UNIVERSITY OF CAMBRIDGE

A Brief Sprint Through Battery Science

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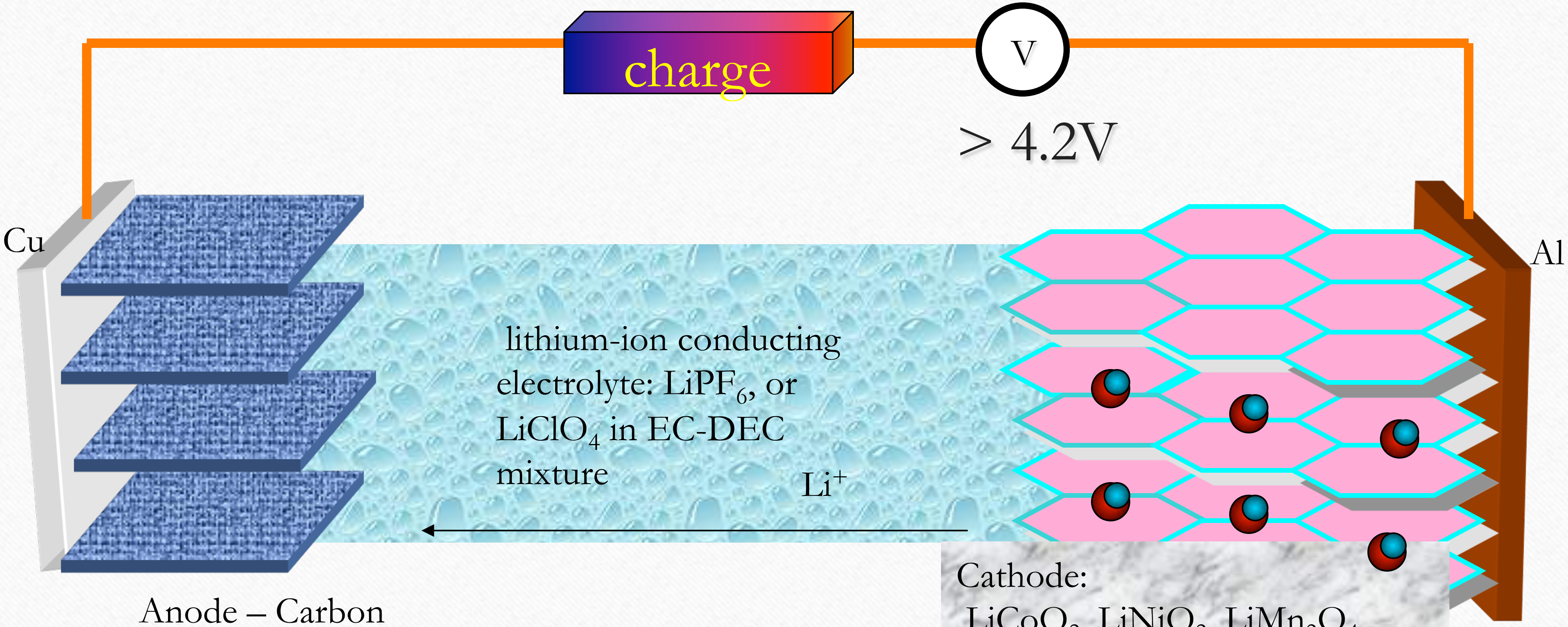
Formation of a Li-ion battery↔ by in-situ Electrochemical transfer of Li from Cathode to Anode



Anode – Carbon (Graphite)

