Batteries and Electric Vehicles - How materials will decarbonise transport

Hatfield Lecture
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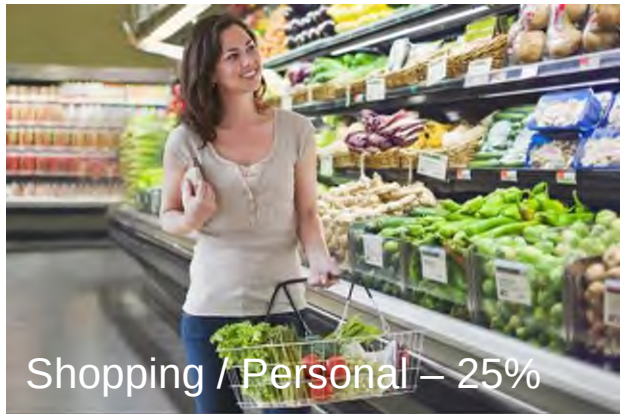
December 2024 d.greenwood@warwick.ac.uk

Transport is essential to our personal and business lives

Moving People



Moving Goods

Source: UK Department for Transport National Travel Survey 2014

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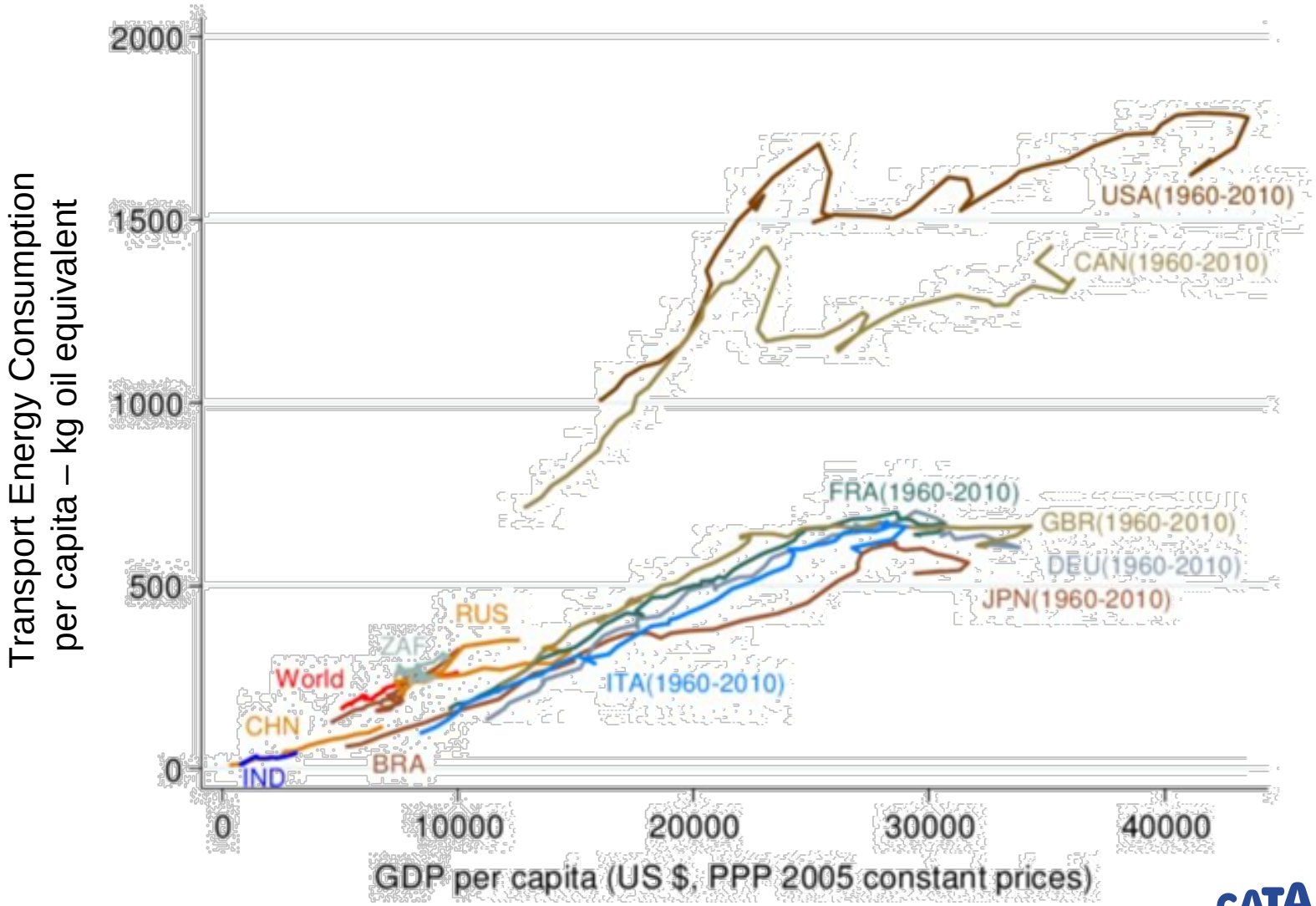
Transport is strongly correlated to economic growth



