MINISTRY OF BUSINESS, INNOVATION & EMPLOYMENT
HĪKINA WHAKATUTUKI

ROYAL SOCIETY
TE APĀRANGI

The MacDiarmid Institute
for Advanced Materials and Nanotechnology

Energy Education
Trust of New Zealand

Next-Generation Batteries

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Fellow – New Zealand Institute of Chemistry
Fellow – Royal Society of Chemistry

Outline of this Seminar

This seminar will introduce some of the new rechargeable battery systems being developed for the energy sector. Topics that will be touched upon include:

- Global energy outlook & the need for renewables
- Challenges around renewable energy storage at scale
- Current rechargeable battery systems and their limitations
  - Lead-acid batteries
  - Li-ion batteries
- Emerging battery technologies
  - Metal-air batteries
  - Redox flow batteries

I'm particularly interested in how these emerging batteries technologies could be used alongside Green Hydrogen to **decarbonization of the global energy sector**.

Bio – Geoffrey Waterhouse

I was born in Auckland, completed all my primary, secondary, and tertiary education (BSc, MSc and PhD) in Auckland, postdoc'd at Massey University (2004-2007), before returning to the University of Auckland in 2008 (where I have been firmly entrenched ever since!)

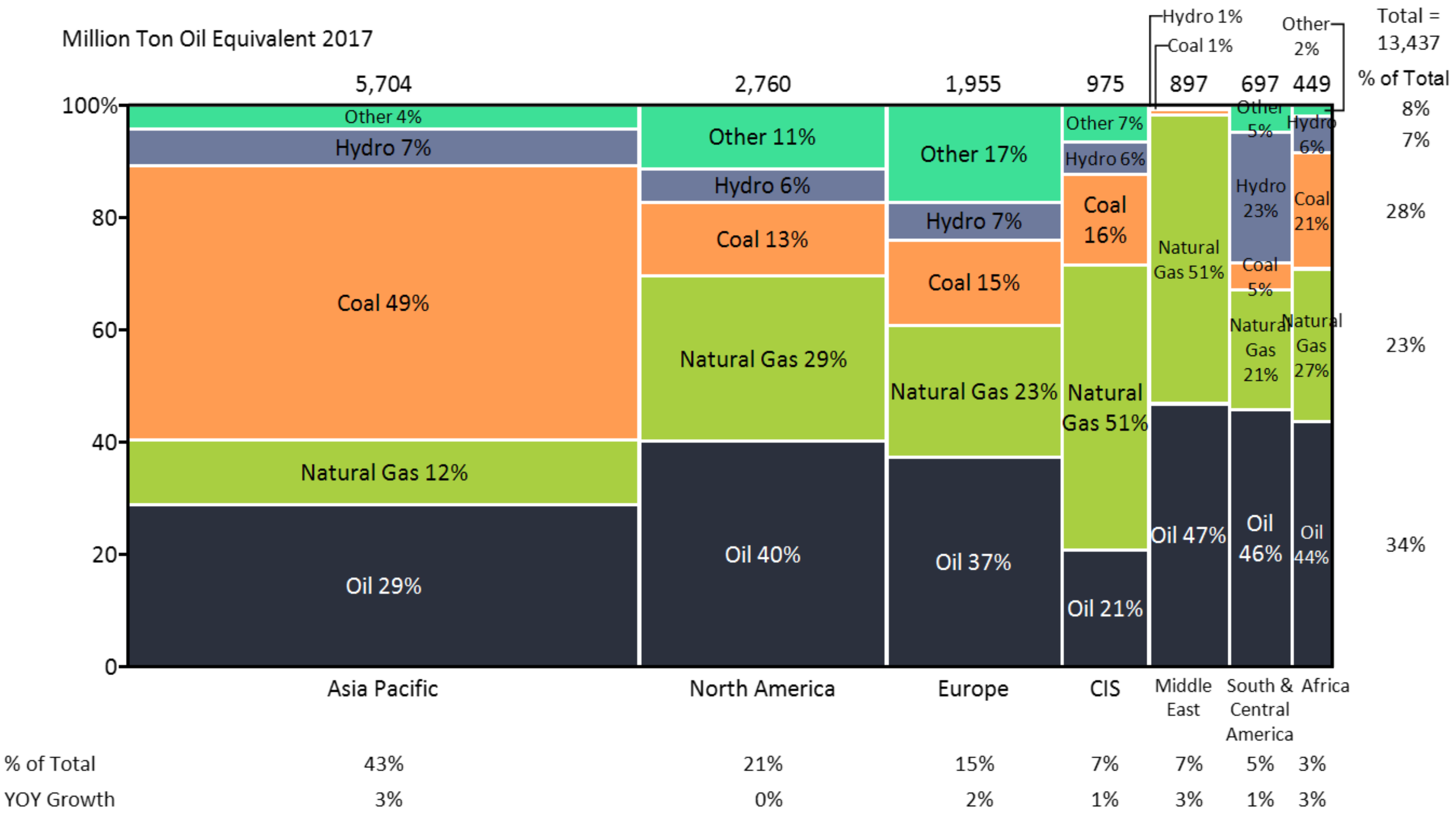
I was awarded the 2023 MacDiarmid Medal from the Royal Society Te Apārangi for discovering low-cost nanocatalysts critical to global decarbonisation efforts and creating energy infrastructures based around renewables.

Prof. Waterhouse receiving the MacDiarmid Medal from the Governor General of New Zealand, Dame Cindy Kiro, at Government House, Wellington, November 23, 2023

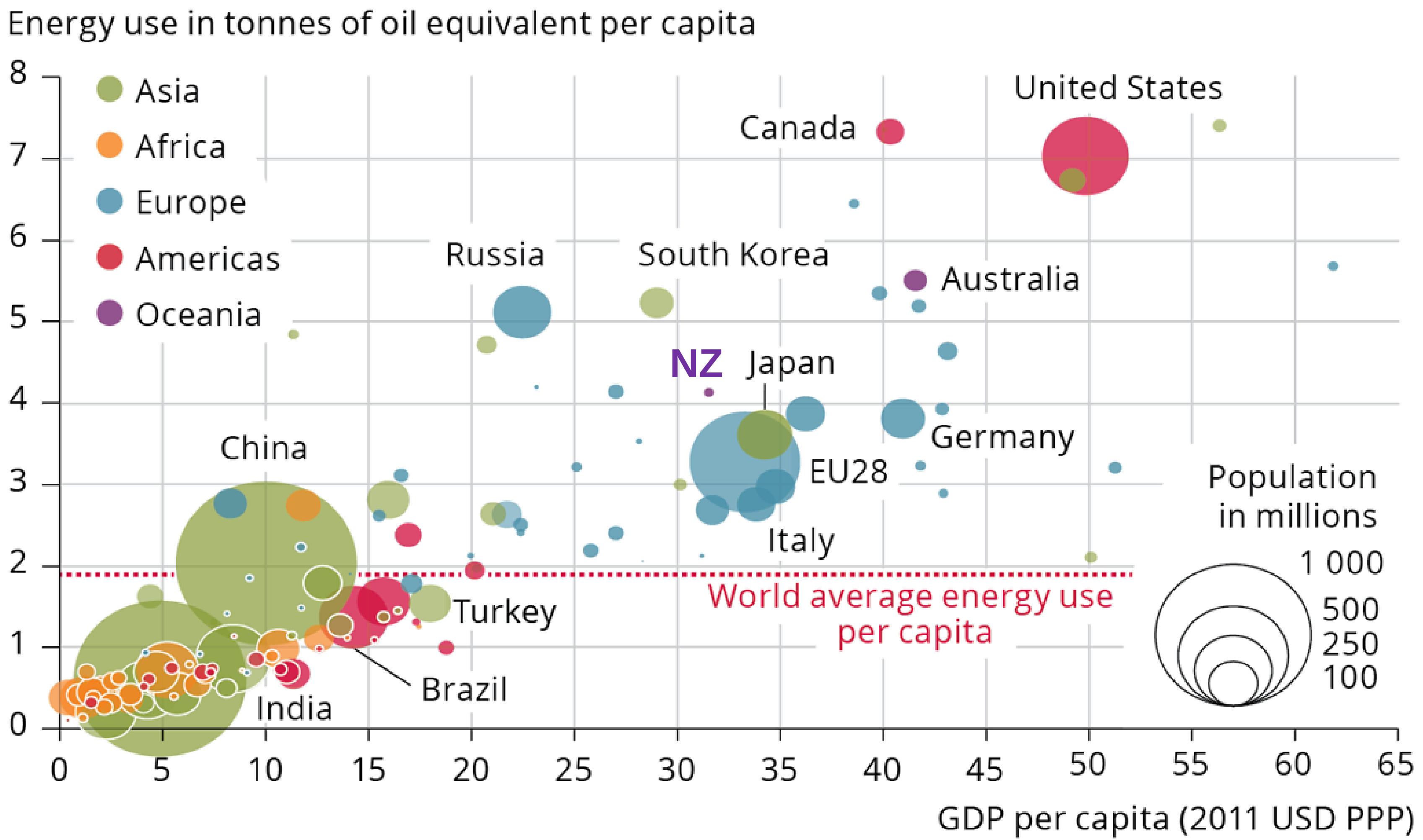
Powering the Planet – Energy Challenges

Modern societies remain heavily dependent on **fossil fuel energy**, in-spite of the strong link between fossil fuel use and global warming.

The **Asia-Pacific Region** consumes 43% of energy resources (half of which is coal) and consumption is growing at 3% year-on-year (https://www.mekkographics.com)



Powering the Planet – Energy Challenges

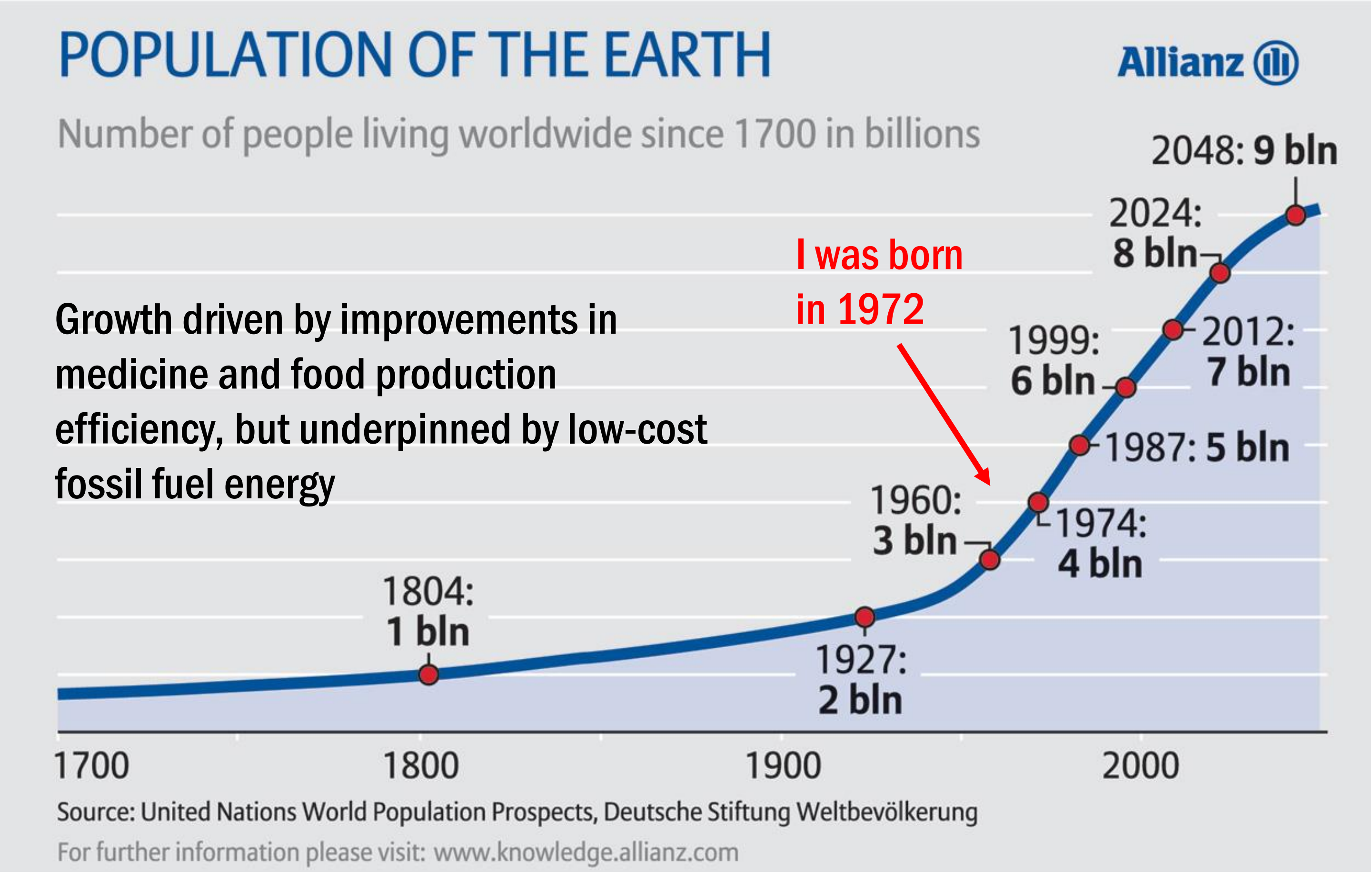


Total energy consumption: 13.5 TW in 2001, <u>16 TW currently</u>, 28 TW by 2050, 43 TW by 2100

China's GDP per capita now 12,621 USD and New Zealand's GDP per capita now 47,000 USD

Population Growth

- Since 1960, the human population on Earth has increased by ~1 billion every 12 years.
- Over the same period the average temperature on Earth has increased by ~1 °C.



POPULATION OF THE EARTH

Number of people living worldwide since 1700 in billions

Growth driven by improvements in medicine and food production efficiency, but underpinned by low-cost fossil fuel energy

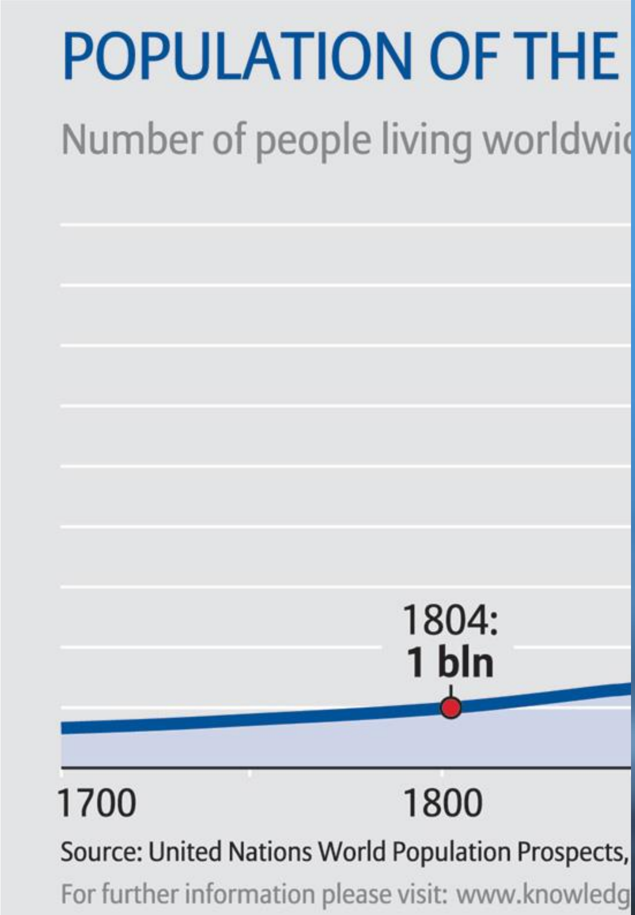
I was born in 1972

Source: United Nations World Population Prospects, Deutsche Stiftung Weltbevölkerung

For further information please visit: www.knowledge.allianz.com

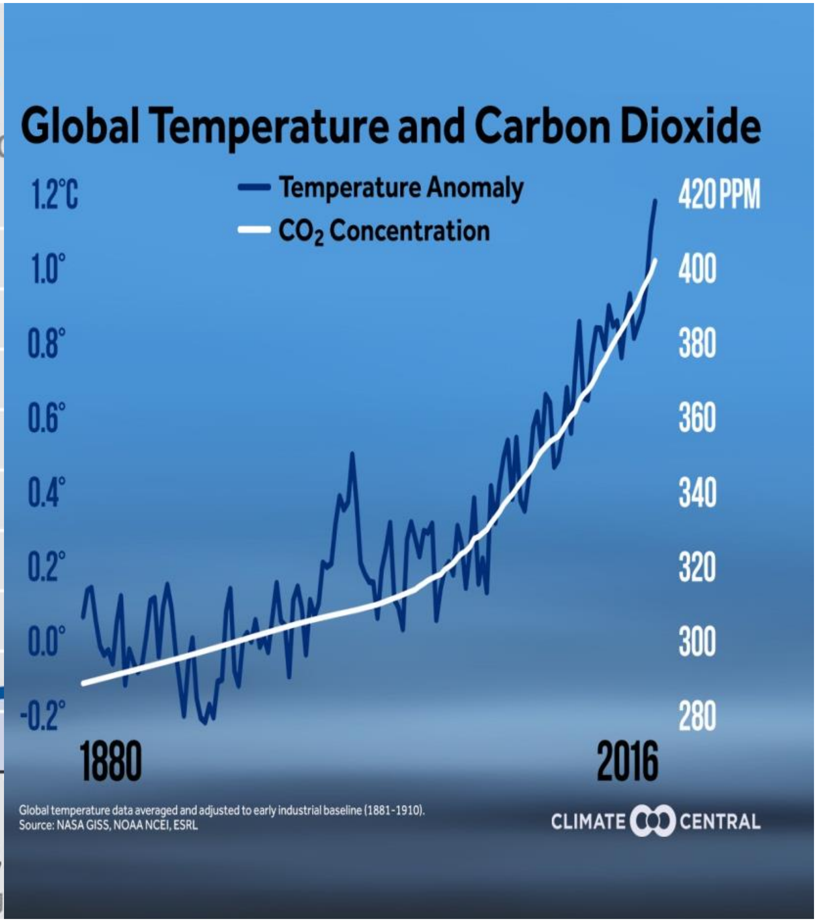
Is Global Warming Real?