Cathode:
$LiCoO_2$, $LiNiO_2$, $LiMn_2O_4$, NMCs, $LiCoAlO_2$, LFP

Lithium-ion Batteries

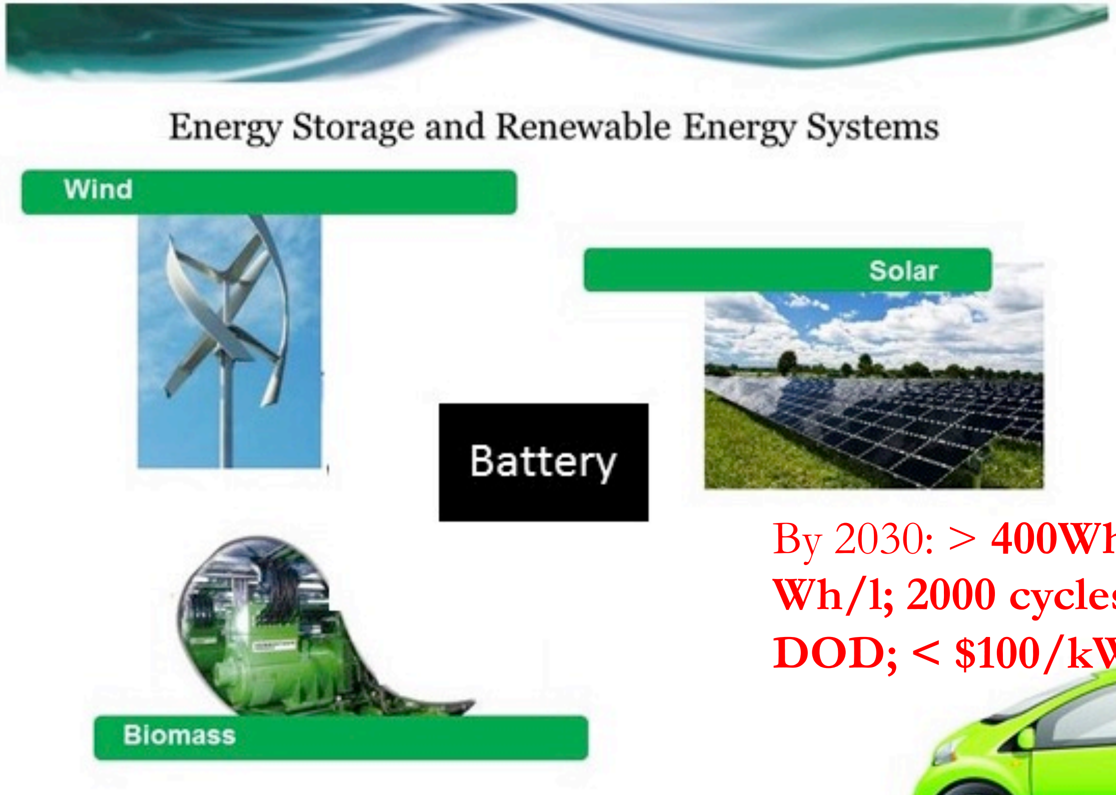
In 1995,
$3000/kWh!

NCA –
NiCoAl Cathode
Graphite Anode

11000 small **18650 cells**

(85 kWh, 170 Wh/Kg, 500 Wh/l, $200/kWh, $17,000 pack cost,
200-260 miles range, 1000 cycles;
(Charging at 480 V dc, 120 kW, 30 minutes)

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



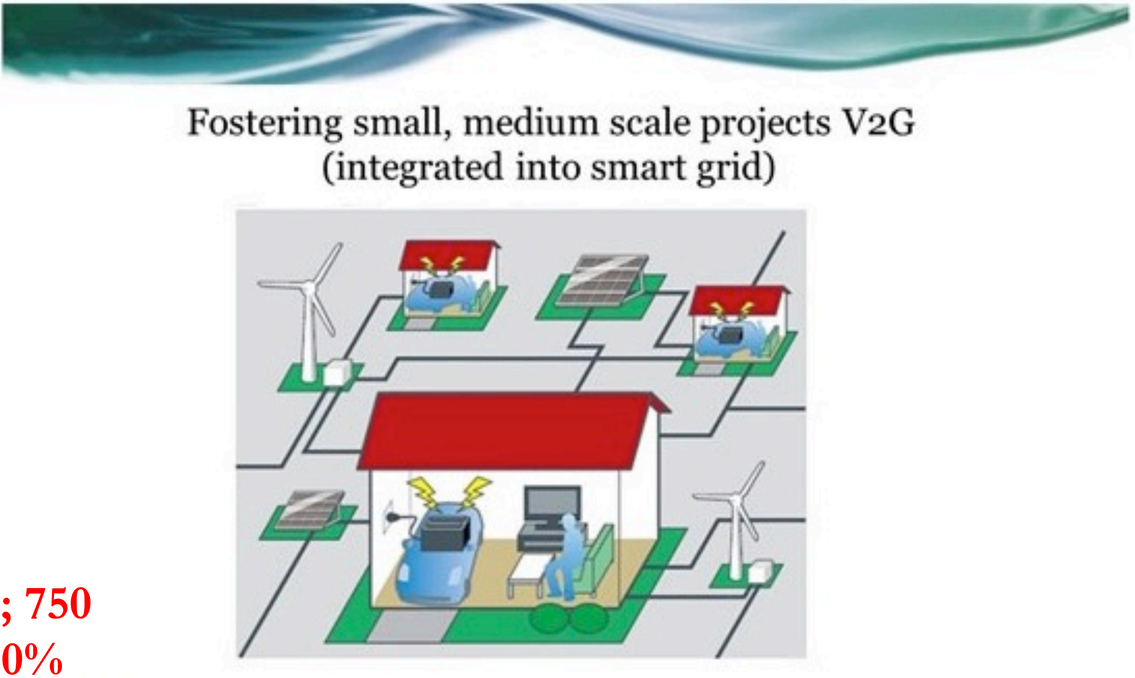
Energy Storage and Renewable Energy Systems

