transition to a Sustainable Society

Energy Storage and Renewable Energy Systems

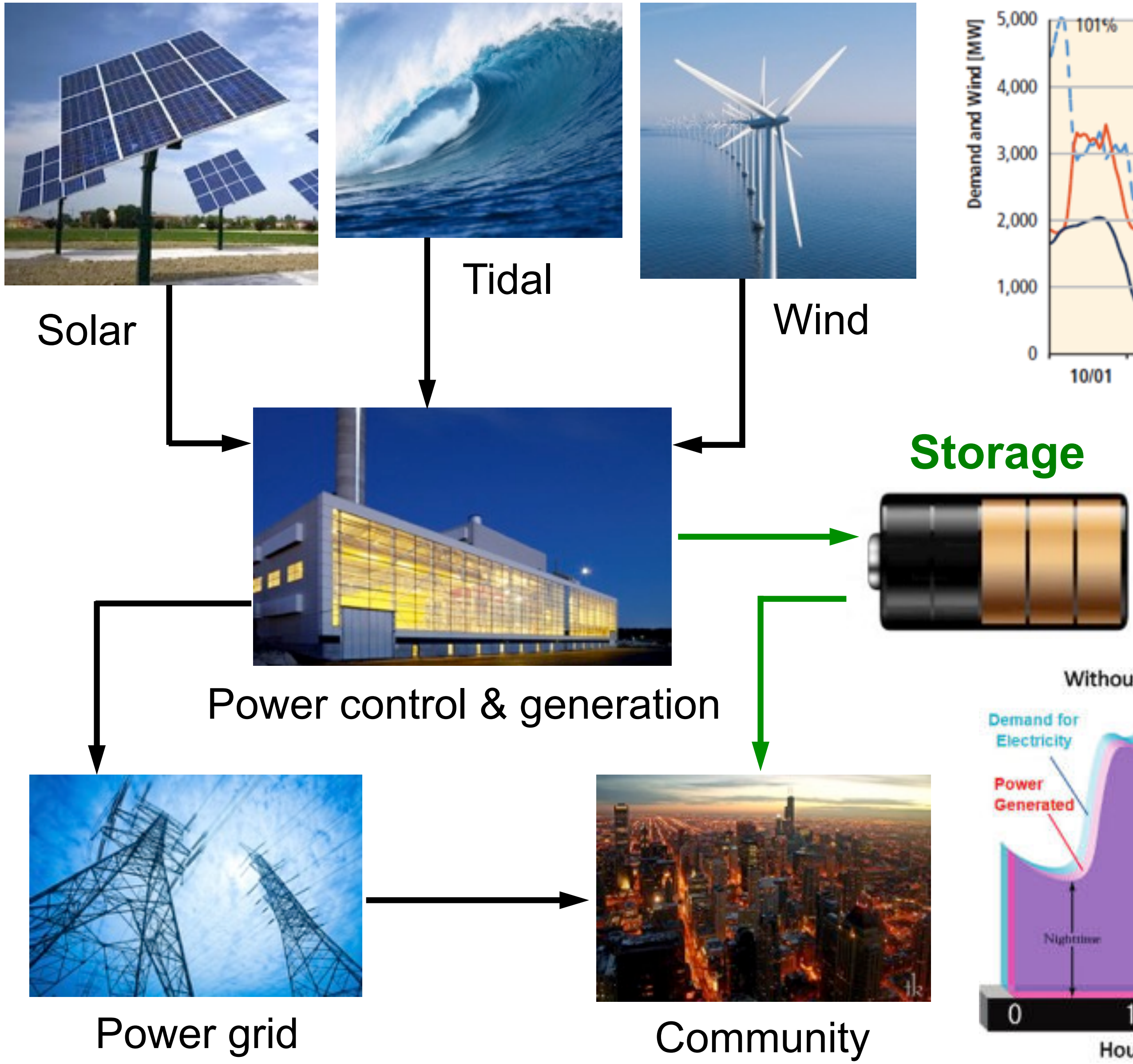
Fostering small, medium scale projects V2G
(integrated into smart grid)

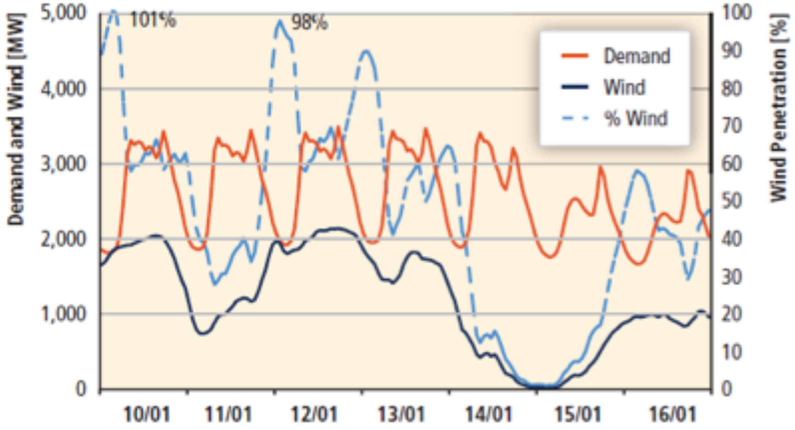


Increasing the system efficiency!!