Increasing global temperatures are leading to increased incidences of extreme weather events (floods, droughts, typhoons, etc.) and losses in biodiversity.



Source: United Nations World Population Prospects,

For further information please visit: www.knowledg



Global temperature data averaged and adjusted to early industrial baseline (1881-1910).
Source: NASA GISS, NOAA NCEI, ESRL

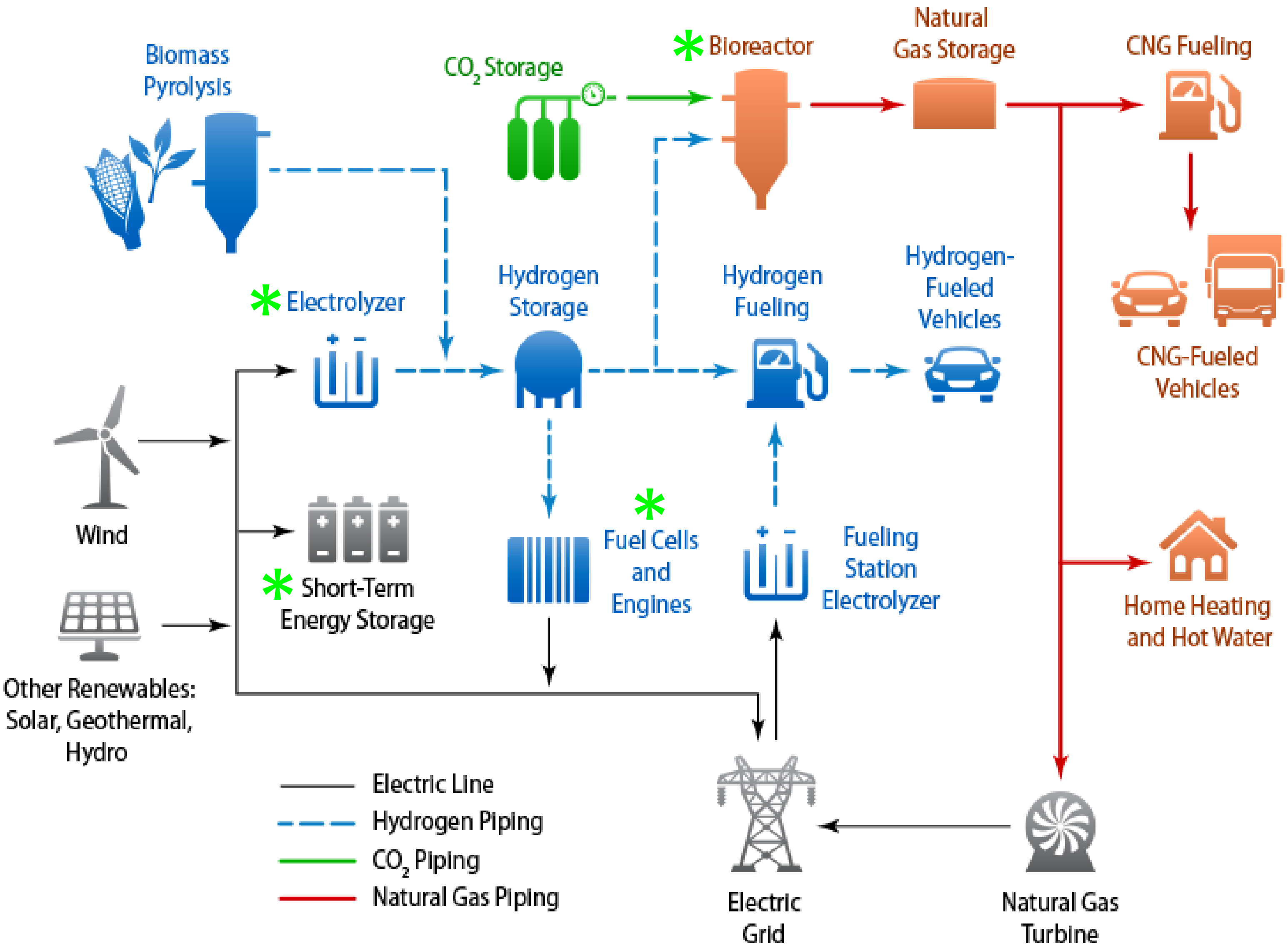
Urgent action is needed to avoid the worst impacts of global warming. Decarbonization of the global energy sector is an imperative.

What Will the World Look Like in 2050 or 2100?

Fishing for Seagulls

A vision of the future from 1899 (Jean-Marc Cote and other artists). A futuristic postcard presented at the 1900 World Exhibition in Paris, showing how nineteenth century artists envisioned France in the year 2000.

Decarbonizing using Batteries and Green Hydrogen



Biomass Pyrolysis

CO$_2$ Storage

* Bioreactor

Natural Gas Storage

CNG Fueling

CNG-Fueled Vehicles

* Electrolyzer

Hydrogen Storage

Hydrogen Fueling

Hydrogen-Fueled Vehicles

Wind

* Short-Term Energy Storage

* Fuel Cells and Engines

Fueling Station Electrolyzer

Home Heating and Hot Water

Other Renewables: Solar, Geothermal, Hydro

Electric Grid

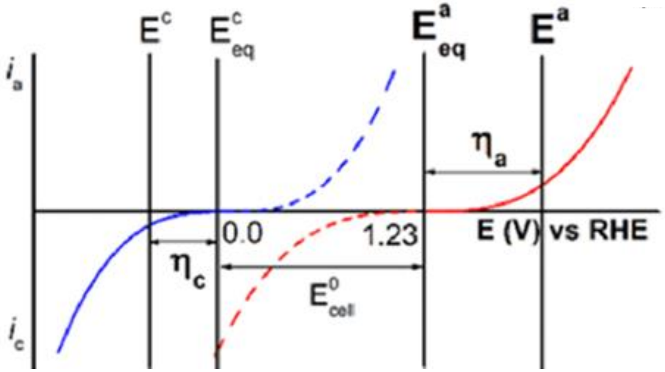
Natural Gas Turbine

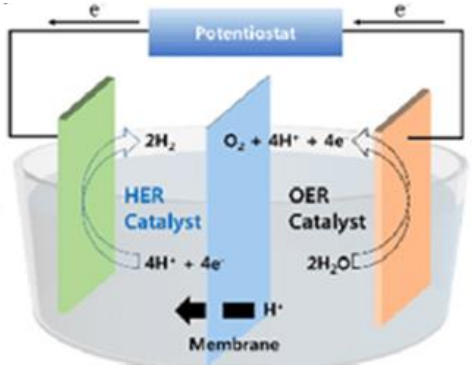
— Electric Line
- - - Hydrogen Piping
— CO$_2$ Piping
— Natural Gas Piping

* My group seeks low-cost catalysts for batteries, water electrolysers, fuel cells and CO$_2$ hydrogenation.

Key Technologies in a Green Hydrogen Economy

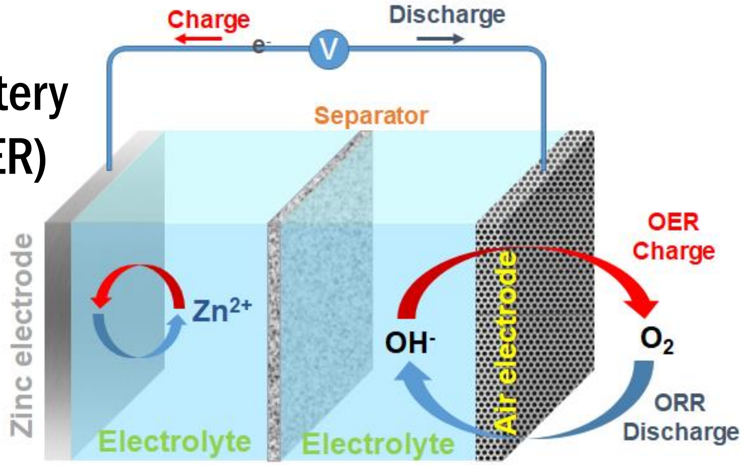
Energy efficient water electrolysers, high energy density rechargeable batteries and low-cost fuel cells are needed for a hydrogen economy to be come a reality. These devices utilize the **oxygen evolution reaction (OER)** and/or the **oxygen reduction reaction (ORR)**.



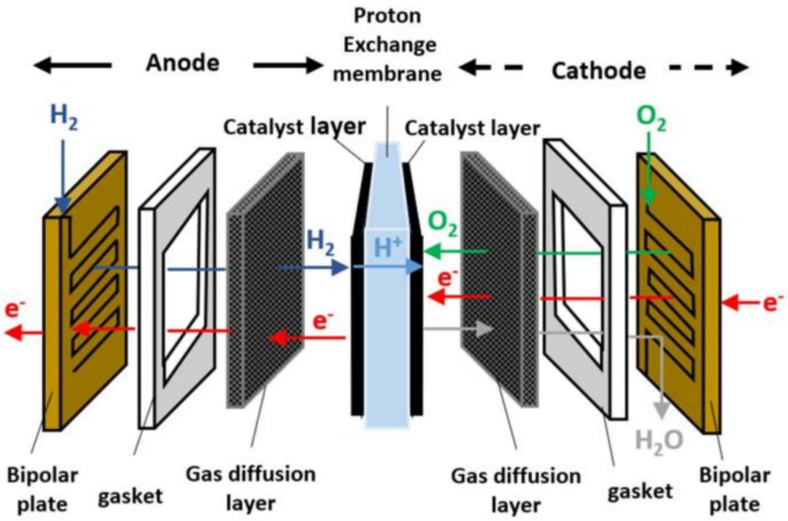


Water electrolysers (HER + OER)

Rechargeable Batteries
Zn-air battery
(ORR + OER)

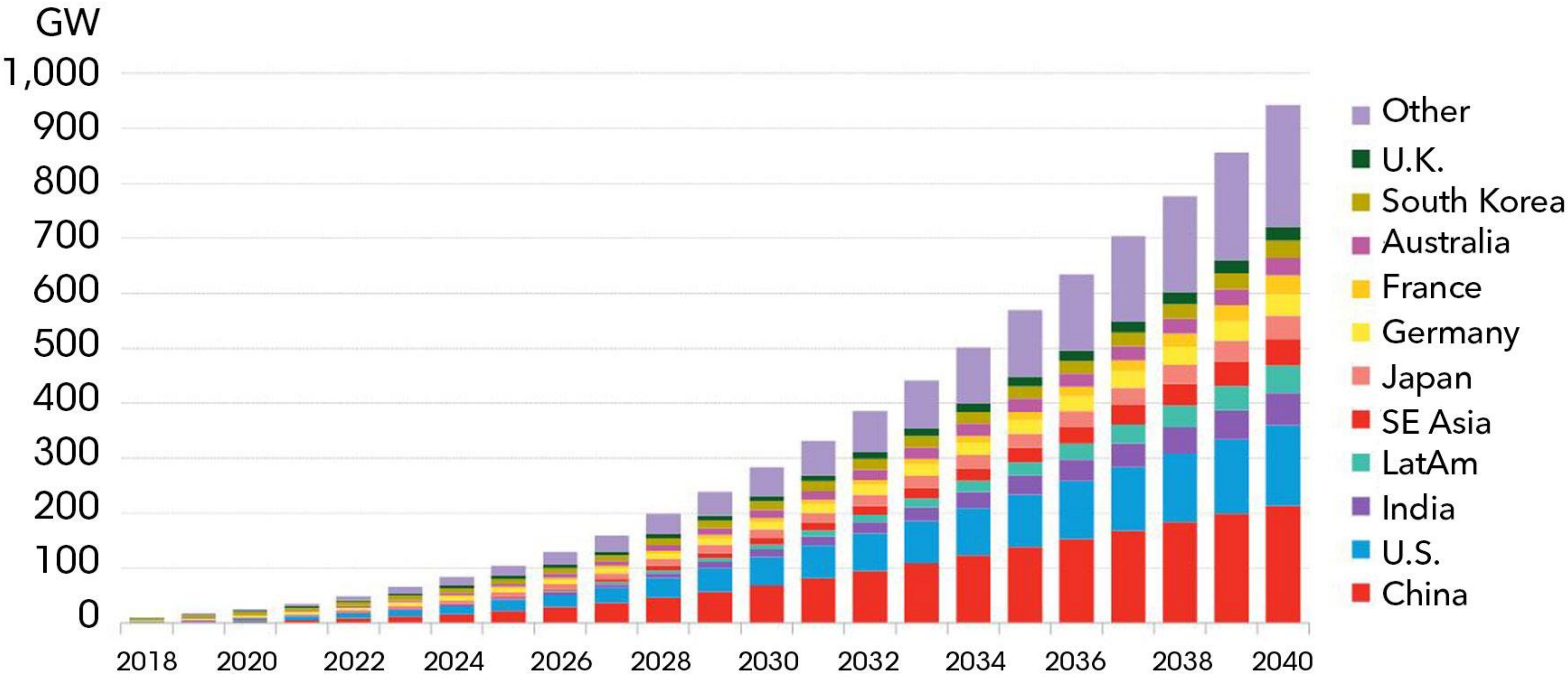


PEM fuel cells (HOR + ORR)



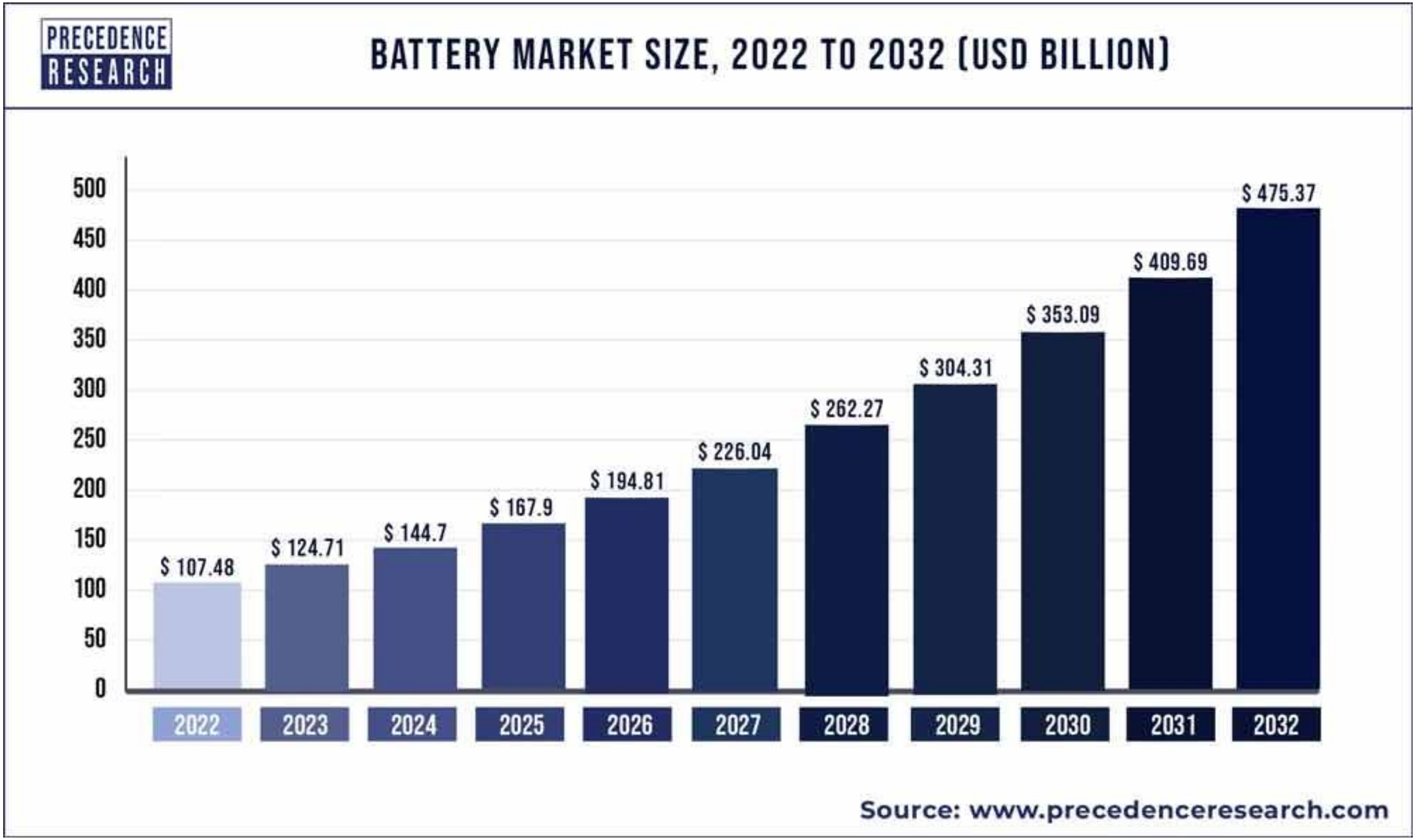
Global Energy Storage

The global energy storage market [1] will grow to a cumulative 942GW/2,857GWh by 2040, attracting $620 billion in investment over the next 22 years. Cheap batteries and low-cost hydrogen generation are key to storing renewably-generated electricity at scale.
https://about.bnef.com/blog/energy-storage-620-billion-investment-opportunity-2040/