Source: Gao Y-X, Liao H, Burke PJ, Wei Y-M. 2014.
Road transport energy consumption in the G7 and BRICS: 1973-2010. CEEP-BIT Working Paper

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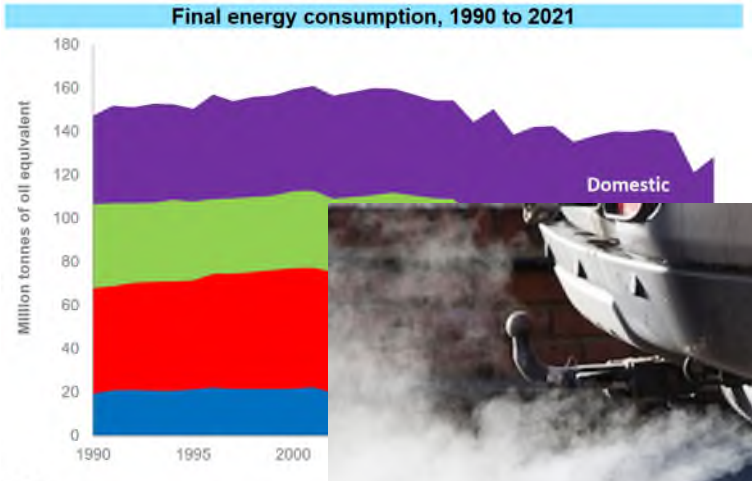
But transport growth comes at a cost



2021

	Indust
Coal & manufactured fuels	1
Gas	9
Oil	2
Electricity	7
Bioenergy and heat	2
Total	**22**

Energy Demand

Air Quality

Climate Change

Congestion

Accidents

Source: London Fire Brigade

What can we do about it ?

Manage Demand

- Travel Less


- Use best transport mode



- Manage transport network


Improve Technology

- Reduce vehicle mass and drag

- Improve powertrain

- Reduce carbon in fuel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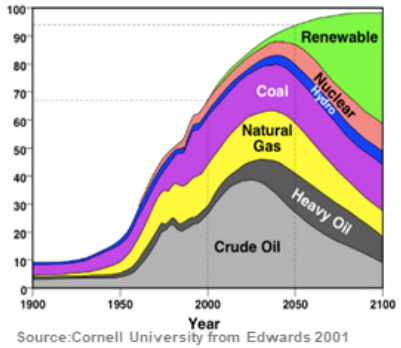
Why will the UK adopt EVs ?

Energy Security



Source:Cornell University from Edwards 2001

Climate Change & Air Quality

Electrification

Industrial Opportunity

Consumer demand

Source:Adweek

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UK Policy context for Electric Vehicles
Bans on sale of new petrol and diesel vehicles

27 June 2019: Chris Skidmore, Energy and Clean Growth Minister signs into UK law to reduce emissions to **Net Zero by 2050**

18 Nov 2020: Boris Johnson, Prime Minister announces 10 point plan. 4. **Phasing out sales of new petrol and diesel cars and vans by 2030**, and requiring **ZEV by 2035**