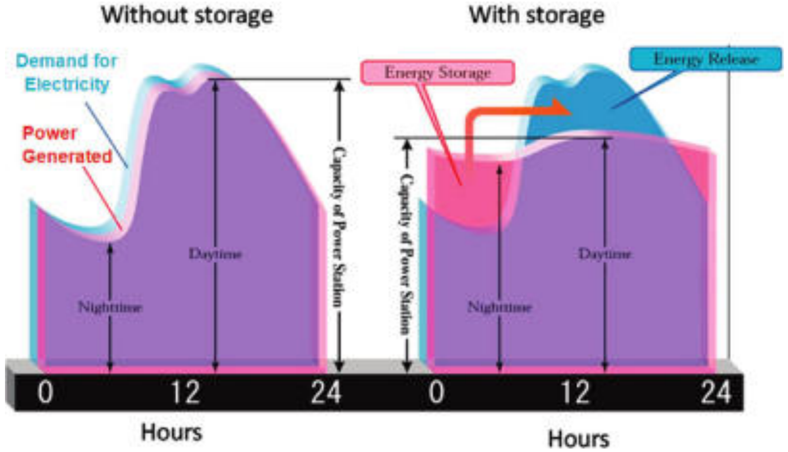
Electric Vehicles

Need for Grid Energy Storage





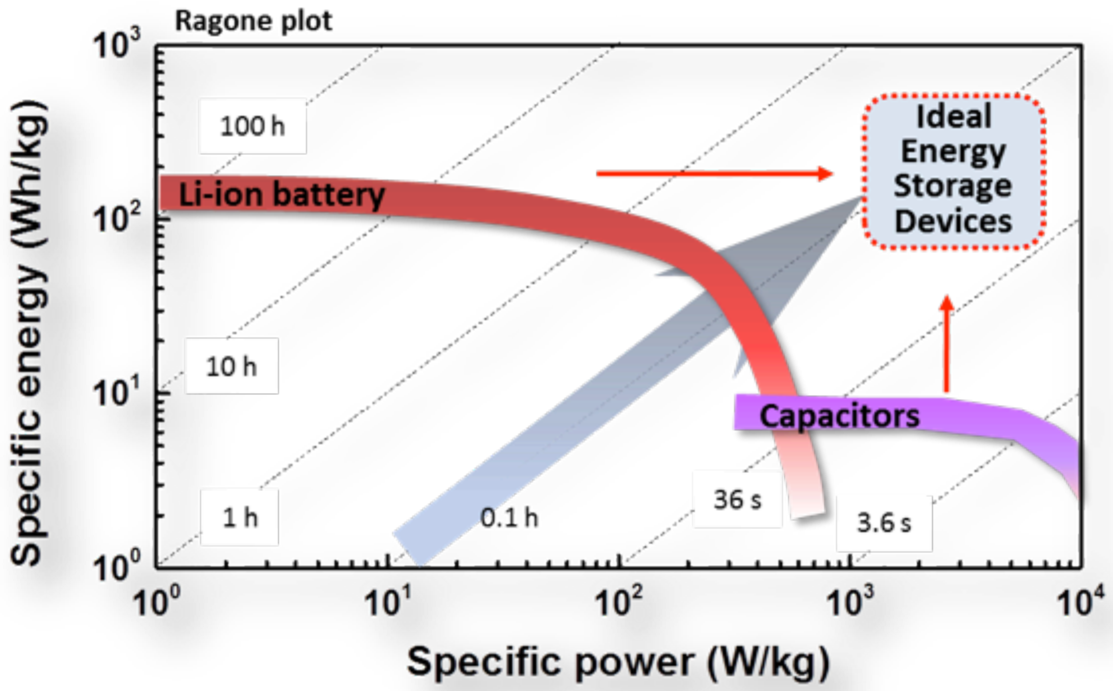
How can excess electricity be utilized?