Global cumulative storage deployments

Source: BloombergNEF

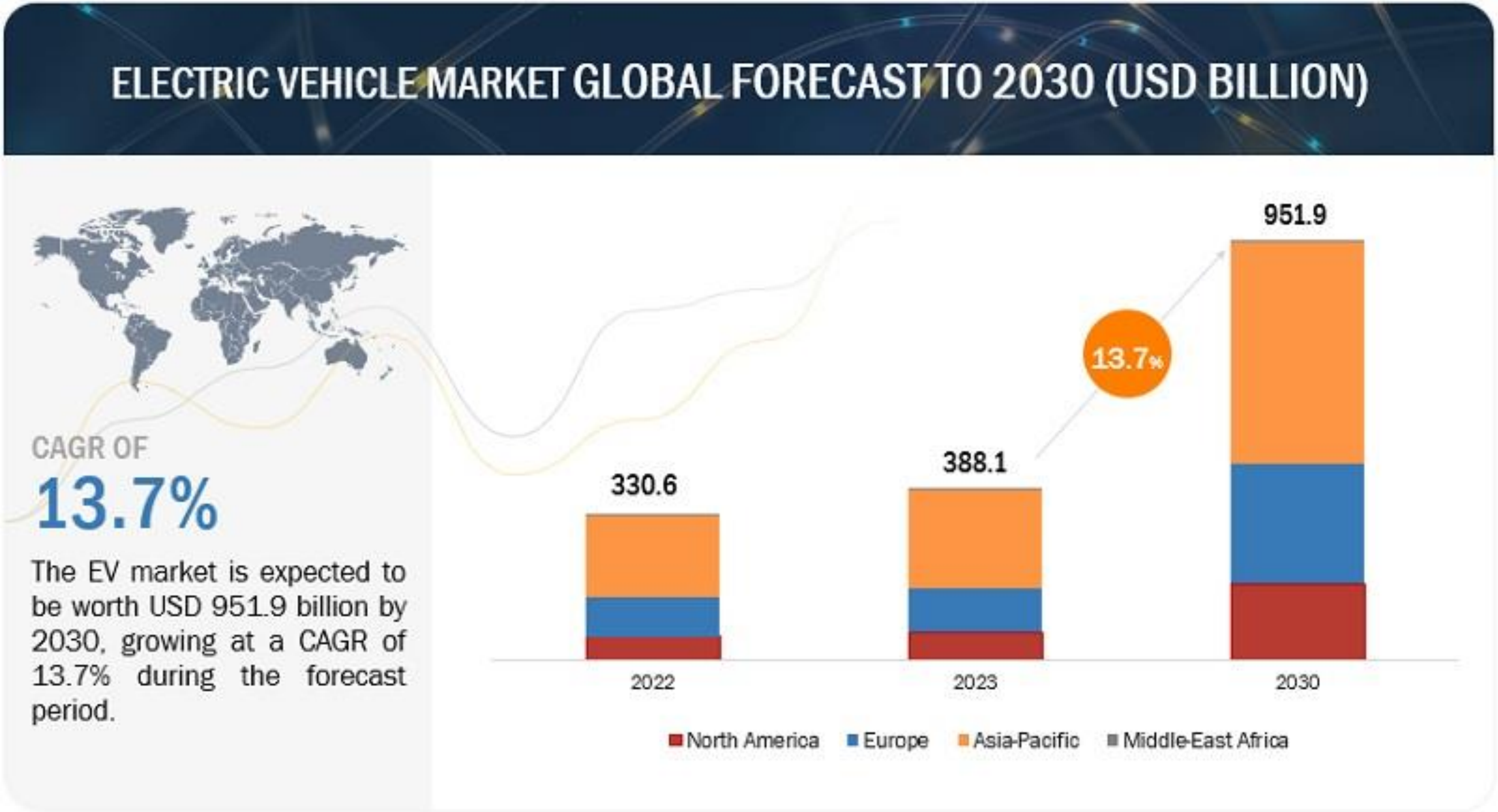
The global battery market size was estimated at USD 107.48 billion in 2022 and it is expected to hit around USD 475.37 billion by 2032, poised to grow at a CAGR of 16.03% over the forecast period 2023 to 2032.



Source: www.precedenceresearch.com

https://www.precedenceresearch.com/battery-market

The growth in the battery market is driven by renewable energy storage and rising demand for electric vehicles.



ELECTRIC VEHICLE MARKET GLOBAL FORECAST TO 2030 (USD BILLION)

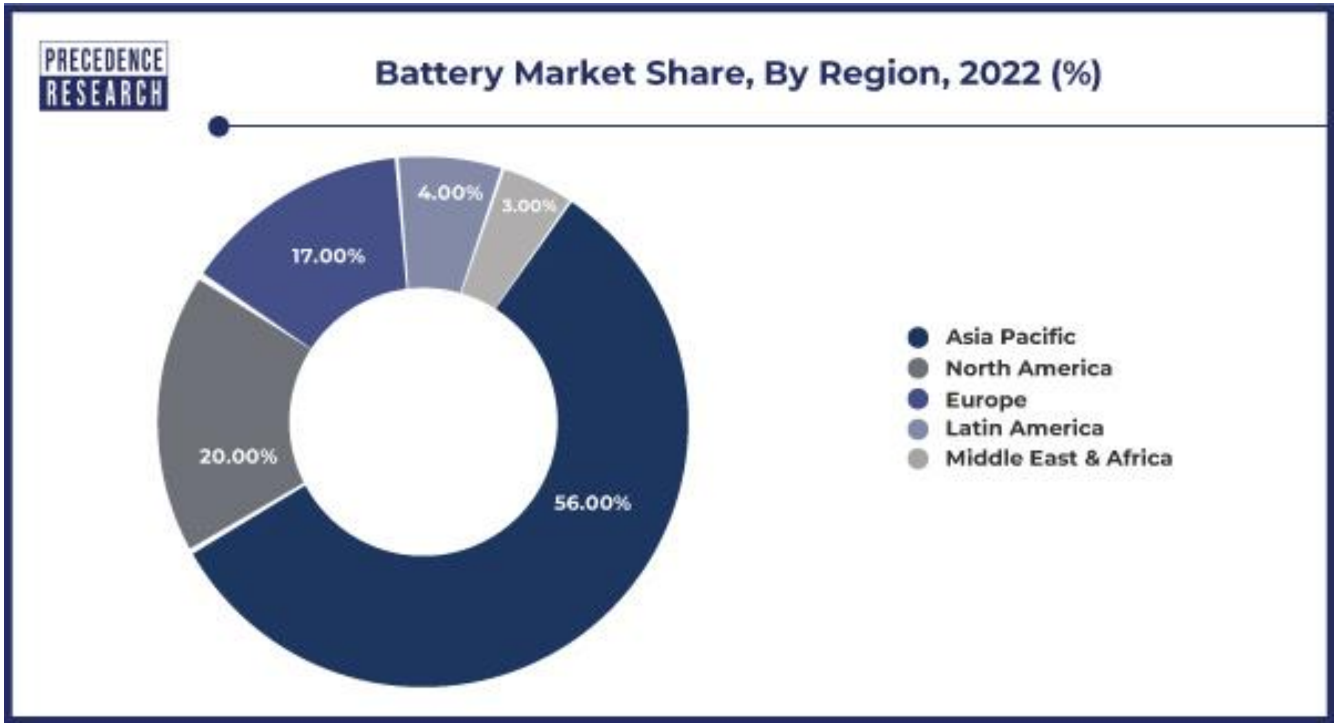
CAGR OF

13.7%

The EV market is expected to be worth USD 951.9 billion by 2030, growing at a CAGR of 13.7% during the forecast period.

https://www.marketsandmarkets.com/Market-Reports/electric-vehicle-market-209371461.html

Regional Insights: The Asia Pacific region is the world's major battery market and accounts for a high share of global battery sales.



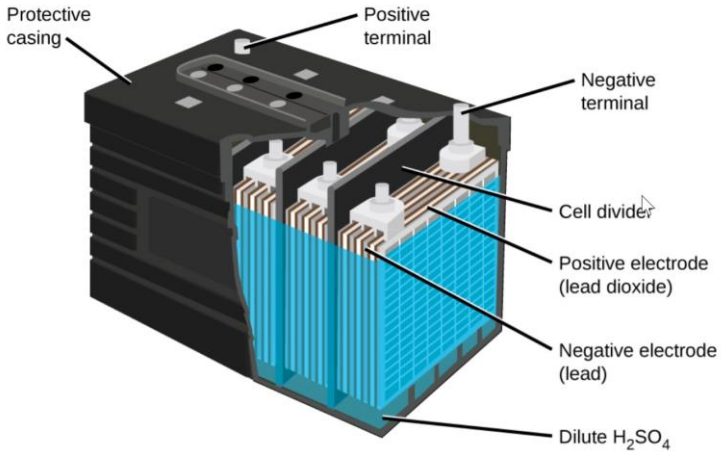
Key Takeaways:

- Asia Pacific region generated more than 56% of the revenue share in 2022.
- By Type, the lithium-ion battery segment has dominated the global market with revenue share of 40.8% in 2022.
- By End-Use, the automotive sector contributed for the largest market share of around 32.4% in 2022.
- By Application, the industrial batteries segment has held revenue share of 35.9% in 2022.
- By Application, the automotive batteries segment has held revenue share of 34.7% in 2022.

Rechargeable Batteries you will be Very Familiar With

There are many types of rechargeable batteries in use today. Very common battery types in include the **lead-acid battery** and **Li-ion batteries.** The batteries are named after their components and the ways charge is stored in the batteries.

LEAD-ACID BATTERY



Negative Electrode: $Pb \longrightarrow Pb^{2+} + 2e^-$

$Pb^{2+} + SO_4^{2-} \longrightarrow PbSO_4 \quad E^0 = -0.356V$

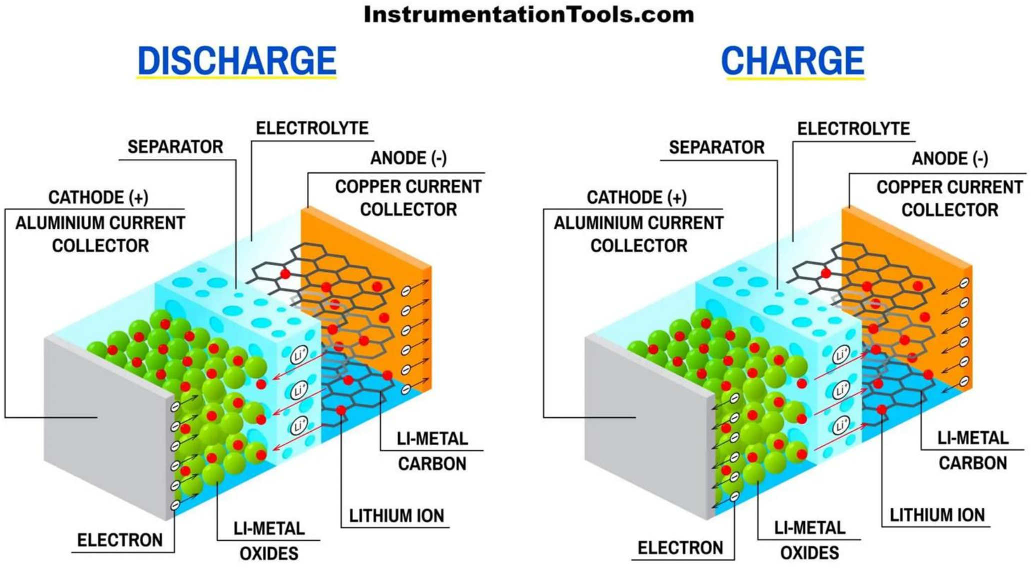
Positive Electrode : $PbO_2 + 4H^+ + 2e^- \longrightarrow Pb^{2+} + 2H_2O$

$Pb^{2+} + SO_4^{2-} \longrightarrow PbSO_4 \quad E^0 = 1.685V$

Combined Reaction: $Pb + PbO_2 + 2H_2SO_4 \longrightarrow 2PbSO_4 + 2H_2O$

$E^0 = 2.041V$

LITHIUM-ION BATTERY

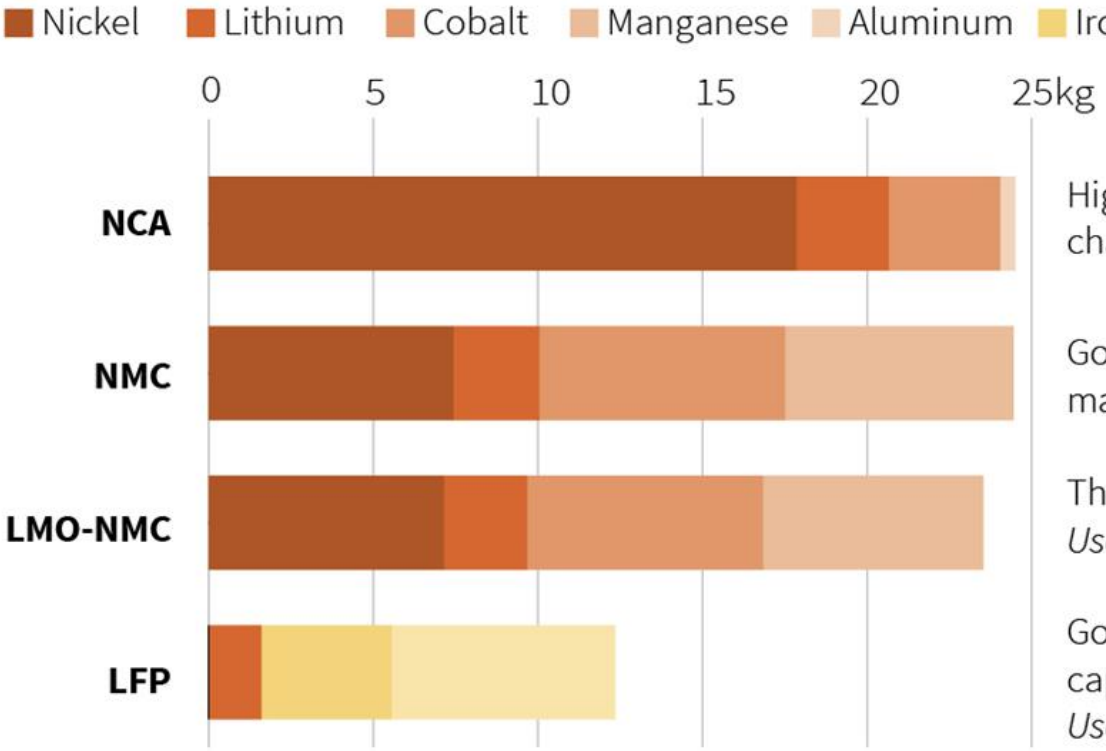


Types of Lithium-ion battery and their makeup

Lithium-ion batteries containing nickel are used to fuel electric cars made by many manufacturers. As the sales of electric vehicles are projected to grow, the demand for nickel is likely to grow over coming years.

WEIGHT OF CATHODE METAL CONTENT PER BATTERY

In plug-in hybrid electric vehicles with driving range of 40 miles using only battery power



High performance but presents safety challenges. *Used in Focus Fusion*

Good overall performance with increasing market share. *Used in Chevrolet Volt*

This combination is chosen by many EVs. *Used in Nissan Leaf*

Good safety and long life span but low capacity; popular in China. *Used in BYD E6* *& Tesla*

Notes: NCA stands for lithium nickel cobalt aluminum oxide; NMC stands for lithium nickel manganese cobalt oxide; LMO stands for lithium ion manganese oxide; LFP stands for lithium iron phosphate.