21 September 2023: Rishi Sunak announces “5 year delay” – “requirement for all cars to be **zero emissions will not come into force until 2035**” (scrapping of 2030 requirement)

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UK Policy context for Electric Vehicles
Zero Emissions Mandate

28 September 2023: Mark Harper, SoS for transport confirms "**Zero Emissions Mandate**" requires 80% of new cars sold to be EV by 2030, and 100% by 2035 (or heavy fines for auto makers)

- Impact of "withdrawal" of 2030 date is minimal
- Car makers already "pregnant" with models for 2030 – unlikely to change plans
- Technically the 20% on non-EVs from 2030-2035 can now be petrol or diesel instead of plug in hybrid

- But - may impact confidence in investment in charging infrastructure ?
- And – dented consumer confidence (along with poor quality press on EVs)

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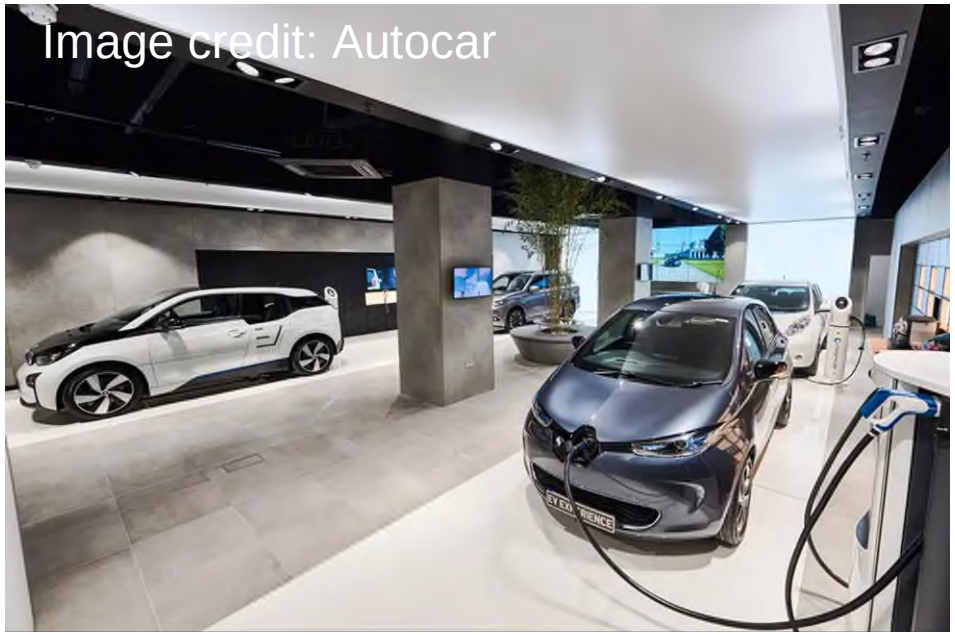
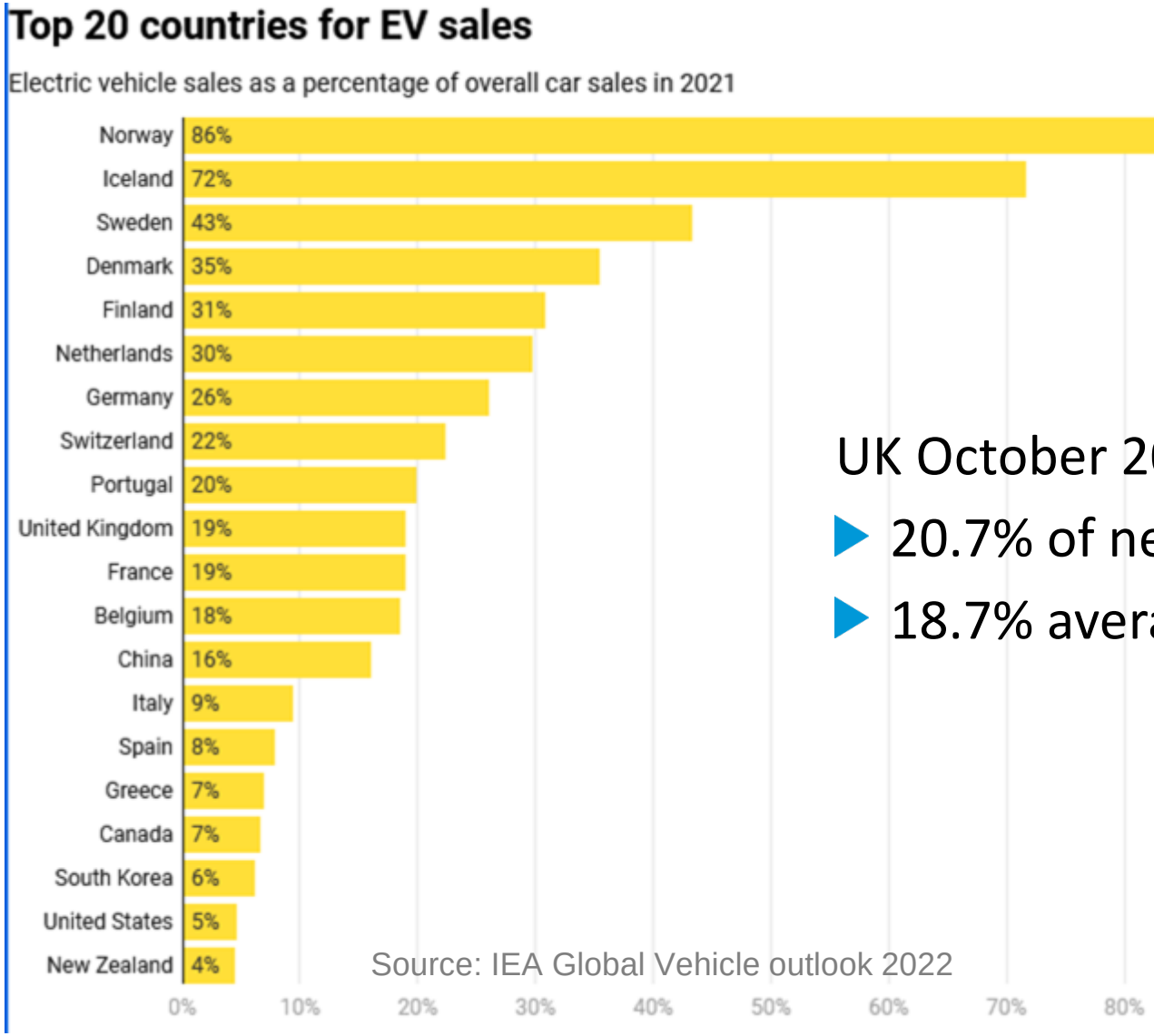
UK Policy context for Electric Vehicles
Measures to promote EV sales