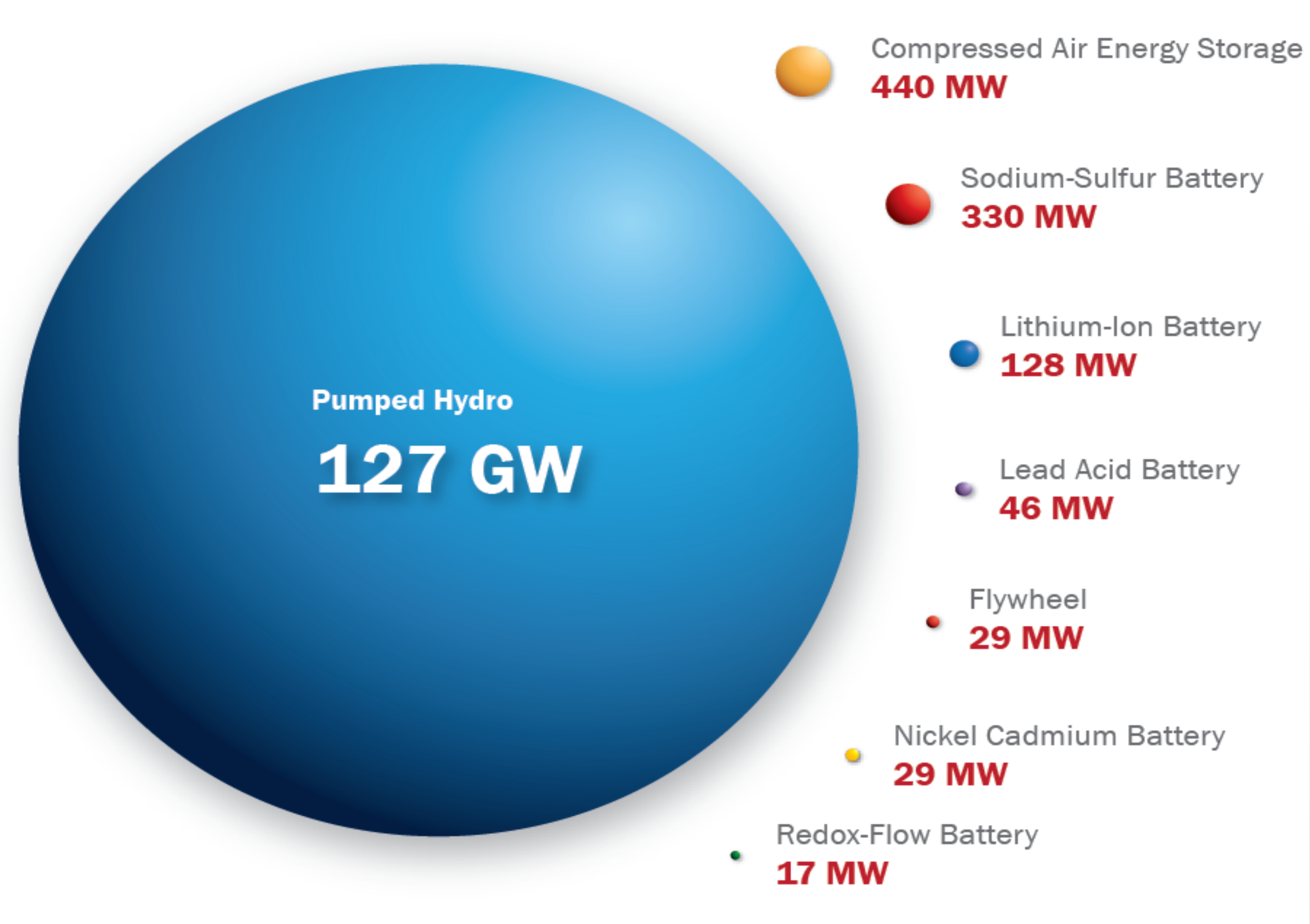
Brushett et al

Electrochemical Energy Storage Devices

Energy storage device with performance characteristics of
high energy density and high power density



Energy : system's capability to do work [Wh/kg]
Power : the rate at which work is performed or energy is converted [energy/time], [W/kg]

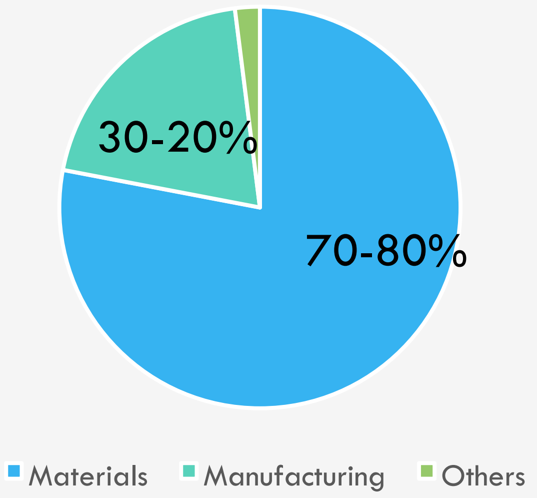


Grid Storage Distribution, 2017

Costs in 100-200 Euros/kWh
And 0.05 per kWh per cycle

Can trade size for life of batteries

Lithium ion Cell Cost Breakdown



- To reduce global warming we need renewable sources therefore we need batteries for storage energy, and we need to have them quickly.

- The batteries manufacturing process is standardized worldwide, there are many industrial plants already built, therefore for quickly implementing new battery technologies, we need to develop new materials compatible with the current industrial manufacturing process utilized for lithium ion batteries.

- We need to reduce the cost of material, furthermore only Lithium would not be enough to power our mobility, our homes and our society.

- Therefore we need to develop also batteries technology based on Na, K, Mg, Ca, Al, Zn…which are more abundant and low cost materials.

Salts mostly present as chlorides (and some sulphates) in wt%

Na 4-6%

K 2-3%

Li 0.2-0.3%

Mg 1 – 3.6 wt%

Ca 0.04 wt%

Solar evaporation concentrates LiCl to over 6 wt%, precipitating NaCl, KCl products

Lithium containing salt-lake

Solubility Data g/100g Water at 20°C

LiCl: 86.2

NaCl: 35.9

KCl: 34.2

$MgCl_2$: 54.6

$CaCl_2$: 74.5

Add lime to remove Mg

$Ca(OH)_2$: 0.16

$Mg(OH)_2$: 0.0009

LiOH: 12.3 (does not form, as LiCl is stable)

Add Na_2CO_3 to Precipitate Li_2CO_3

Na_2CO_3: 21.5

Li_2CO_3: 1.26

Li sold as Lithium Carbonate equivalent (LCE)

ECONOMIC AVAILABILITY OF LITHIUM

- BRINE LAKES LOCATED IN RELATIVELY HIGH ALTITUDES OF 2000 – 5000 M ABOVE SEA-LEVEL (**ABC2**- **A**RGENTINA, **B**OLIVIA, **C**HILE, **C**HINA) [ABC LI TRIANGLE AND TIBET]
- LI CONTENT IN SALT LAKES VARY FROM 0.1 TO 0.15 WT% (IN SEA-WATER IT IS 0.000017 WT%); ALSO FROM LI ROCKS – A GROWING AREA FOR BATTERY GRADE LI (1 – 2.5 WT%) (AUSTRALIA)




Photograph by Noah Friedman-Rudovsky, Bloomberg/Getty Images

MCG
Materials Chemistry Group

SUSTAINABILITY OF LI CELLS

- RECOVERY OF LI FROM RAW MATERIALS OR FROM SPENT BATTERIES BY CONVENTIONAL METHOD IS VERY ENERGY-INTENSIVE AT > 25 KWH/KG OF LI, WHILE ENERGY AVAILABLE FROM A LITHIUM BATTERY RANGES FROM 5 TO 12 KWH/KG OF LI!
- ENERGY DEFICIT PER CHARGE-DISCHARGE CYCLE IS AT LEAST 1KWH/KG OF LI
- IF LI-ION CELLS WERE USED IN AN ESTIMATED 0.1 BILLION EV CARS WORLDWIDE BY 2050, THE DEMAND FOR LI (LCE) WOULD INCREASE FROM 0.34 TO 6 MTPY
- **ENERGY AND MATERIALS SUSTAINABILITY** SHOULD BE CONSIDERED TOGETHER
- ENERGY DEFICIT SHOULD BE GIVEN A HIGH PRIORITY FOR LARGE SCALE USAGE OF LI

Electrode to Electrode Recycling‖Scaffold to Scaffold Recycling|| Reincarnated Battery

AN IMPORTANT POINT TO PONDER

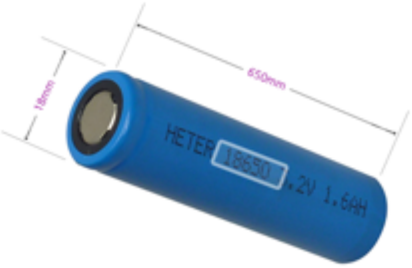
WHILE 1 KG OF GASOLINE CAN GENERATE 15X MORE ENERGY THAN 1 KG OF LI, SPENT GASOLINE CAN NEVER BE RECYCLED, BUT IN PRINCIPLE (AND SOON IN PRACTICE) 100% OF LI CAN BE (AND WILL BE) RECYCLED AT LOW NET ENERGY CONSUMPTION!