Sources: Argonne National Laboratory; GFMS, Thomson Reuters; The Boston Consulting Group; Bank of America, Merrill Lynch

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W. Cai, 10/03/2017

REUTERS

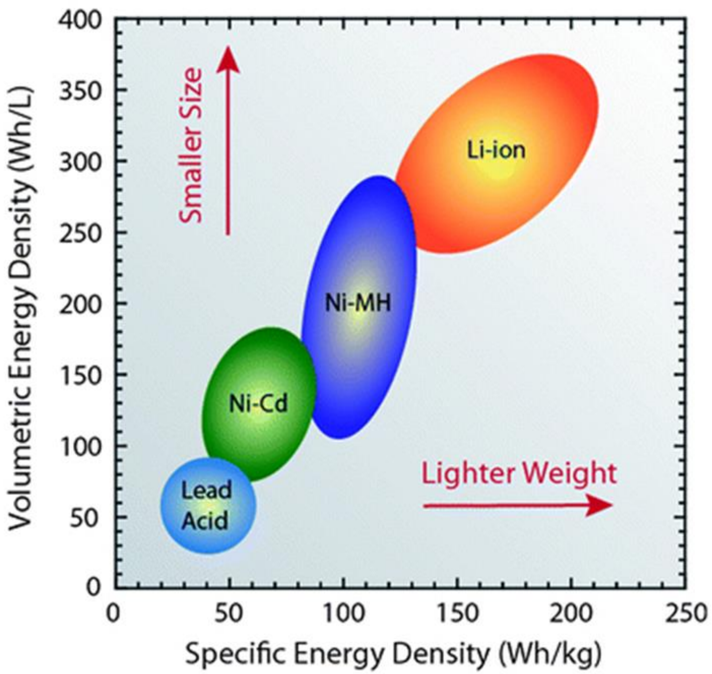
The table below compares different lithium-ion battery types in terms of features such as energy density, power density, battery performance, safety, lifespan, cost and more.

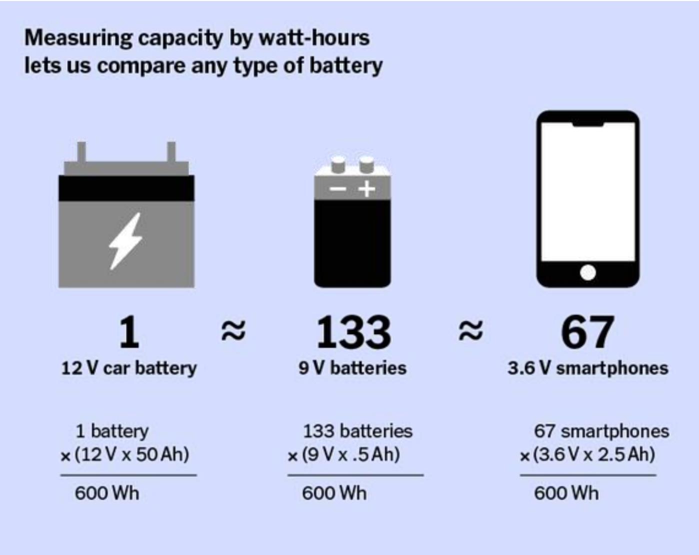
Key Active Material	Lithium-Iron Phosphate	Lithium Nickel Manganese Cobalt Oxide	Lithium Manganese Oxide	Lithium Nickel Cobalt Aluminum	Lithium Titanate
Technology Short Name	LFP	NMC	LMO	NCA	LTO
Cathode	$LiFePO_4$	$LiNi_xMn_yCo_{1-x-y}O_2$	$LiMn_2O_{4 (spinel)}$	$LiNiCoAlO_2$	variable
Anode	C (graphite)	C (graphite)	C (graphite)	C (graphite)	$Li_4Ti_5O_{12}$
Safety	▮▮▮▮▮▮▮▮▮	▮▮▮▮▮▮	▮▮▮▮▮▮	▮▮▮▮	▮▮▮▮▮▮▮▮▮
Power Density	▮▮▮▮▮▮	▮▮▮▮	▮▮▮▮▮▮	▮▮▮▮▮▮▮▮▮	▮▮▮▮▮▮
Energy Density	▮▮▮▮	▮▮▮▮▮▮▮▮▮	▮▮▮▮▮▮	▮▮▮▮▮▮▮▮▮	▮▮▮▮
Cell Costs Advantage	▮▮▮▮▮▮	▮▮▮▮▮▮	▮▮▮▮▮▮	▮▮	▮▮
Lifetime	▮▮▮▮▮▮▮▮▮	▮▮▮▮▮▮	▮▮▮▮	▮▮▮▮▮▮▮▮▮	▮▮▮▮▮▮▮▮▮
BESS Performance	▮▮▮▮▮▮▮▮▮	▮▮▮▮	▮▮▮▮	▮▮▮▮	▮▮▮▮▮▮▮▮▮

Energy Density: Amount of energy that can be stored in a given volume or mass of a battery. It is typically measured in watt-hours per liter (Wh/L) or watt-hours per kilogram (Wh/kg). A higher energy density indicates that the battery can store more energy.

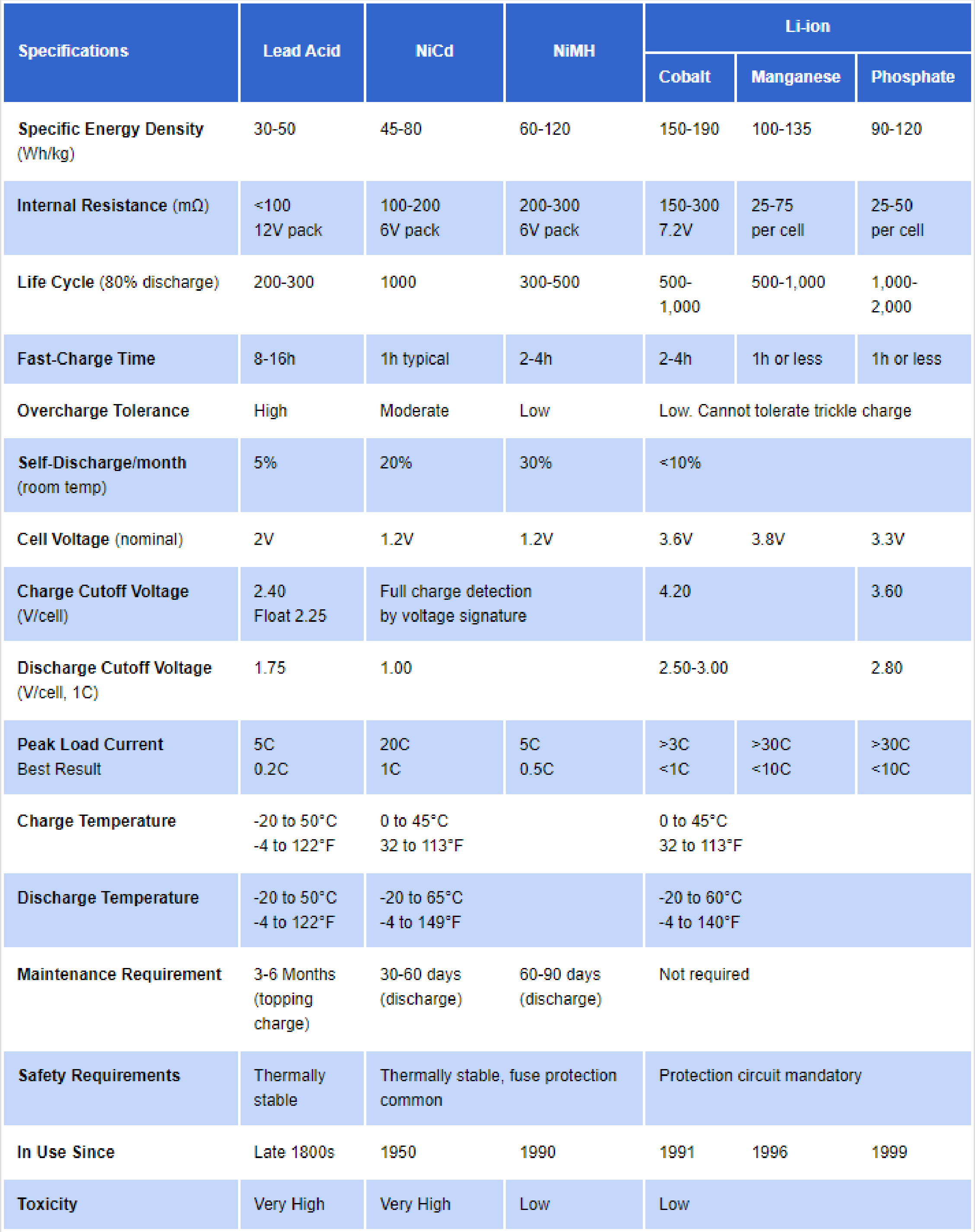
Power Density: Rate at which energy can be delivered or extracted from a battery. It is measured in watts per liter (W/L) or watts per kilogram (W/kg). Fast discharging/charging is important for EVs.

Battery Performance Comparison





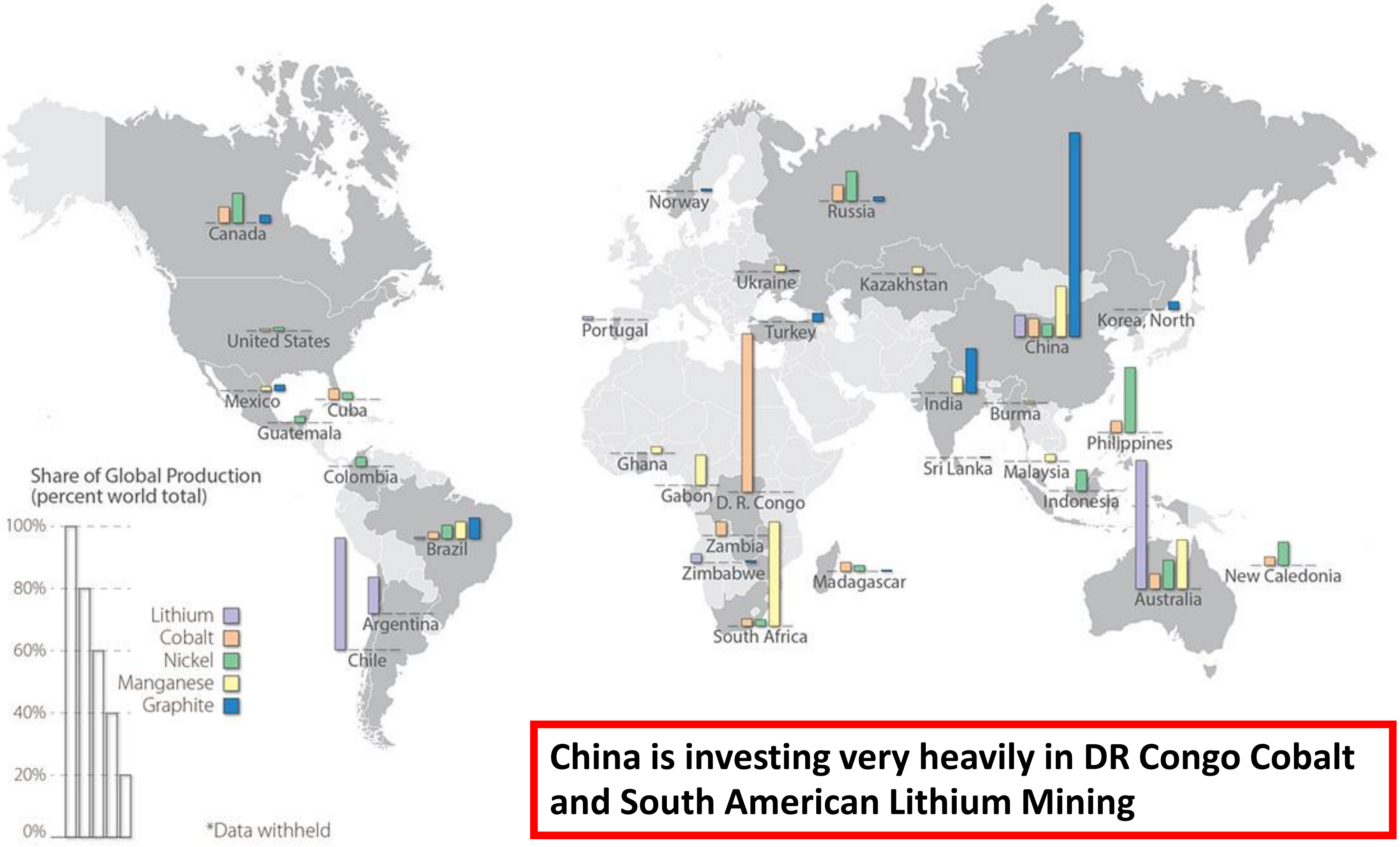
Measuring capacity by watt-hours lets us compare any type of battery



Specifications	Lead Acid	NiCd	NiMH	Li-ion		
				Cobalt	Manganese	Phosphate
Specific Energy Density (Wh/kg)	30-50	45-80	60-120	150-190	100-135	90-120
Internal Resistance (mΩ)	<100 12V pack	100-200 6V pack	200-300 6V pack	150-300 7.2V	25-75 per cell	25-50 per cell
Life Cycle (80% discharge)	200-300	1000	300-500	500-1,000	500-1,000	1,000-2,000
Fast-Charge Time	8-16h	1h typical	2-4h	2-4h	1h or less	1h or less
Overcharge Tolerance	High	Moderate	Low	Low. Cannot tolerate trickle charge		
Self-Discharge/month (room temp)	5%	20%	30%	<10%		
Cell Voltage (nominal)	2V	1.2V	1.2V	3.6V	3.8V	3.3V
Charge Cutoff Voltage (V/cell)	2.40 Float 2.25	Full charge detection by voltage signature		4.20		3.60
Discharge Cutoff Voltage (V/cell, 1C)	1.75	1.00		2.50-3.00		2.80
Peak Load Current Best Result	5C 0.2C	20C 1C	5C 0.5C	>3C <1C	>30C <10C	>30C <10C
Charge Temperature	-20 to 50°C -4 to 122°F	0 to 45°C 32 to 113°F		0 to 45°C 32 to 113°F		
Discharge Temperature	-20 to 50°C -4 to 122°F	-20 to 65°C -4 to 149°F		-20 to 60°C -4 to 140°F		
Maintenance Requirement	3-6 Months (topping charge)	30-60 days (discharge)	60-90 days (discharge)	Not required		
Safety Requirements	Thermally stable	Thermally stable, fuse protection common		Protection circuit mandatory		
In Use Since	Late 1800s	1950	1990	1991	1996	1999
Toxicity	Very High	Very High	Low	Low		

Ready for the “White Petroleum” War?

Lithium prices have increased ~5-fold in the last decade, peaking in 2022, driven by demand for lithium-ion batteries needed to power electric vehicles, laptops and cell phones.



China is investing very heavily in DR Congo Cobalt and South American Lithium Mining

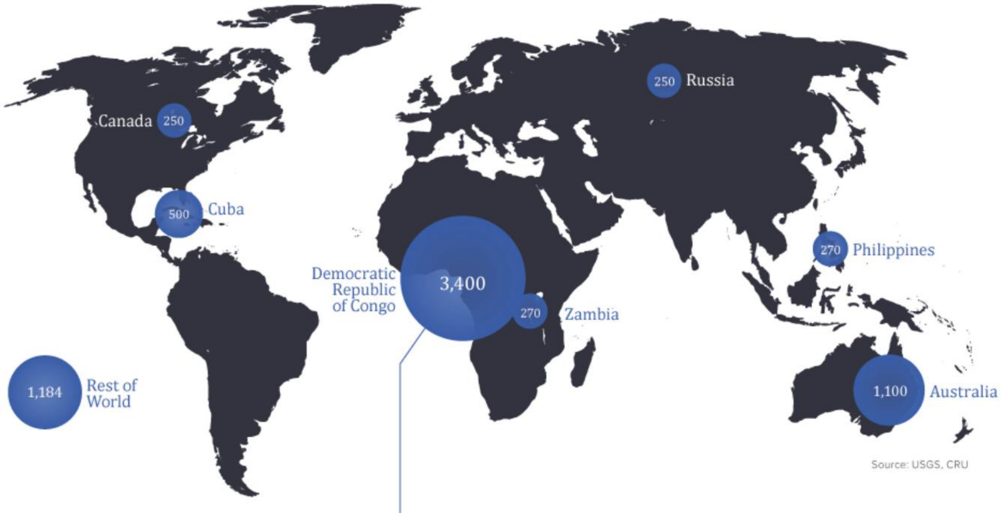
Cobalt, the Congo and Underage Child Labour

The Future of Cobalt Supply

Companies like Tesla and Panasonic need reliable sources of cobalt, and right now there aren't many failsafes.