Target cycle costs $0.05/kWh/cycle; 3000-5000 cycles; safe; recyclable

By 2030: > **400Wh/Kg; 750 Wh/l; 2000 cycles at 80% DOD; < $100/kWh**

Electric Vehicles

<12 minutes charging time;
Safe, 2nd life, Recyclable



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

Increasing the system efficiency!!

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]
- **NMCs** – 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, high energy, requires progress in more stable electrolytes

Economic Availability of Lithium Carbonate Equivalent (LCE)

- **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]-300,000 tpy LCE ($15-25/Kg LCE)
- 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)- 300,000 tpy LCE (x2 CAPEX)

Photograph by Noah Friedman-Rudovsky, Bloomberg/Getty Images

Important points 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! [Research Phase]
- Increasing electricity from **renewable sources** for manufacturing, charging, recycling
- Lower "bill of materials", CAPEX and OPEX- at $100/kWh (achievable by 2022-25?) will be a tipping point, when EV powertrain net system costs comparable to ICE powertrain
- Other Materials – **cobalt, vanadium, tin, rare earths, nickel, copper, graphite**..
- Betting on **NMC811** to dominate LIBs, demand for Ni, Co, Li will increase dramatically
- Assuming 20% EV penetration in 2025, 40% in 2030, tonnes per year demand:
- **Ni:** 46,000 tpy→ 827,000 (2025)→3,000,000 (2030) **Co:** 13,000 →194,000→670,000
- **Li:** 14,000 →234,000→852,000
- **Co** will a bottleneck (despite NMC811) **- recycling** will become key in the supply-chain!

Important points to ponder

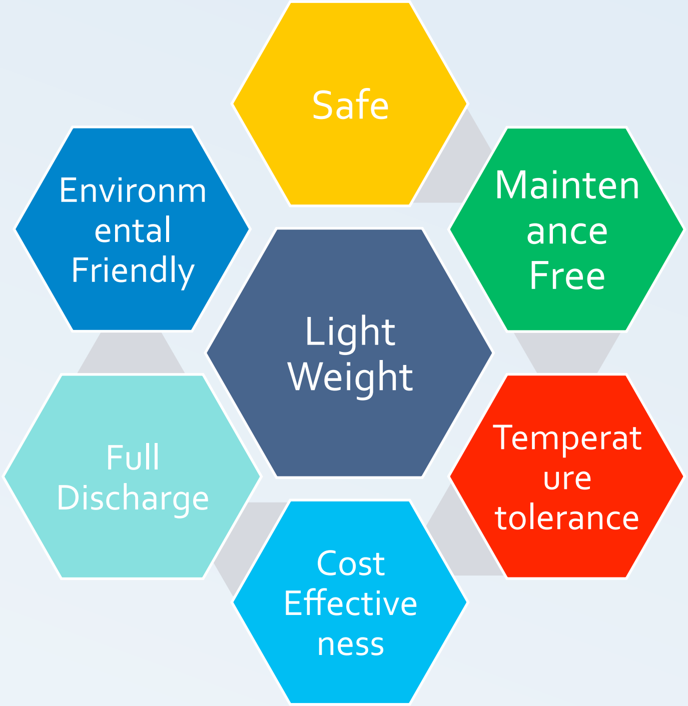
- For 40% BEV penetration by 2030, will require ***60 Giga factories*** (from ***5*** now) – market will be dominated by China and EU – Innovations centred also in the UK, USA, Japan, S Korea, Taiwan, Singapore
- Europe plans to achieve 250 GWh per year in 20 years ***(50 Giga factories!)*** and zero – carbon economy by massive change in transportation, renewable energy source, buildings, industry, carbon capture and sequestration or utilization
- Demand for **Li, Ni, Co, Mn, Graphite, Si, catalytic materials, V, Cu, Al, Sn, REE, organic solvents, separators, ceramics, polymers** ….will dramatically increase
- Infrastructure changes, charging stations, off-grid energy….