- **Benefit in Kind tax**
  - Fixed at 2% until 2025
  - rising 1% per year until 5% at 2028
  - (compared with 37% for big conventional car)
  - combined with salary sacrifice schemes
- **Vehicle Excise Duty**
  - £0, until April 2025
  - Then £10 in first year and £165 thereafter
  - (+£390 per year “expensive car supplement” for 5 years)
- **Cost of Fuel**
  - Much cheaper when domestic charging
  - VAT and higher rates charged for public charging
- Currently **few real incentives for private buyers, or second hand** buyers…
  - though these are in place in Scotland and under discussion for UK



And market penetration is increasing



Source: IEA Global Vehicle outlook 2022

UK October 2024 (SMMT) Statistics:

- 20.7% of new car sales were EV in October 2024
- 18.7% average EV sales for 2024 YTD

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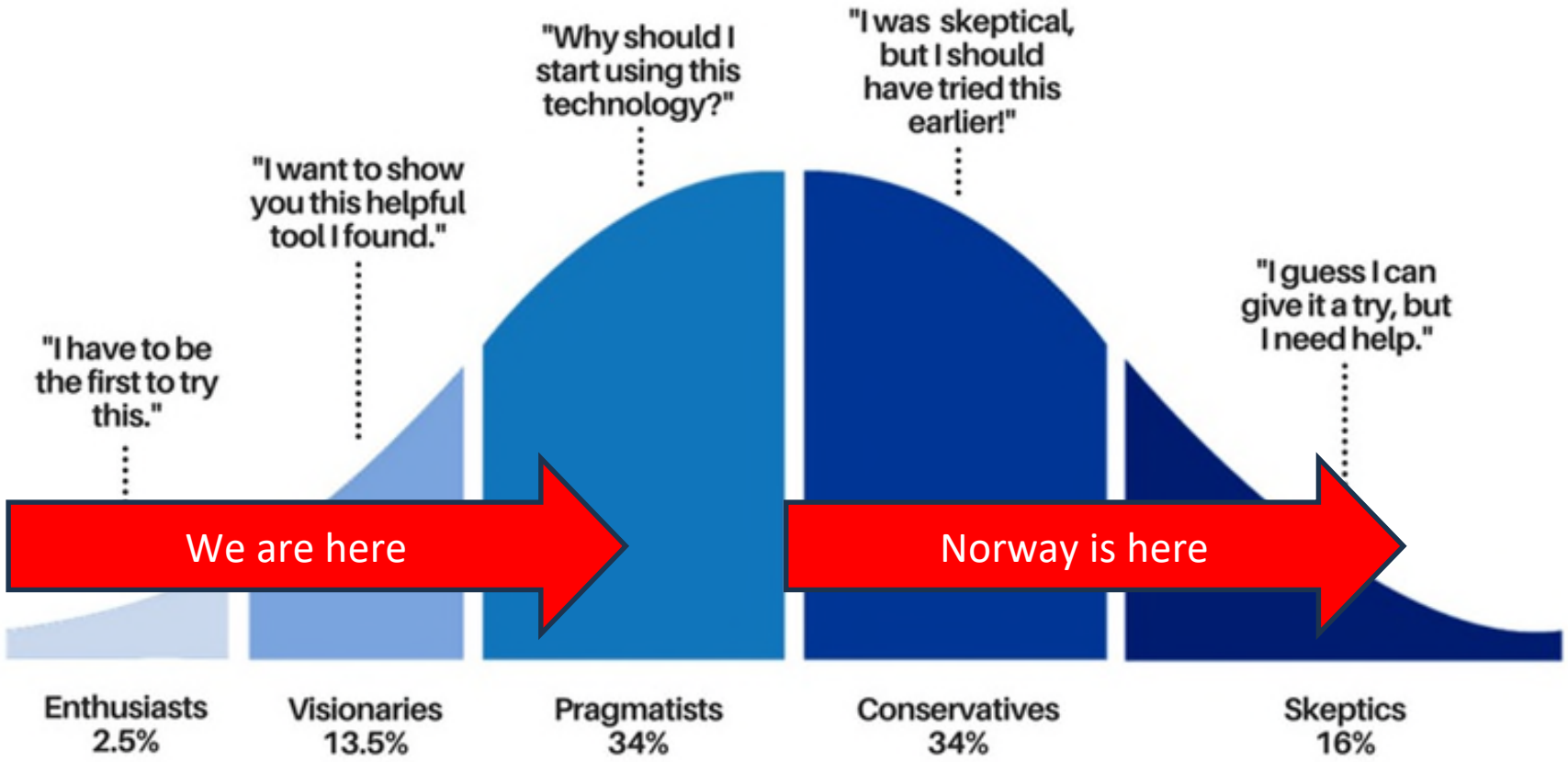
Market Adoption Curve



https://www.cblohm.com/blog/uncategorized/adoption-curve-education-marketing-strategy/

Why don’t people buy EVs ?

Why would you not buy (or lease) an electric vehicle?