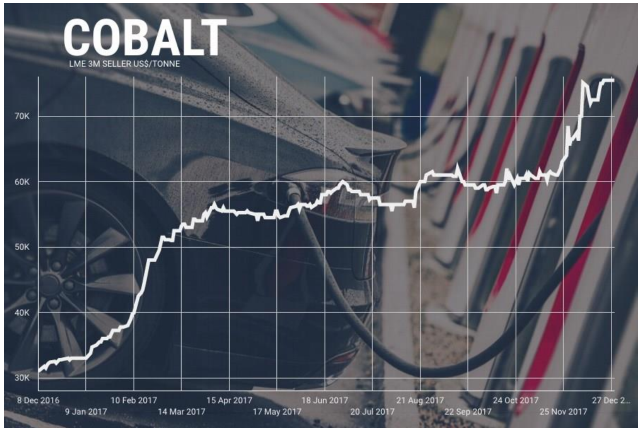
The U.S. hasn't mined cobalt in significant volumes since 1971, and the USGS reports that the United States only has 301 tonnes of the metal stored in stockpiles.

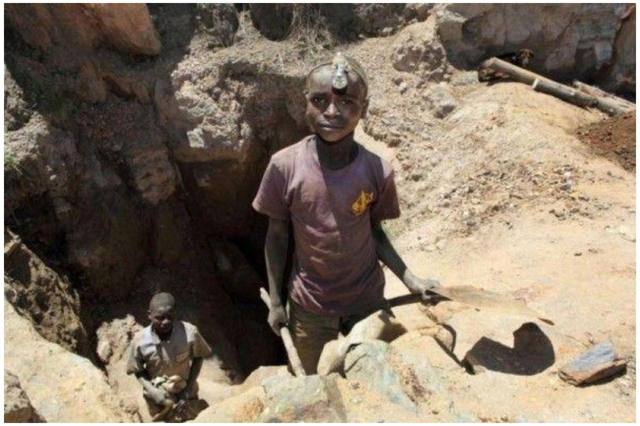
Here's where cobalt is found throughout the world:
(2014 identified deposits, thousands of tonnes)



Source: USGS, CRU

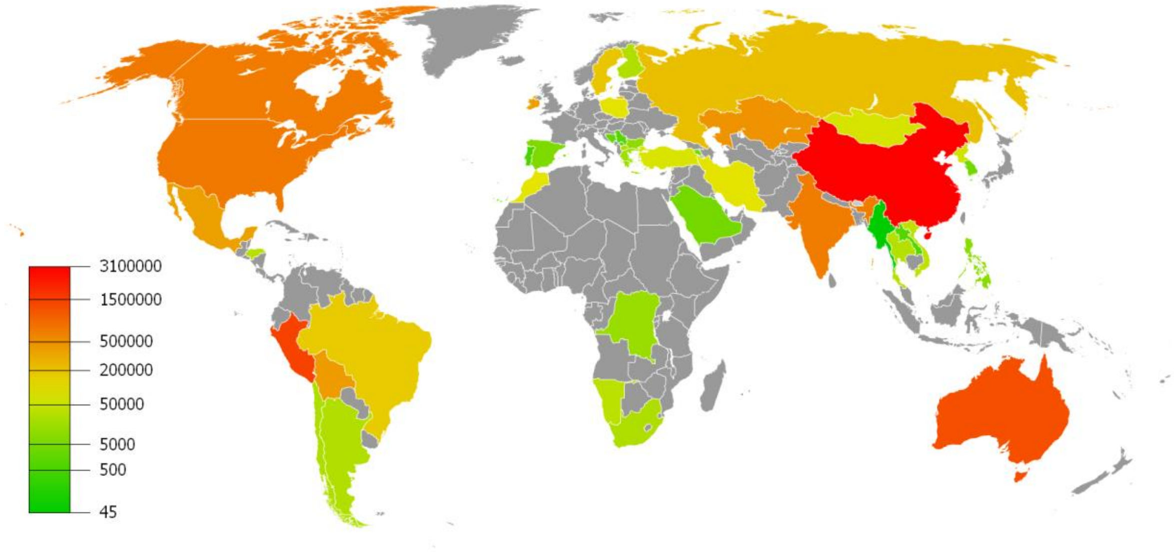
Main cobalt containing minerals include cobaltite (CoAsS), safflorite ($CoAs_2$), glaucodot ((Co,Fe)AsS), and skutterudite ($CoAs_3$).



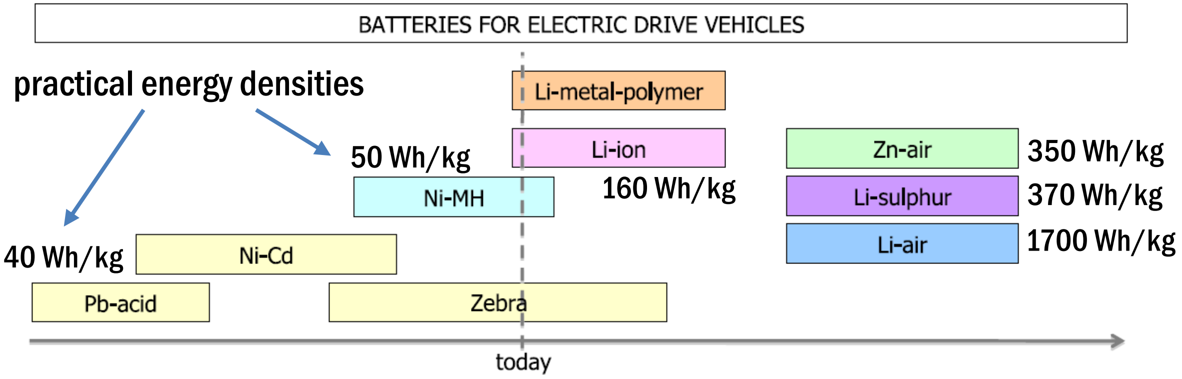


Time for a Rethink With Zinc?

https://en.wikipedia.org/wiki/List_of_countries_by_zinc_production



Zinc has a higher earth abundance than Cobalt and is distributed across all continents.



BATTERIES FOR ELECTRIC DRIVE VEHICLES

practical energy densities

50 Wh/kg

40 Wh/kg

Li-metal-polymer

Li-ion

160 Wh/kg

Ni-MH

Ni-Cd

Pb-acid

Zebra

Zn-air 350 Wh/kg

Li-sulphur 370 Wh/kg

Li-air 1700 Wh/kg

today

Rank	Country/Region	Zinc production 2009 (tonnes)
—	World total	11,200,000
1	China	3,100,000
2	Peru	1,509,129
3	Australia	1,290,000
4	United States	736,000
5	Canada	698,901
6	India	695,000
7	Kazakhstan	480,000
8	Bolivia	421,721
9	Mexico	390,000
10	Ireland	385,670
11	Russia	225,000
12	Sweden	192,538
13	Brazil	174,000
14	Iran	160,000
15	Poland	100,000

Rechargeable Zinc-air Batteries

Rechargeable zinc-air batteries (ZABs) are very attractive for the short-term storage of electrical energy owing to their low cost, safety and very high specific energy densities.

Zinc-air battery discharge reactions

Cathode: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$ (**ORR**)

Anode: $2Zn + 8OH^- \rightarrow 2Zn(OH)_4^{2-} + 4e^-$

Overall: $2Zn + O_2 + 2H_2O + 4OH^- \rightarrow 2Zn(OH)_4^{2-}$

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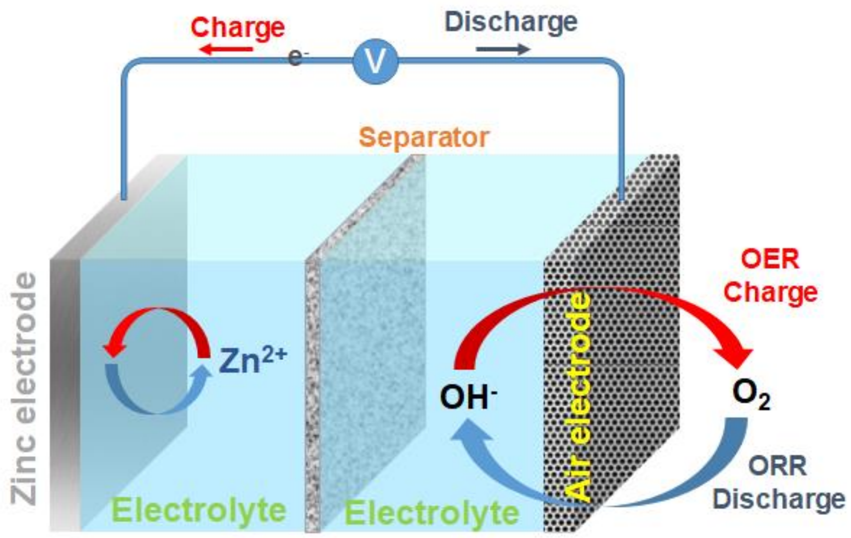
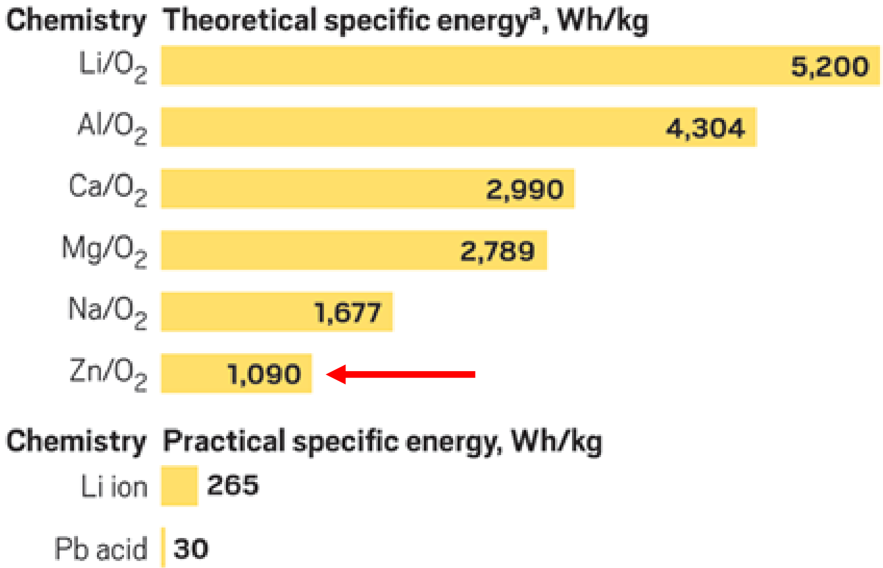
Theoretical voltage: 1.65 V, Actual voltage: 1.4 V





https://cen.acs.org/articles/95/i9/Batteries-breathe-air.html

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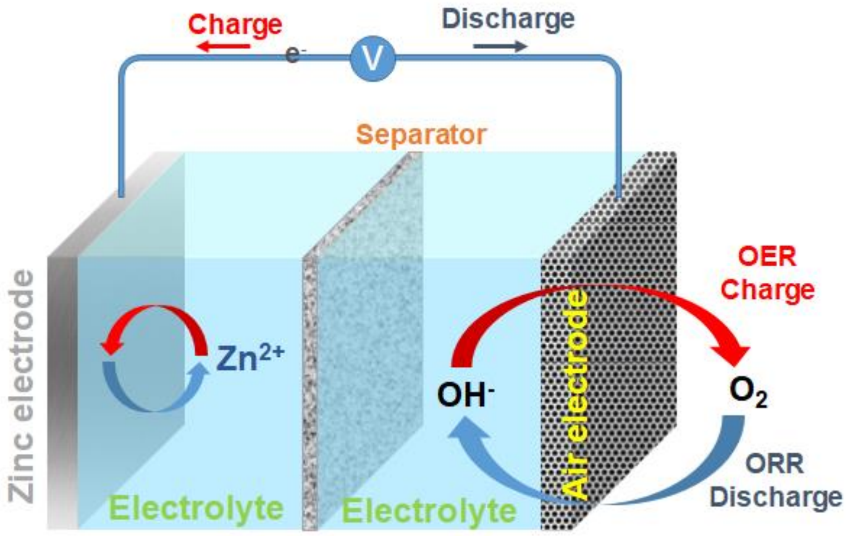
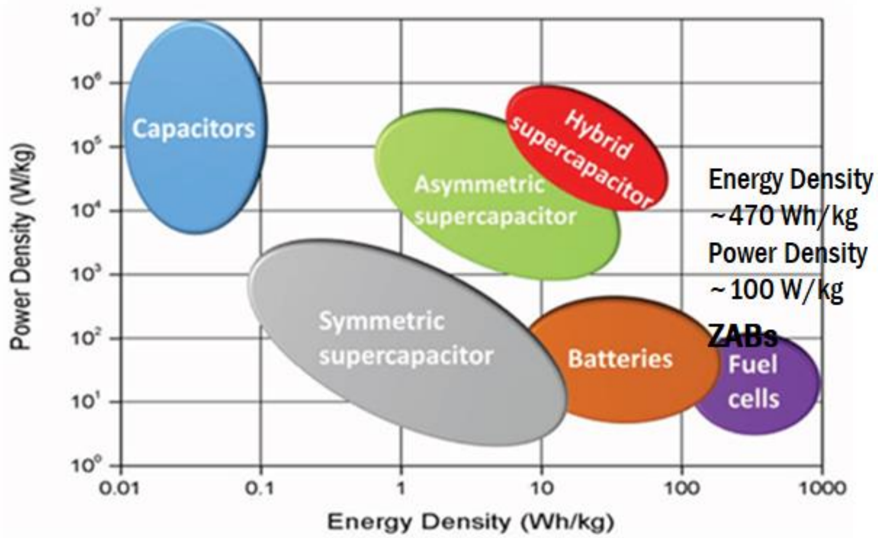
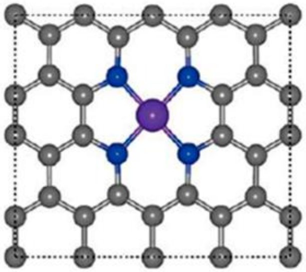
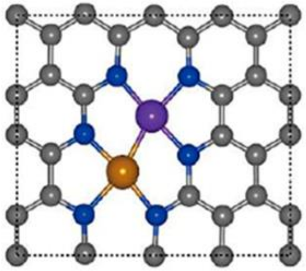


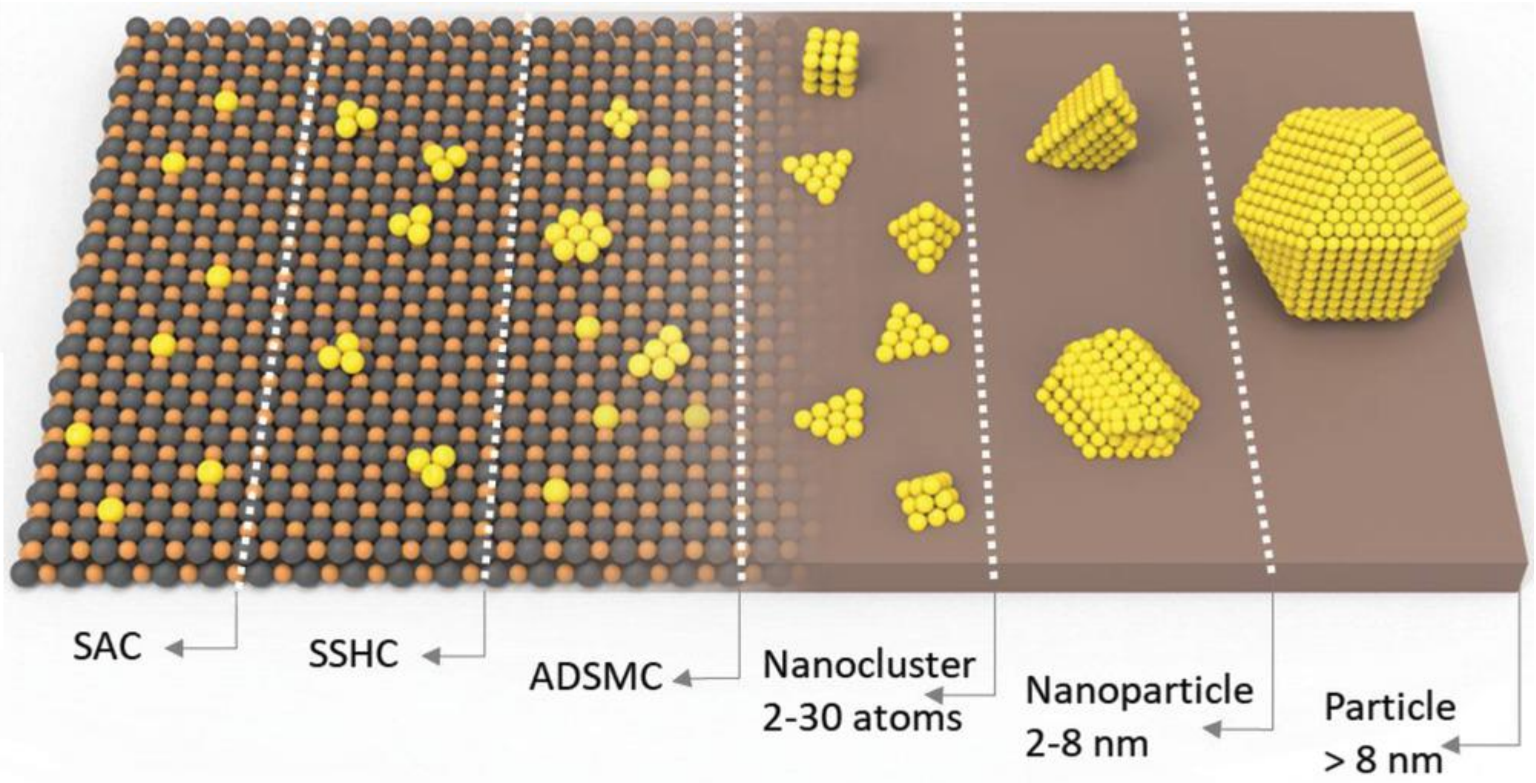


Metal Single Atom Catalysts (SACs) for ORR/OER

Traditionally, supported metal nanoparticle catalysts have been used for HER, HOR, and ORR (e.g. 10-20 wt.% Pt/C), and RuO_2 or IrO_2 for OER. This results in poor metal atom utilization since only surface metal atoms participate in catalysis. **SACs offer ~100% metal utilization.**