INCREASING ELECTRICITY FROM RENEWABLE SOURCES

LOWER "BILL OF MATERIALS", CAPEX AND OPEX

OTHER CRITICAL MATERIALS – COBALT, VANADIUM, TIN, RARE EARTHS, NICKEL, COPPER..

Lithium-ion Batteries



NCA - Graphite

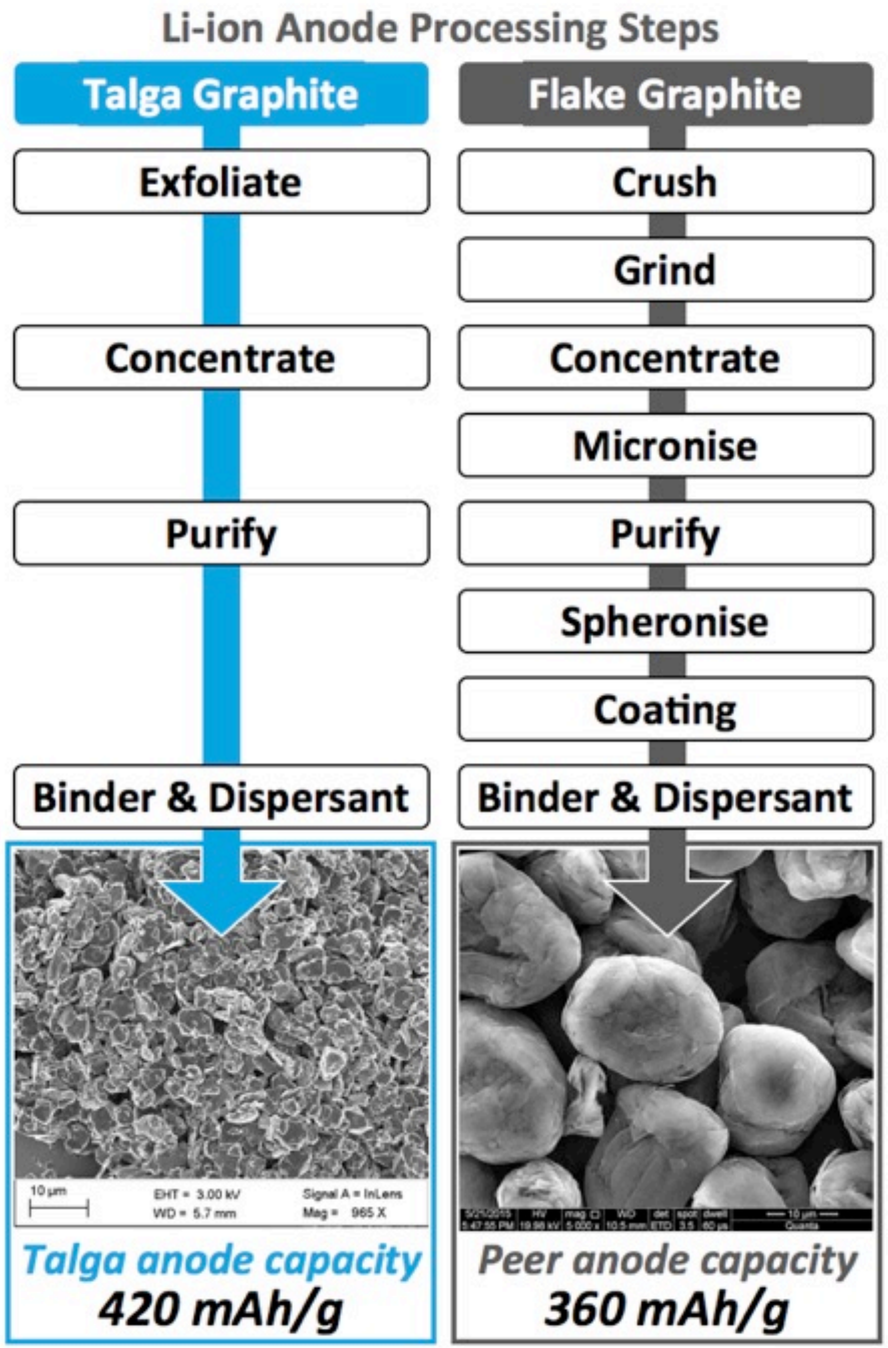
5000~7000 small batteries
(18650 size, 18 mm diameter x 650 mm height)

CATHODE MATERIALS FOR LI-ION BATTERIES – L: Li; C-Co; N: Ni; M: Mn; A: Al; F: Fe: P: Phospate; O:O

- LCO – HIGH CAPACITY, LOW SELF-DISCHARGE, HIGH VOLTAGE, GOOD CYCLING [HIGH COSTS, LOW THERMAL STABILITY, CAPACITY FADE AT HIGH RATES OD DEEP CYCLING] – HISTORICAL, MAINSTAY OF PORTABLE ELECTRONICS, UNIQUE COBALT CATALYSIS
- NCA – HIGH USABLE CAPACITY, LOW SELF DISCHARGE AT RT, LONG LIFE, GOOD CYCLING, MODERATE COSTS AS NICKEL/COBALT RATIO IS >5 [SERIOUS CAPACITY FADE AT T> 40C DUE TO NICKEL CATION DISORDER, SAFETY ISSUES] – PANASONIC TESLA EV BATTERIES
- LFP – SAFETY GOOD, LOW SELF DISCHARGE, GOOD FOR DEEP CYCLING, LOW COST [LOW ENERGY]
- NMC – DECREASING COBALT CONTENT TO LOWER COST[111, 532, 622, 811]