Challenges and Opportunities

Lithium Ion Battery (LIB) Market Potentially Worth $80 Billion by 2022 Led by Automotive Industry (Source: RnRMarketResearch, 2014)

Euro Batteries forecast/ambition to achieve 250b Euro Battery market in Europe in 2025-2030!

Can Lithium-Sulfur Battery compete with LIBs, in costs and performance?



Safe

Environmental Friendly

Maintenance Free

Light Weight

Full Discharge

Temperature tolerance

Cost Effectiveness

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.

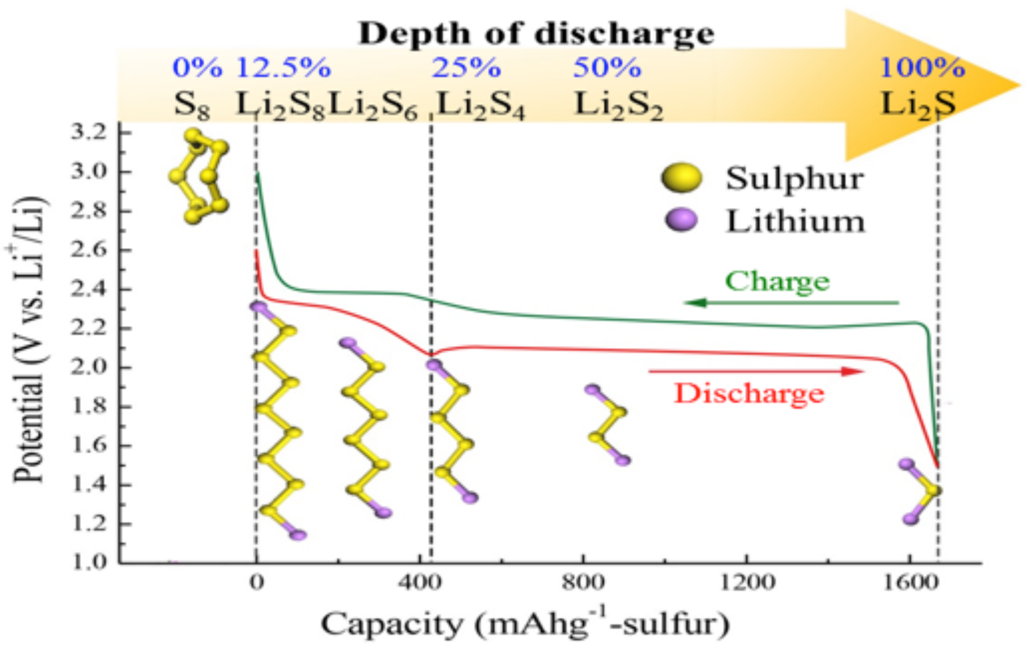
LI-S BATTERIES – IN TRANSPORTATION, POTENTIALLY LOWER COST, HIGHER ENERGY DENSITY

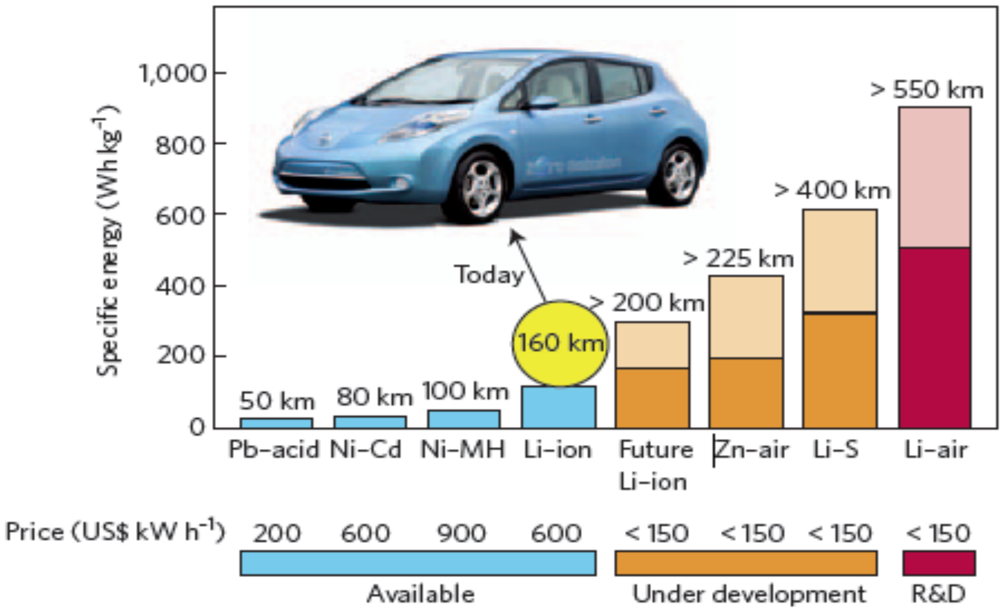
$$\boxed{2Li^{+}+2e^{-}+S \leftrightarrow Li_2S}$$