Mono metal site

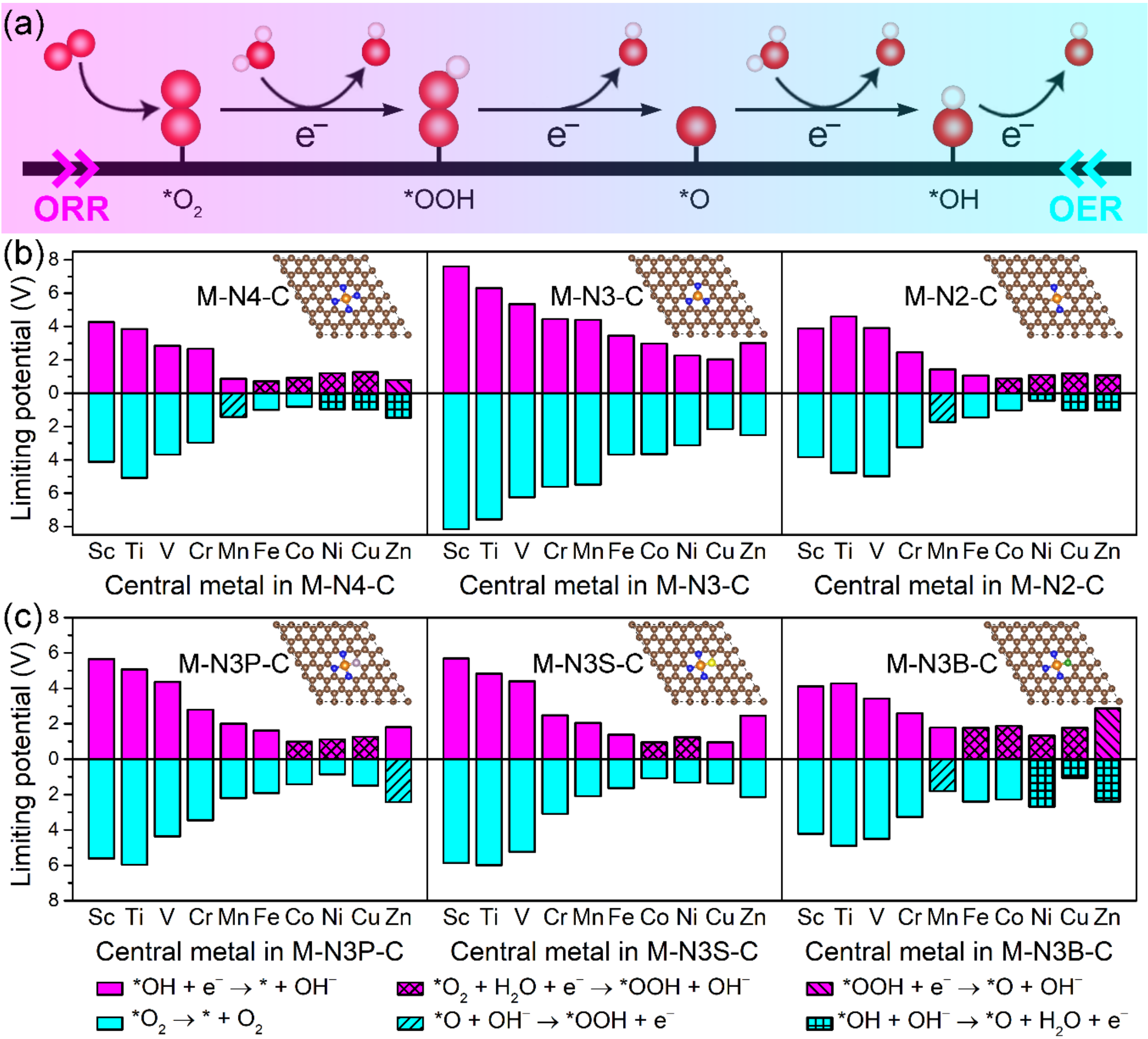

Dual metal site



SAC = single atom catalyst, **SSHC** = single site heterogeneous catalyst, **ADSMC** = atomically dispersed supported metal catalyst (Wu et al. *Small Methods* (2020), 4, 19005-40)

Computational Screening of SACs for ORR/OER

Computational methods are very useful for screening SACs for particular reactions.
Chemical Engineering Journal (2021), 427, 132038.



(right) (a) Scheme for four-electron ORR (forward reaction) and OER (reverse reaction) via an associative pathway. White and red spheres represent H and O atoms, respectively.

(b,c) Limiting potentials of ORR (pink bars) and OER (aqua bars) on 3d-TM-SACs in six different configurations at U = 0.402 V vs NHE.

Results reveal that FeN_4-C, CoN_4-C and NiN_4-C SACs are the best for ORR and OER, respectively, whilst Ni-N_2-C, Fe-N_4-C, Co-N_4-C, Co-N_2-C, and Ni-N_3P-C SACs are the best bifunctional ORR/OER catalysts.

Rechargeable ZAB based on a Fe-N_4-C/Fe_3C Catalyst

Recently we discovered a Fe single atom seed-mediated strategy for the fabrication of **novel Fe-N_4-C/Fe_3C catalysts with outstanding bifunctional ORR/OER performance in alkaline media.**

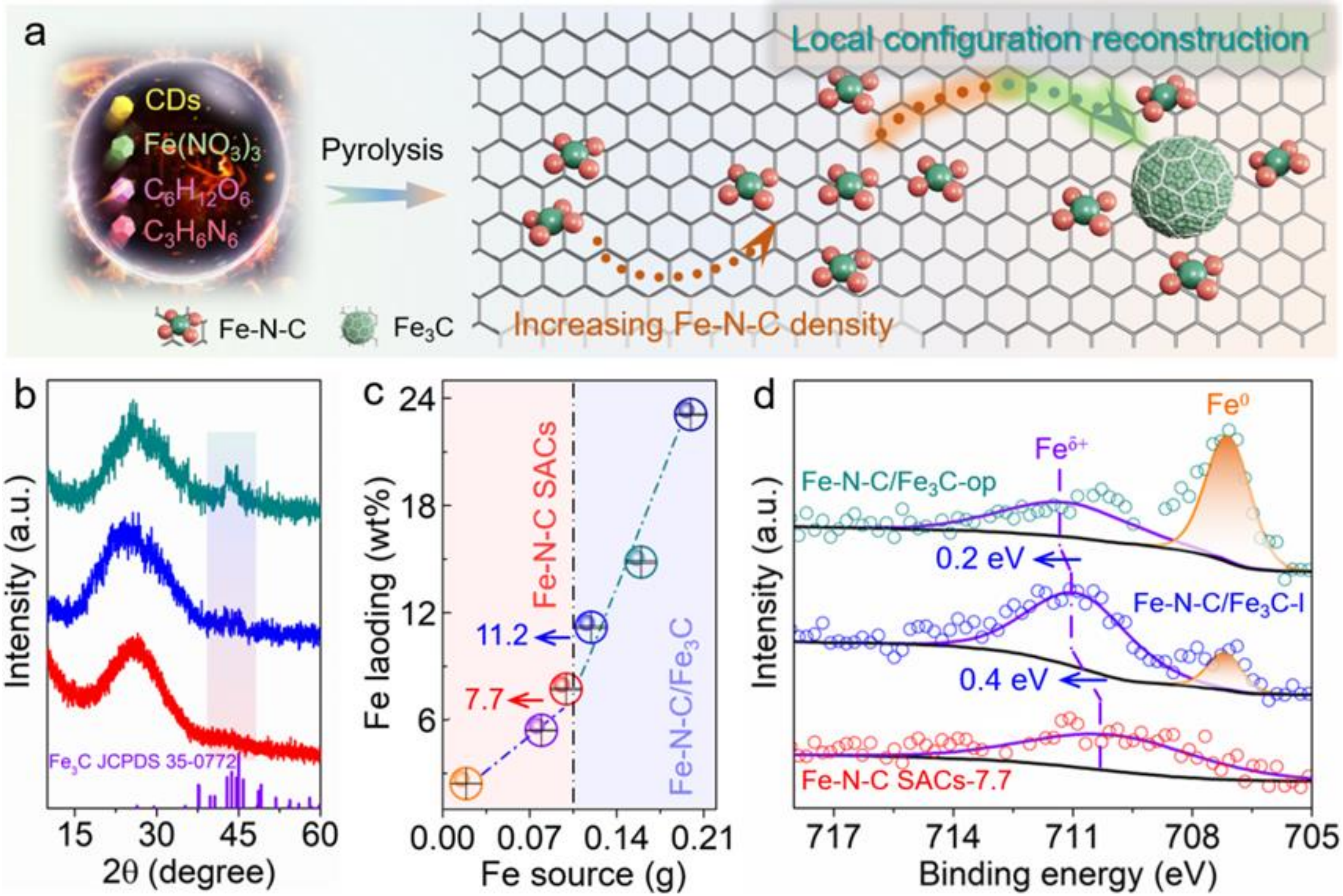
The introduction of Fe_3C species near iron single atom (Fe-N_4-C) sites allows optimization of the adsorption energies of oxygen intermediates formed during ORR and OER, resulting in superior ORR/OER activities and kinetics.

A zinc-air battery constructed with Fe-N-C/Fe_3C-op as the air-cathode catalyst delivered a remarkable **specific capacity (818.1 mAh g_{Zn}^{-1})** and a **power density (1013.9 mWh g_{Zn}^{-1})**, along with excellent long-term durability (>450 h). The open circuit voltage was 1.568 V. This work demonstrates that metallic Fe_3C can be used to modulate FeN_4-C single atom sites for improved bifunctional oxygen electrocatalysis.

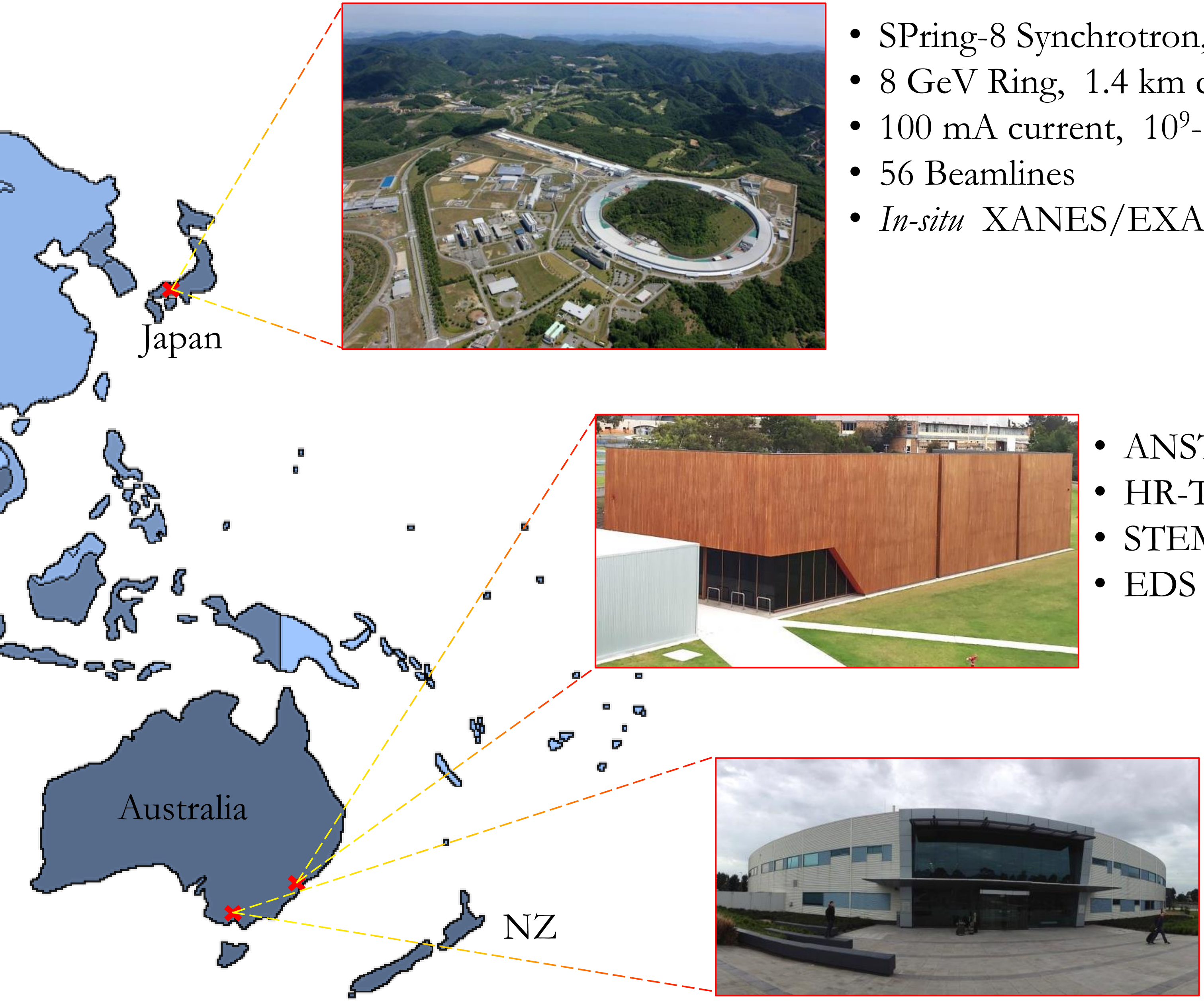
Advanced Science (2023), 10(22), 2301656

Rechargeable ZAB based on $Fe\text{-}N_4\text{-}C/Fe_3C$ Catalyst

A $Fe\text{-}N_4\text{-}C/Fe_3C$ catalyst was synthesized by the pyrolysis of carbon dots, $Fe(NO_3)_3$, glucose and melamine. *Advanced Science* (2023) 2301656



Catalyst Characterisation is Fun



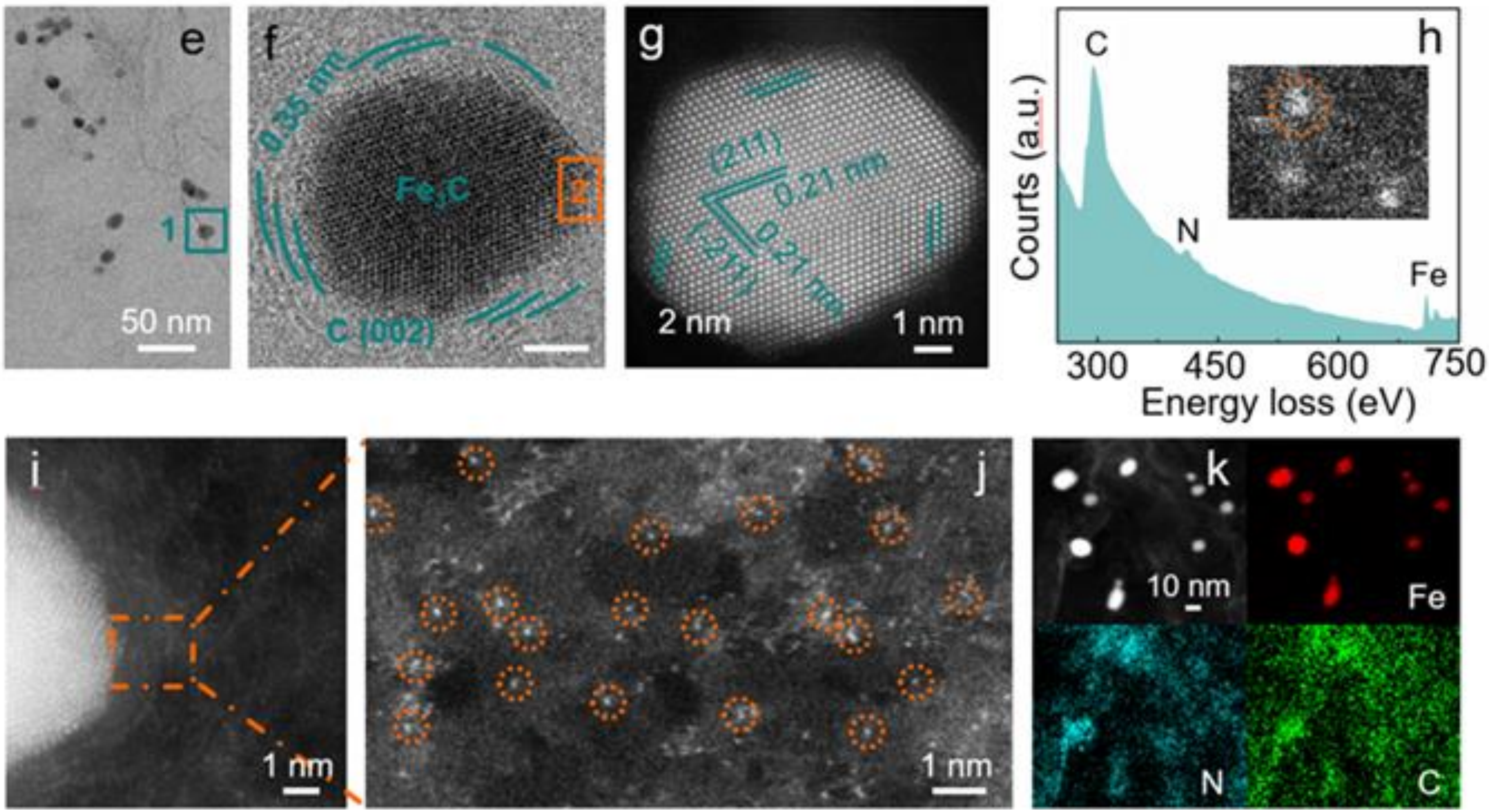
- SPring-8 Synchrotron, Hyogo
- 8 GeV Ring, 1.4 km circumference
- 100 mA current, 10^9-10^{11} photons/s
- 56 Beamlines
- *In-situ* XANES/EXAFS