ANODE MATERIALS FOR LIBS

- GRAPHITE – NATURAL OR SYNTHETIC
- HARD CARBON – COMBINES GRAPHITIC REGIONS WITH MICROPOROUS REGIONS FOR LI STORAGE IN MICRO-VOIDS [HIGH CAPACITY] – GOOD FOR SODIUM ION BATTERIES
- SILICON – HIGH CAPACITY, LOW COST [LARGE VOLUME CHANGE, RAPID CAPACITY FADE]
- CARBON- SILICON - IMPROVED PERFORMANCE
- NIOBATES – SAFER AND MORE RELIABLE [ALSO SUITABLE FOR SODIUM ION BATTERIES]
- LITHIUM – SAFETY ISSUES



PROCESS ADVANTAGE - BATTERIES

Talga's patent pending technology liberates conductive material from raw graphite ore, skipping processing steps required by peers

higher performance with less manufacturing steps = lower eco-impact

Unmilled Talga micrographite anode shows promising results of 420mAh/g, higher capacity than graphite theoretical limit 372mAh/g

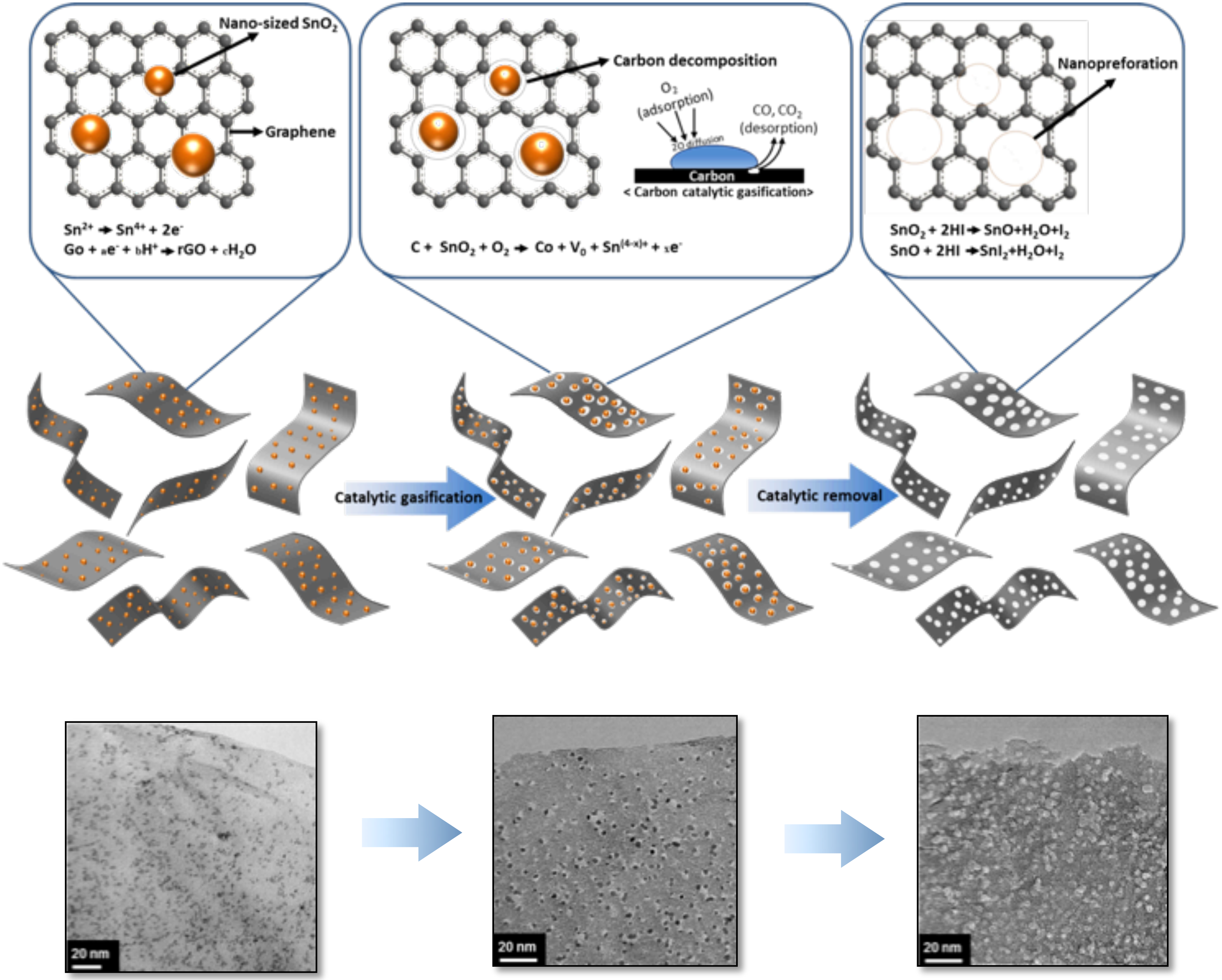
Excellent stability with 99.9% coulombic efficiency and low capacity loss (reversible capacity >99.5%)

Graphene is more conductive than graphite, enabling faster charging and longer life cycle, and role across multiple new battery types going forward.