	Reason given	% of responses
1	Cost	64.1%
2	Lack of charging infrastructure	53.9%
3	Limited driving range	53.8%
4	Charging time	48.2%
5	Concerns about battery life	45.8%
6	Inconvenience	29.4%
7	Prefer to drive a car with a manual transmission	16.9%
8	Prefer to drive a vehicle with an internal combustion engine	16.4%
9	Lack of Incentives and subsidies	14.0%
10	Limited model availability	11.1%
11	Environmental concerns	9.4%
12	Limited performance options	8.3%
13	Other (please specify)	3.5%

- Battery
- Charging Infrastructure
- Other

DriveElectric

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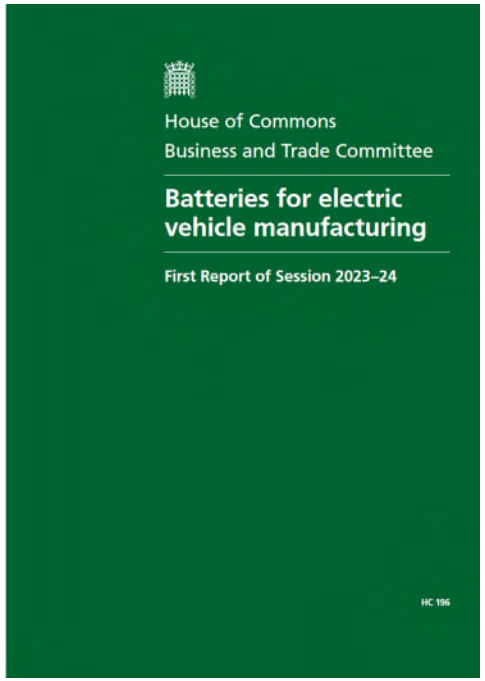
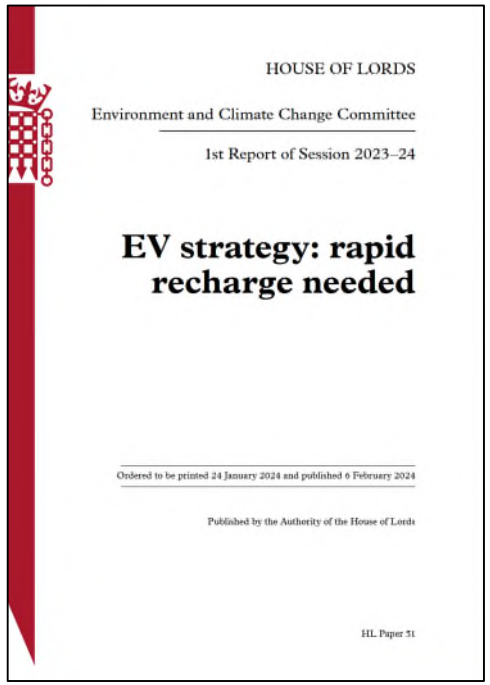
Recent UK policy announcements





- £2bn in new Automotive R+D funding up to 2030
- R&D grants, Scale up grants, Capital grants, linkage of public to private finance
- Secure supply chain and critical minerals (including recycling)
- Manufacturing skills
- “Battery Strategy Taskforce”

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Batteries

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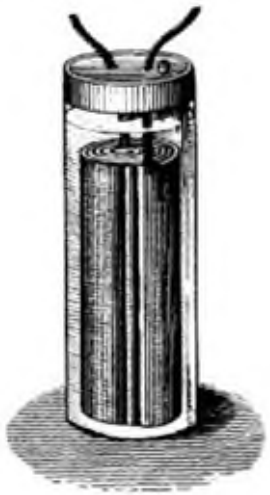
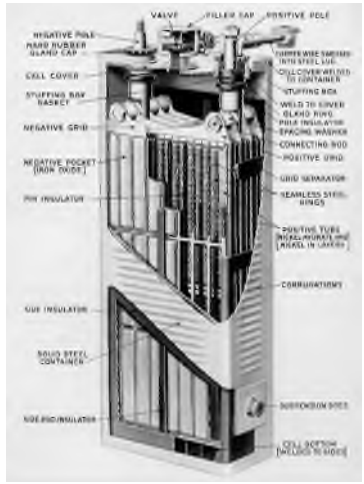
Batteries have been improving for over 2000 years