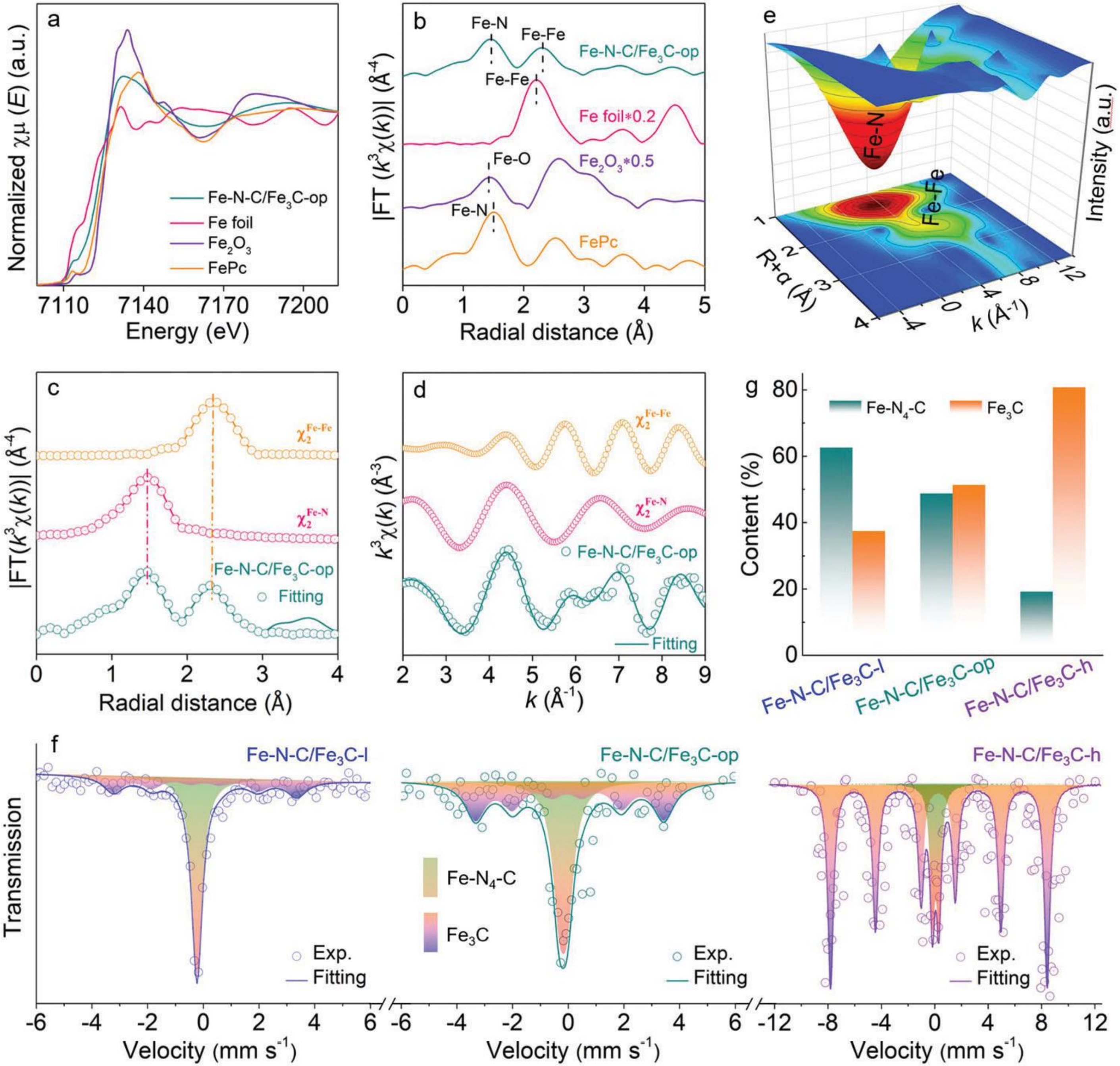
- ANSTO, Sydney
- HR-TEM, 200 kV
- STEM/HAADF
- EDS

- Australian Synchrotron, Melbourne
- 3 GeV Ring
- XPS/NEXAFS

Rechargeable ZAB based on Fe-N_4-C/Fe_3C Catalyst

A Fe-N_4-C/Fe_3C catalyst was synthesized by the pyrolysis of carbon dots, $Fe(NO_3)_3$, glucose and melamine.

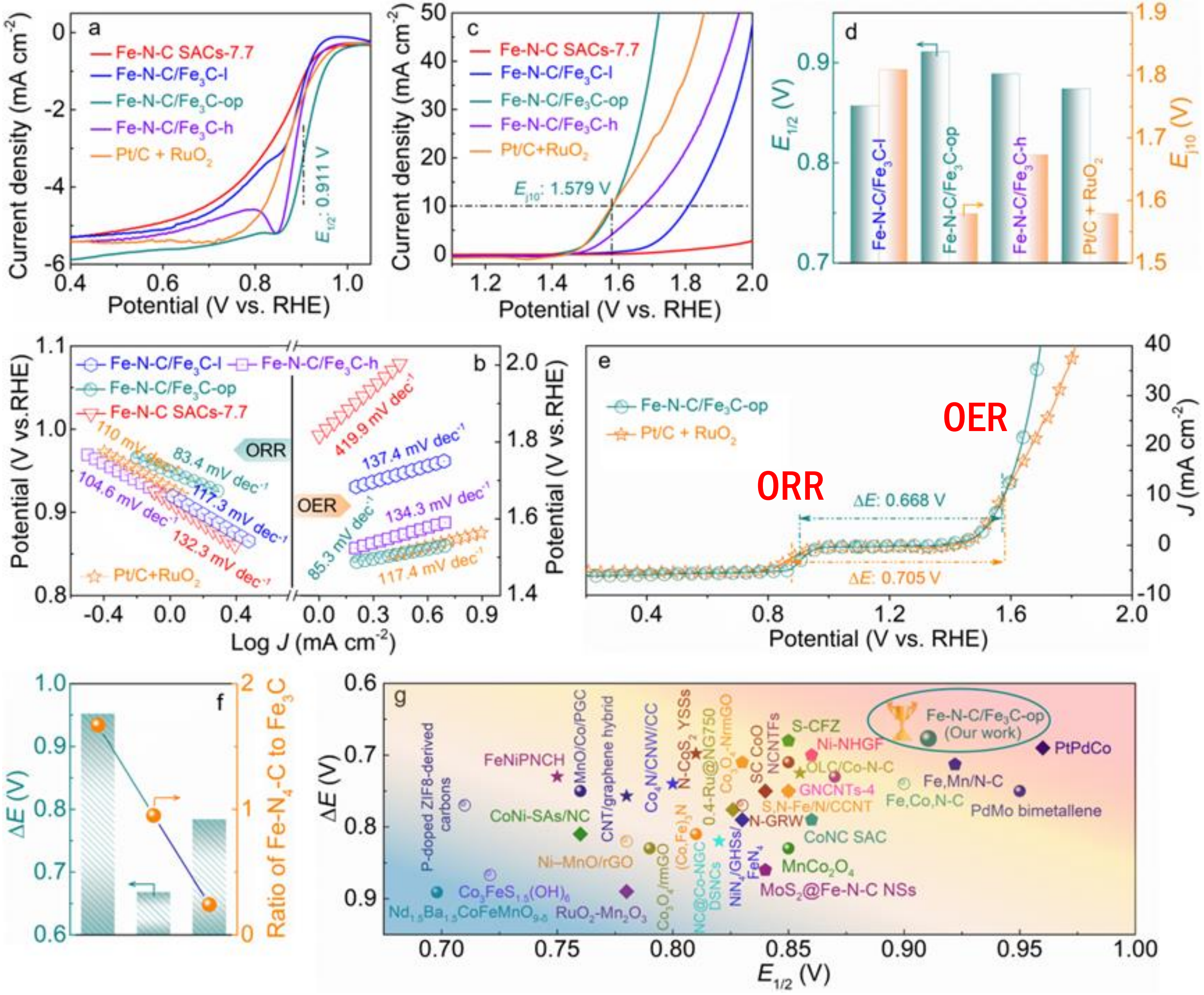




Optimizing the FeN_4-C to Fe_3C ratio important.

Rechargeable ZAB based on $Fe-N_4-C/Fe_3C$ Catalyst

The $Fe-N_4-C/Fe_3C$ catalyst delivered state-of-the-art bifunctional ORR/OER activity.



Bifunctional ORR/OER activity evaluation.

a) ORR LSV curves.

c) OER LSV curves.

b) Tafel plots for ORR and OER on different electrocatalysts.

d) $E_{1/2}$ and E_{j10} of different electrocatalysts.

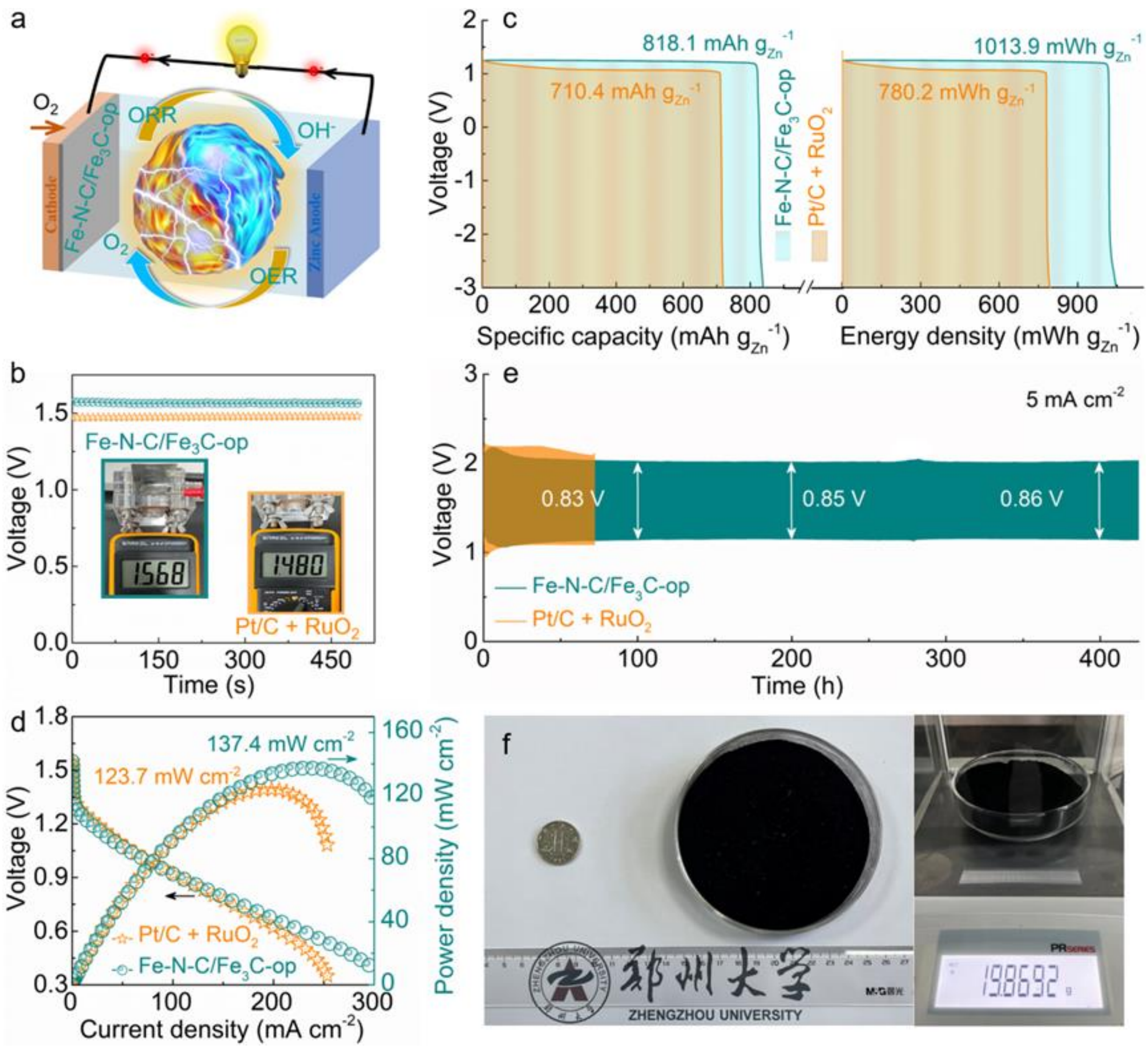
e) Bifunctional LSV curves tested in a 0.10 M KOH solution.

f) Correlation between the value of ΔE and $Fe-N_4-C/Fe_3C$ ratio , revealing the optimal ratio in $Fe-N-C/Fe_3C$-op.

g) Comparison of the bifunctional ORR/OER activity of $Fe-N-C/Fe_3C$-op and other electrocatalysts.

Rechargeable ZAB based on Fe-N_4-C/Fe_3C Catalyst

The Fe-N_4-C/Fe_3C catalyst delivered state-of-the-art bifunctional ORR/OER activity.



Performance of rechargeable ZABs.

a) Schematic diagram of the Fe-N-C/Fe_3C-op-based ZAB.

b) Open-circuit voltage test. The inset shows the VOC of the assembled ZABs.

c) Specific capacity and energy-density curves of ZABs fabricated with Fe-N-C/Fe_3C-op and Pt/C + RuO_2

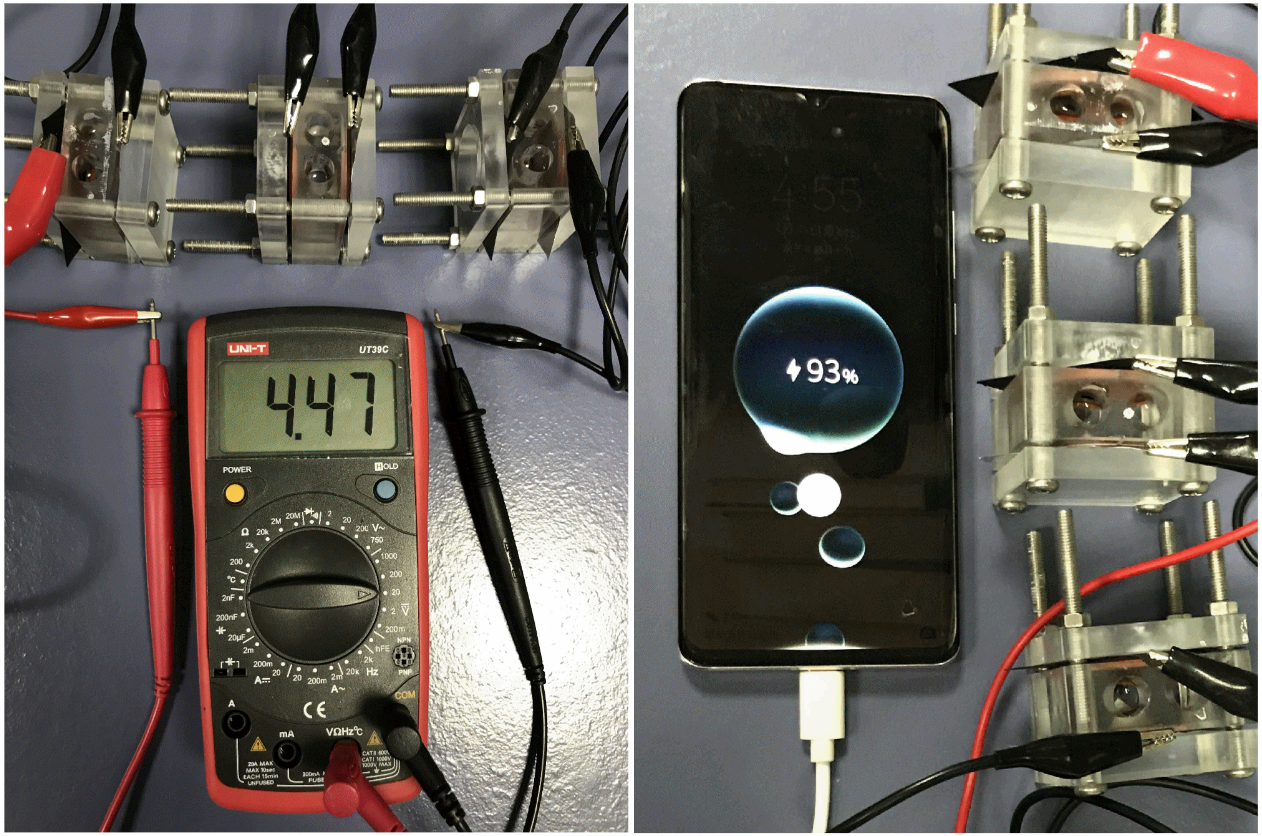
d) LSV profiles and power density curves of the ZABs with Fe-N-C/Fe_3C-op and Pt/C + RuO_2

e) Charge-discharge cycling curves of rechargeable ZABs with Fe-N-C/Fe_3C-op and Pt/C + RuO_2 electrocatalysts at a constant current density of 5 mA cm^{-2}.

f) Photograph of a 20 g batch of the Fe-N-C/Fe_3C-op electrocatalyst.