Water-based environmentally friendly coating technology

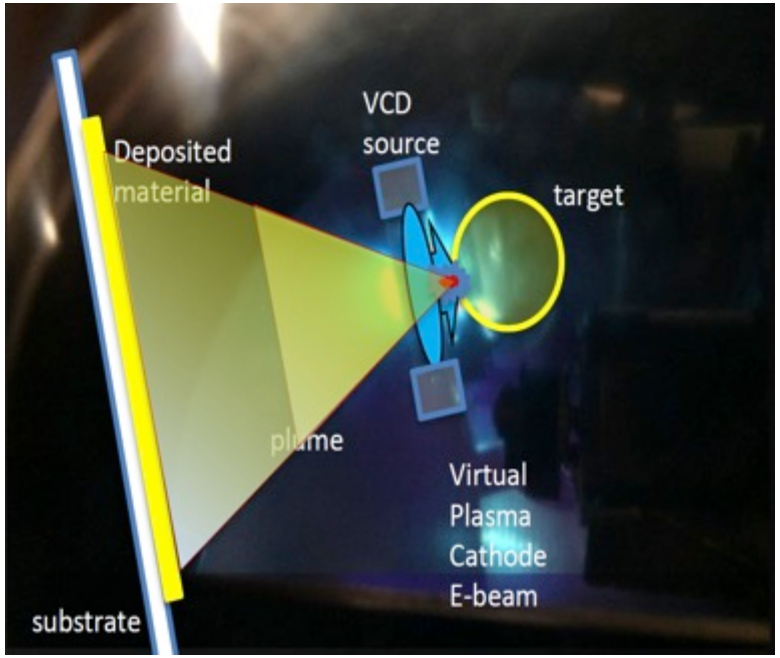
For video see https://www.youtube.com/watch?v=xrp4Nzle-B8&feature=youtu.be

Catalytic Carbon Gasification – Graphene Nano-Mesh!

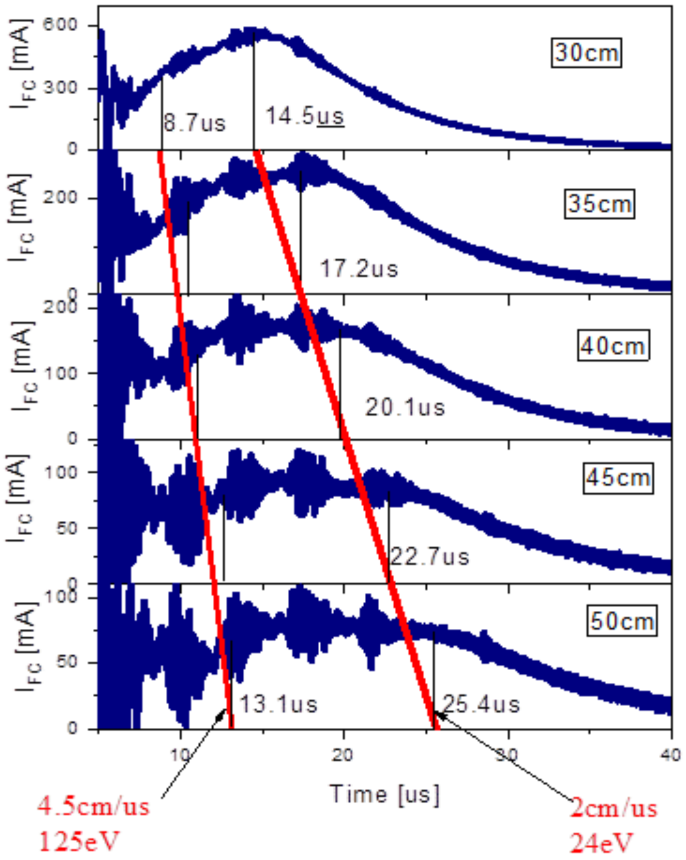


--By HK Kim et al EES,2016

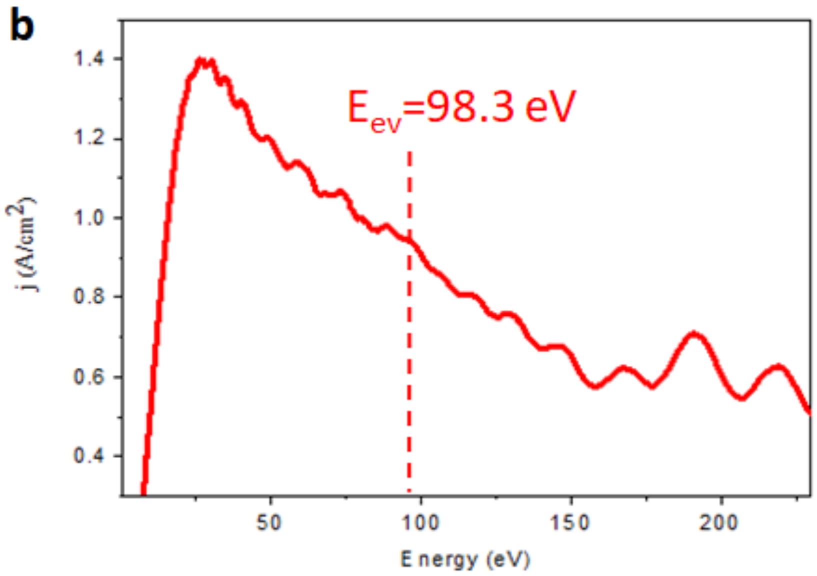
CARBON ION PLUME GENERATION WITH VIRTUAL CATHODE DEPOSITION (PLASMA)



VCD Generates Plume of Carbon Ions from Graphite Target



TOF of Carbon Ions



Energy Distribution

CALIB (ACRONYM)

NOVEL CARBON ALLOTROPE FOR LITHIUM ION BATTERIES

The project goal is to develop a new type of Li-ion battery anode based on a totally new form of carbon material containing in-situ graphene regions - Carbon Allotrope for Lithium Ion Batteries (CALIB).