0
Bhagdad Cell
Cu Fe, Vinegar

1800
Volta
Ag Zn, brine



1860
“Lead Acid”
Plante
Pb, H_2SO_4



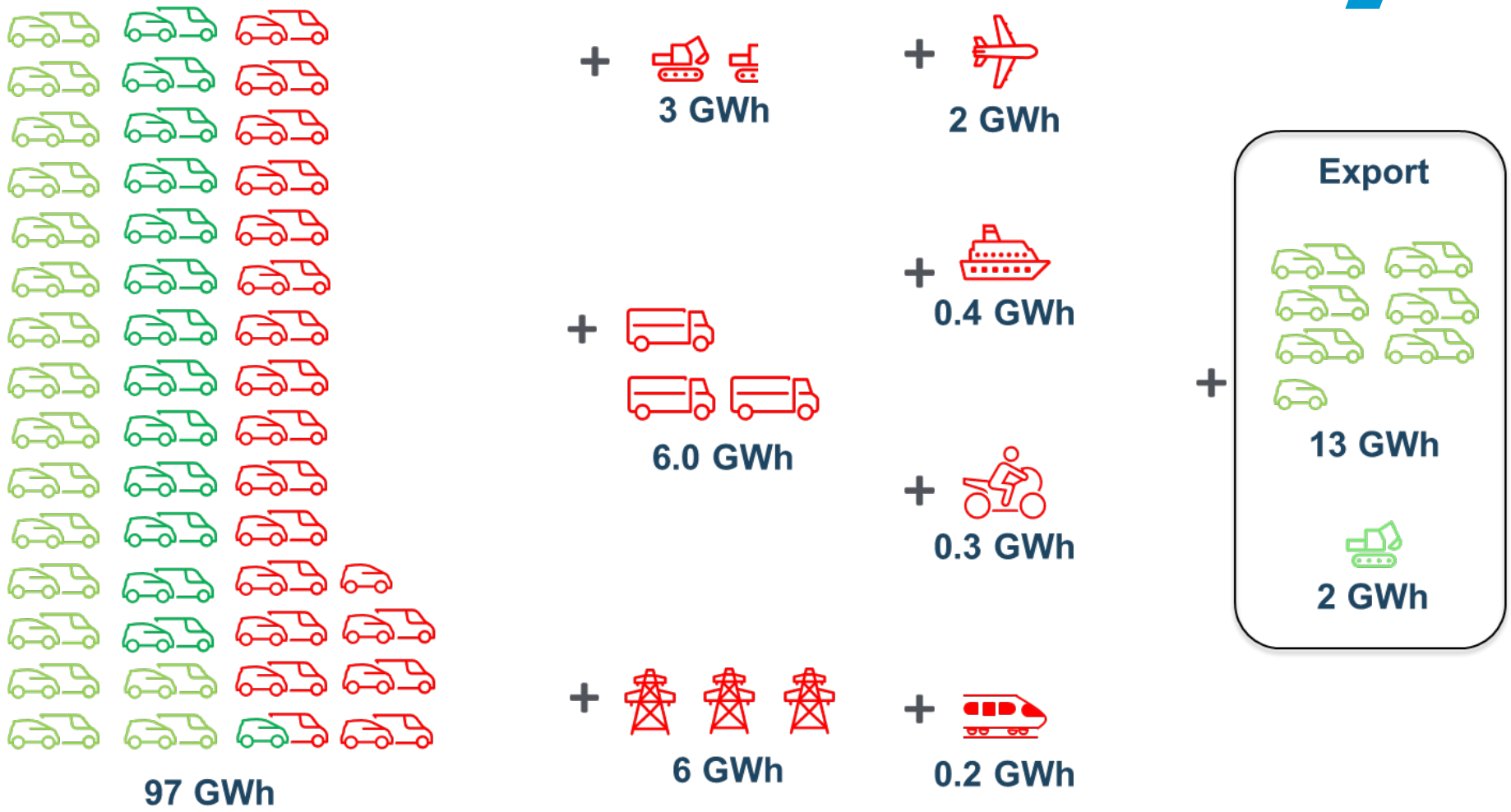
1898
“Alkaline”
Edison
Fe Ni, KOH

1936-40
“Ni-Cad”
Various
Ni Cd, KOH

1970s
“NiMH”
Various
Ni “M”, KOH