Journey from Lab to Real Batteries

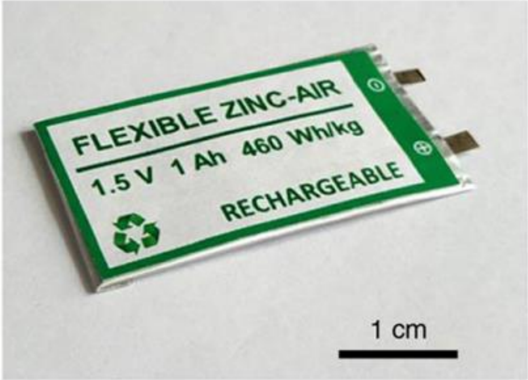
Having designed excellent ORR/OER catalysts for zinc-air batteries, we now need to work on building larger, space efficient modular battery systems.

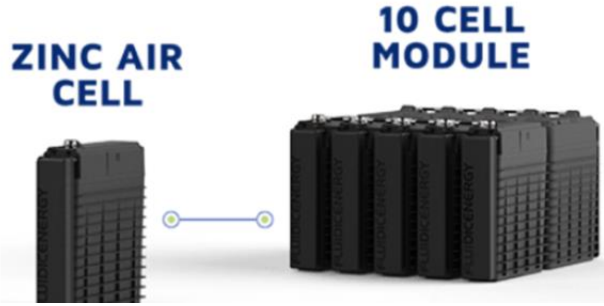


Open circuit voltages (OCV) for three zinc-air batteries in series, and a demonstration of smart phone (Huawei) charging by three zinc-air batteries linked in series.

Journey from Lab to Real Batteries

Aim to fabricate cells that can be assembled into modules, as well as pouch type flexible batteries. Market needs batteries operating **below the $100 per kWh mark.**



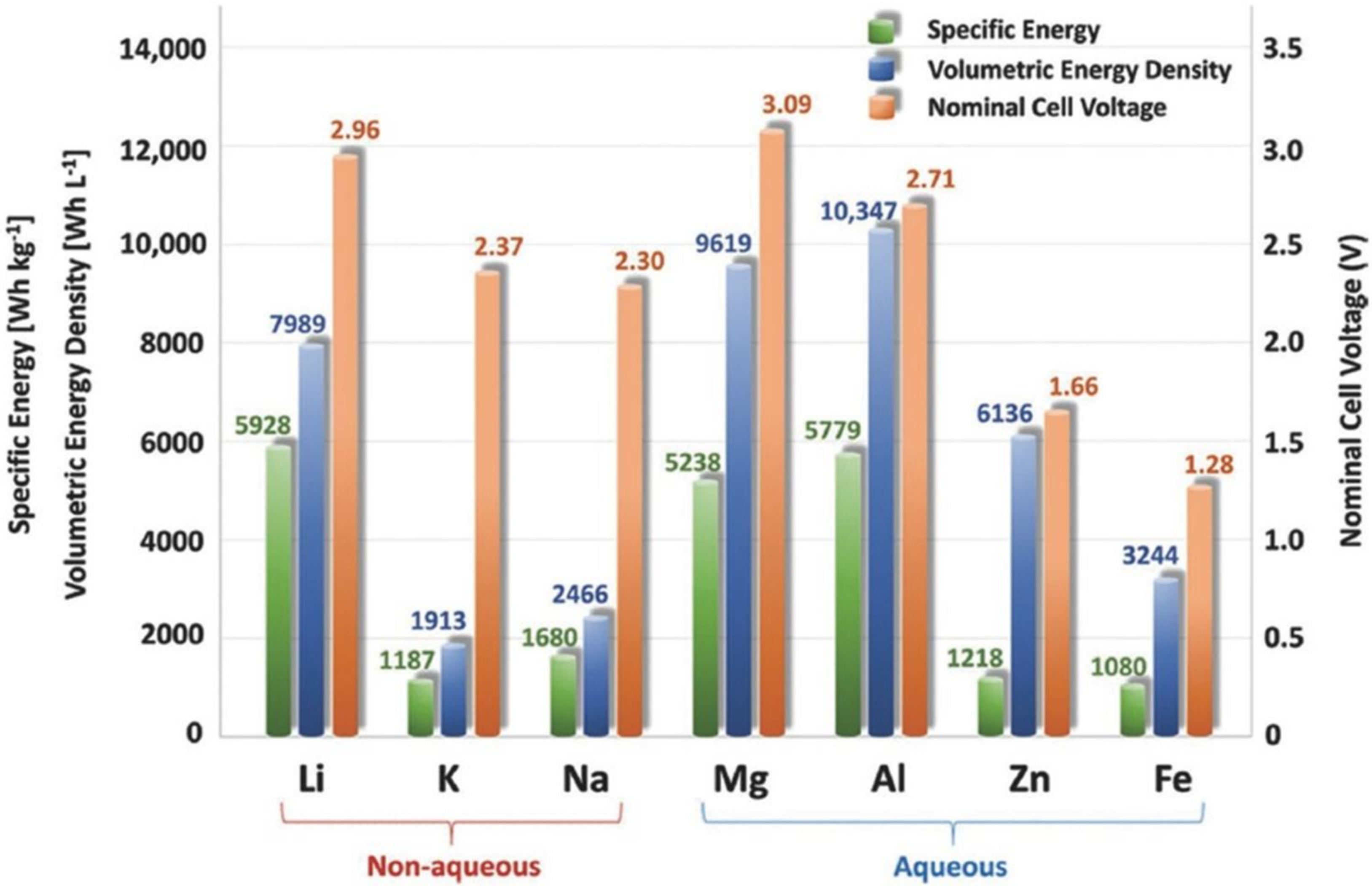


EV enthusiasts Kathryn and Greg Trounson who fund our zinc-air battery research.

https://cleantechnica.com/2018/09/28/nantenergy-says-zinc-air-battery-ideal-for-grid-storage/

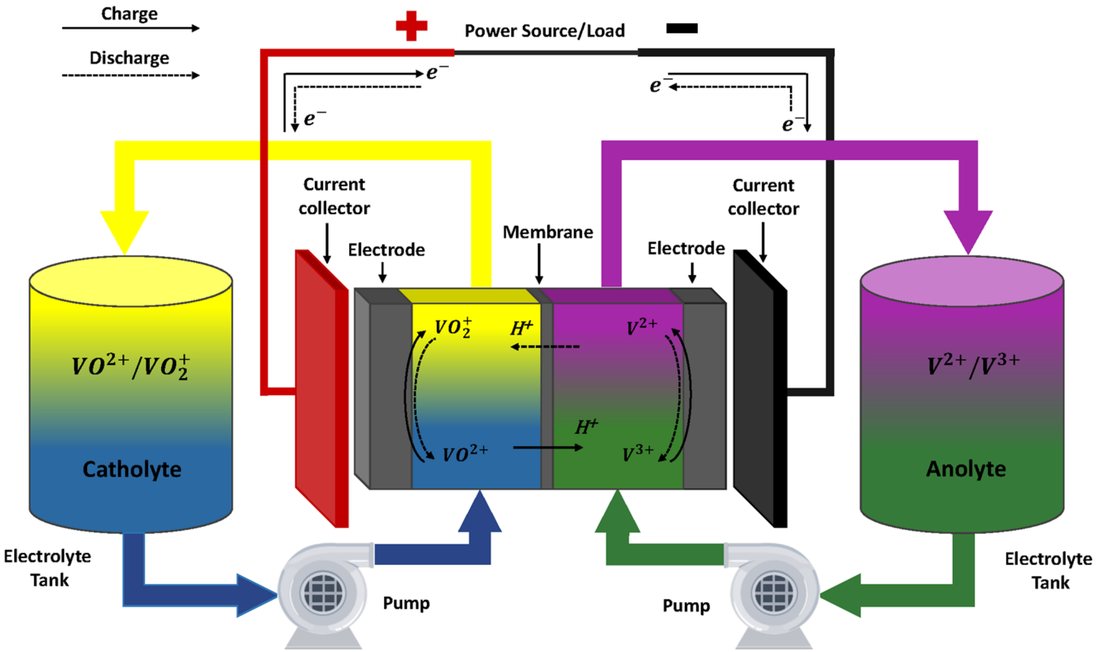
Other Rechargeable Metal-air Batteries

The same catalyst is now being used in the development of other types of metal-air battery with higher energy densities.



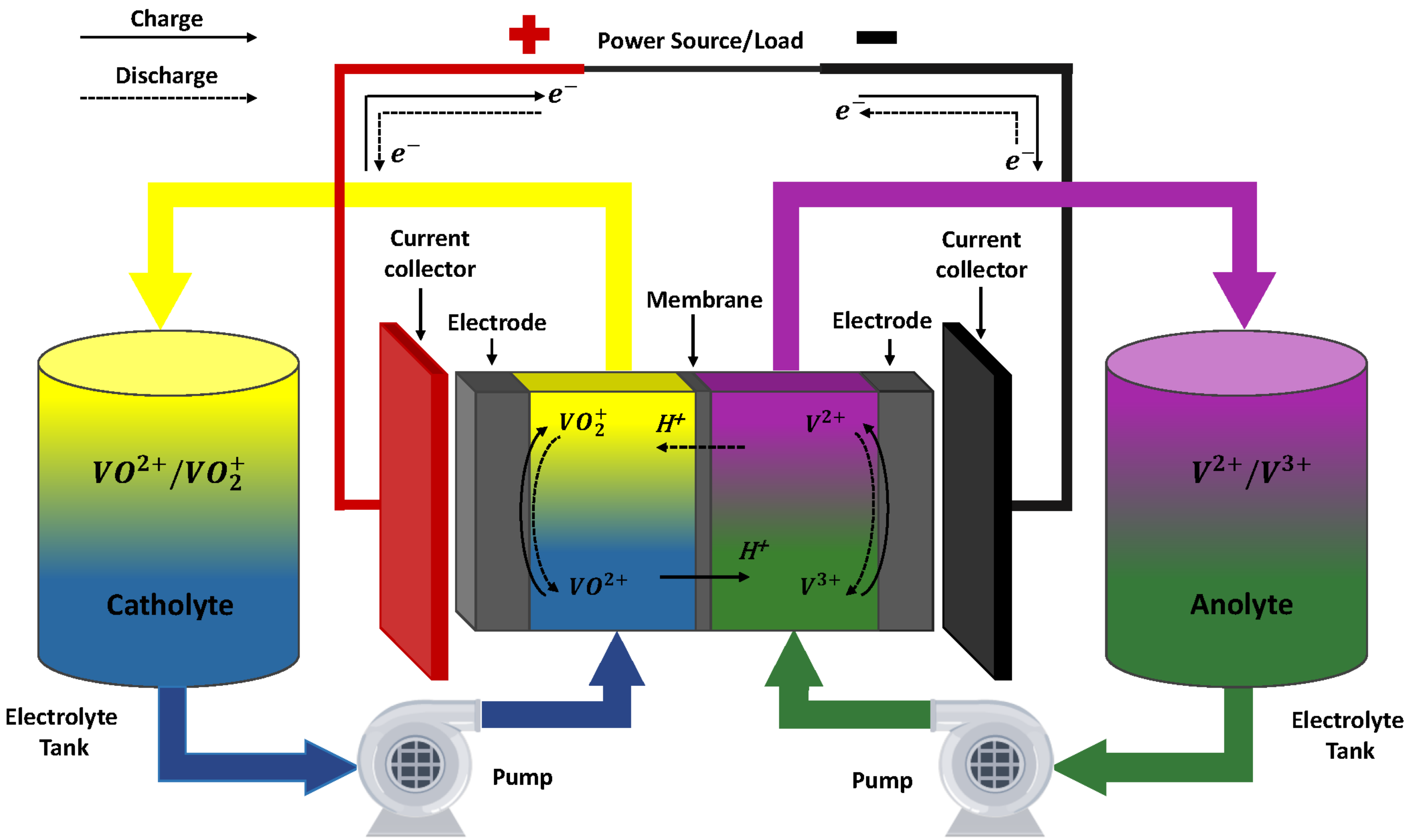
Vanadium Redox Flow Batteries

Vanadium redox flow batteries hold great promise for large-scale stationary electricity storage.



Under standard conditions, the overall cell potential is 1.26 V at 25 °C, but for an electrolyte composition of 2 M vanadium in 5 M sulfuric acid open-circuit potentials of 1.4 and 1.6 V can be measured at 50% and 100% state-of-charge (SOC), respectively .

https://www.youtube.com/watch?v=TSsqCazP1V0



Positive electrode reactions:

$VO^{2+}(aq) + H_2O \longrightarrow VO_2^{+}(aq) + 2H^{+}(aq) + e^{-}$ **charge**

$VO_2^{+}(aq) + 2H^{+}(aq) + e^{-} \longrightarrow VO^{2+}(aq) + H_2O$ **discharge**

Negative electrode reactions:

$V^{3+}(aq) + e^{-} \longrightarrow V^{2+}(aq)$ **charge**

$V^{2+}(aq) \longrightarrow V^{3+}(aq) + e^{-}$ **discharge**

Overall cell reactions:

$V^{3+}(aq) + VO^{2+}(aq) + H_2O \longrightarrow V^{2+}(aq) + VO_2^{+}(aq) + 2H^{+}(aq)$ **charge**

$V^{2+}(aq) + VO_2^{+}(aq) + 2H^{+}(aq) \longrightarrow V^{3+}(aq) + VO^{2+}(aq) + H_2O$ **discharge**

Vanadium redox flow batteries (VRBs) are ideal for medium- and large-scale energy storage.

An **all-vanadium redox flow battery (VRB) that was pioneered at the University of New South Wales** in Australia is currently considered one of the most promising battery technologies that will be able to meet the growing global need for stationary energy storage. It has been extensively field tested in a range of applications, including wind and solar energy storage, load leveling, peak shaving, and emergency backup systems with kW to MW power rating, and has demonstrated overall energy efficiencies of up to 80% and more than 200,000 cycles.

Summary

- Decarbonisation of the global energy sector will require massive investment in technologies for electricity generation from renewables and in efficient electrical energy storage technologies.

- Both hydrogen and rechargeable batteries will play important roles in energy storage.

- The battery market is growing rapidly, driven by the renewable energy sector and the EV sector.

- Current rechargeable battery technologies, such as Li-ion batteries, are good but rely on certain critical elements (Li, Co, Mn, Ni) which are not geographically well-distributed.

- Metal-air batteries hold great promise for EVs and portable electronic devices due to their extremely high energy densities (>> Li-ion batteries), whilst redox flow batteries are attractive for long-term stationary electricity storage.

Thanks for your attention! **g.waterhouse@auckland.ac.nz**

Metal/air battery	Calculated OCV, V	Theoretical specific energy, Wh/kg	
		Including oxygen	Excluding oxygen
Li/O_2	2.91	5200	11140
Na/O_2	1.94	1677	2260
Ca/O_2	3.12	2990	4180
Mg/O_2	2.93	2789	6462
Zn/O_2	1.65	1090	1350