Capacity fade, sudden death, from shuttling of soluble Li_2S_x via electrolyte

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

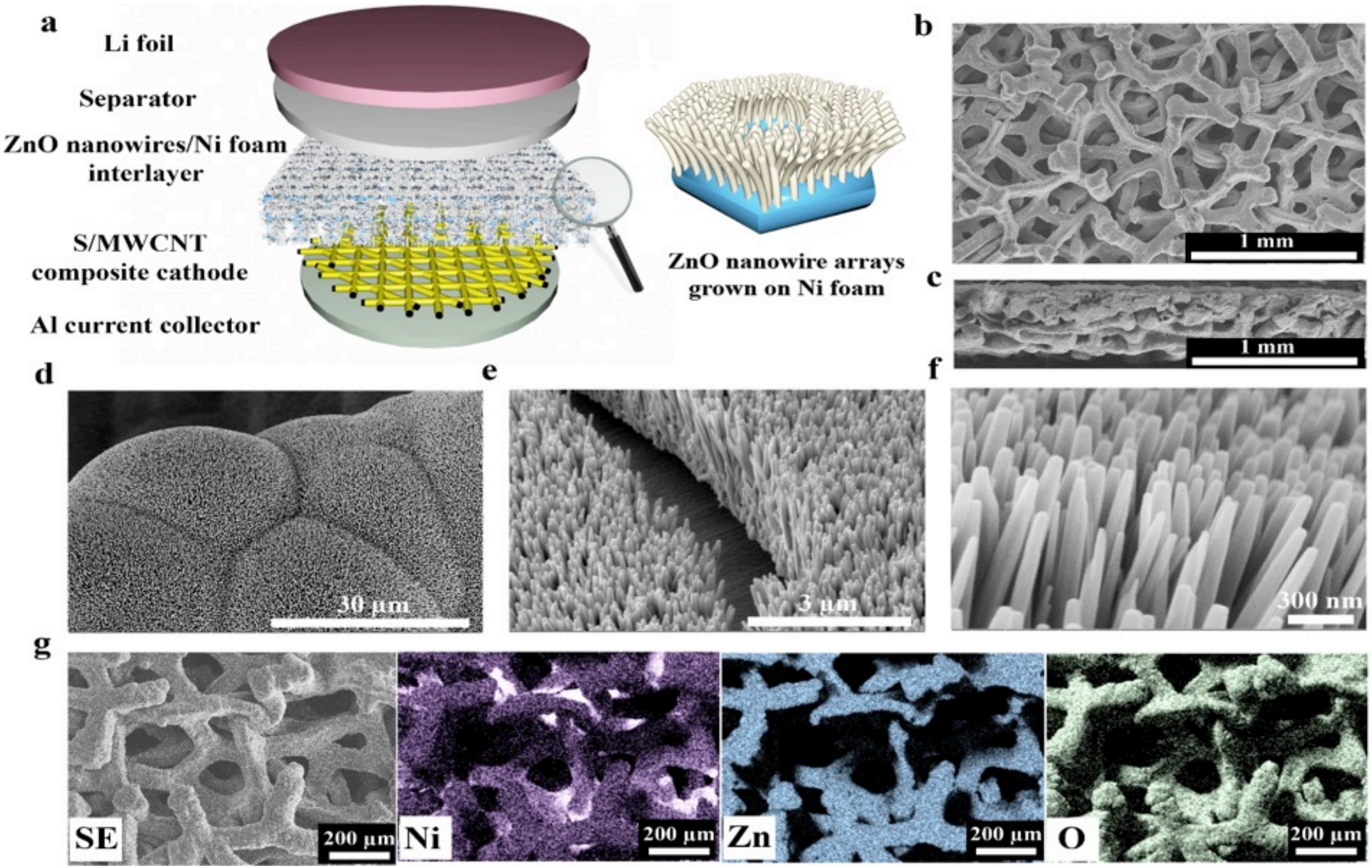
High Energy





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, RV Kumar et al, Adv. Funct. Mater. 2016, 26, 8418–8426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Thanks for your attention