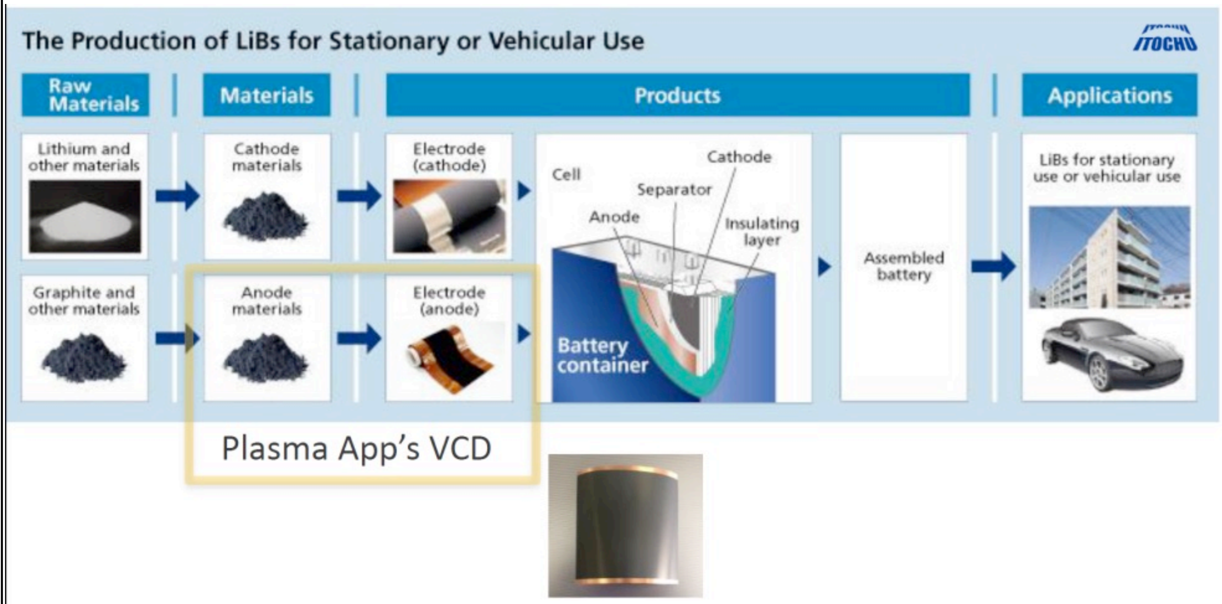
Use of CALIB as active anode material allows

- Specific capacity increase
- Cycle-life improvement

Virtual Cathode deposition method for the anode electrode manufacturing enables

- One-step manufacturing process
- High purity of the materials without binders
- Automated process

PLASMA APP	Anode & Cathode manufacture
UNIVERSITY OF CAMBRIDGE	Materials characterization & test
JM Johnson Matthey Inspiring science, enhancing life	Battery manufacturing & test



A mix of 2D and 3D composite porous structured electrodes and thin, dense solid electrolytes;

Patent Pending – Yarmolich, Kumar,Zhao, Kim Tomov et al

Challenges and Opportunities

Lithium Ion Battery (LIB) Market Potentially Worth $80 Billion by 2022 Led by Automotive Industry (Source: RnRMarketResearch)

New Lithium-Sulfur Battery compete with LIBs, in costs for off-grid storage

Commercialization of lithium–sulfur batteries has so far been limited due to the cyclability problems associated with both the sulfur cathode and the lithium–metal anode.

Projects to overcome the technical challenges and lead a new wave of Li-S battery commercialization.

Gleb Ivanov, RV Kumar, Lei Wang

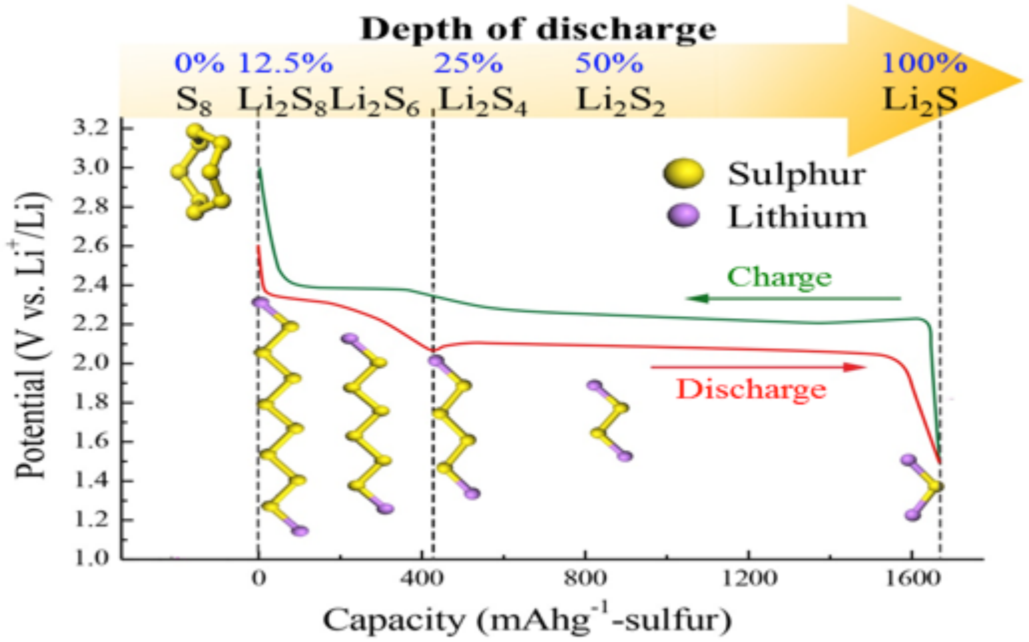
LI-S BATTERIES – IN TRANSPORTATION, POTENTIALLY LOWER COST, HIGHER ENERGY DENSITY

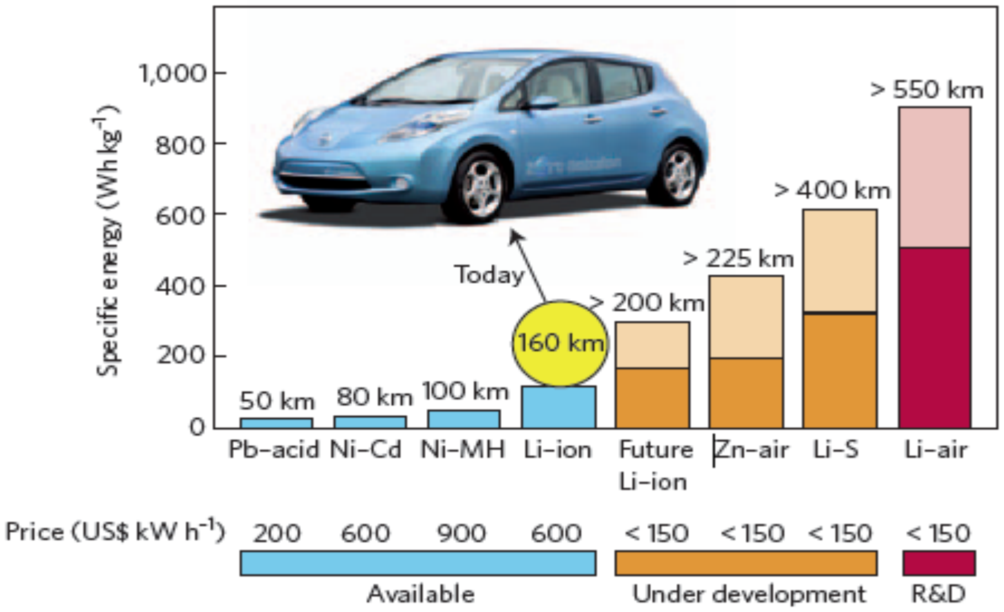
$$2Li^{+}+2e^{-}+S \leftrightarrow Li_2S$$

1675 mAh g^{-1} of S
2600 Wh kg^{-1} or 2800 Wh l^{-1} of cell

Voltage hysteresis: 0.2-0.3V;
shuttling; capacity fade

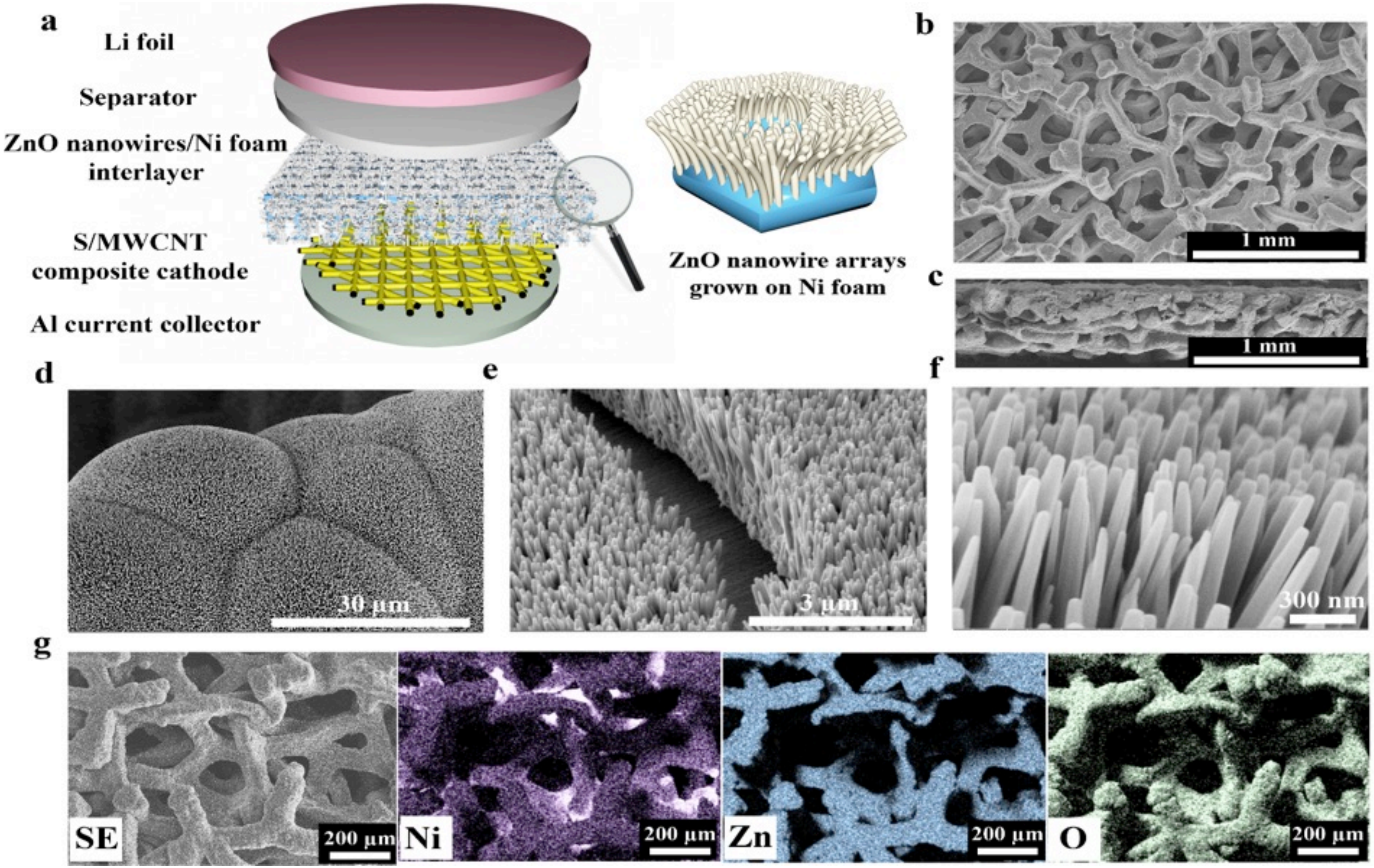
High Energy





Nature Materials, 2012, 11: 19-29. & *Nano Energy*, **2015**, 12, 538-546.

Gatekeepers to control Shuttling of Sulphur, improved cycle life, safety



--By T Zhao, et al, Adv. Funct. Mater. 2016, 26, 8418–8426

Thanks for your attention