1980s
“Li-Ion”
Goodenough
$LiCoO_2$ C,

Forecast Battery Demand for UK-Manufactured Products



115GWh cell demand for UK manufactured products by 2035

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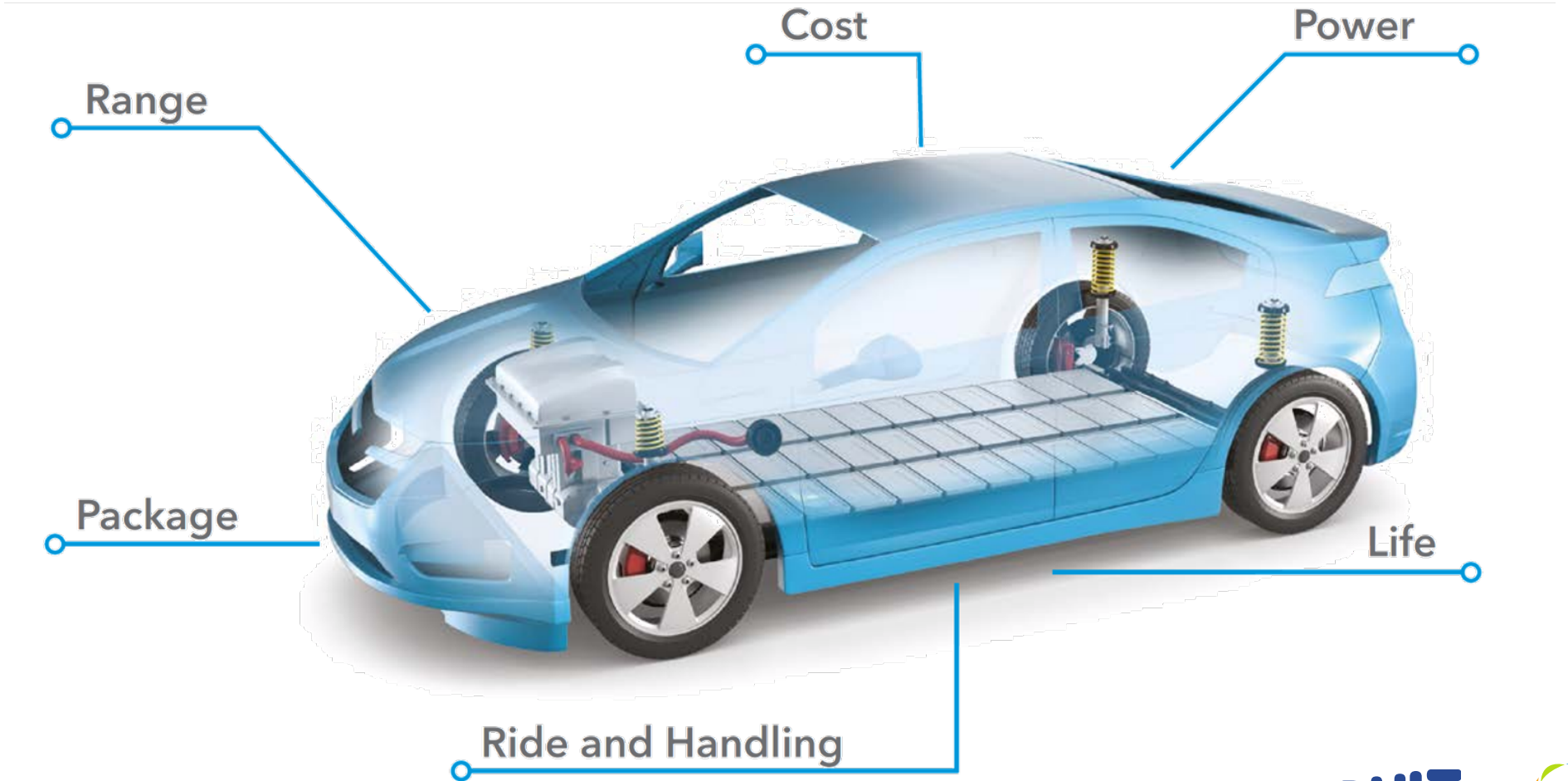
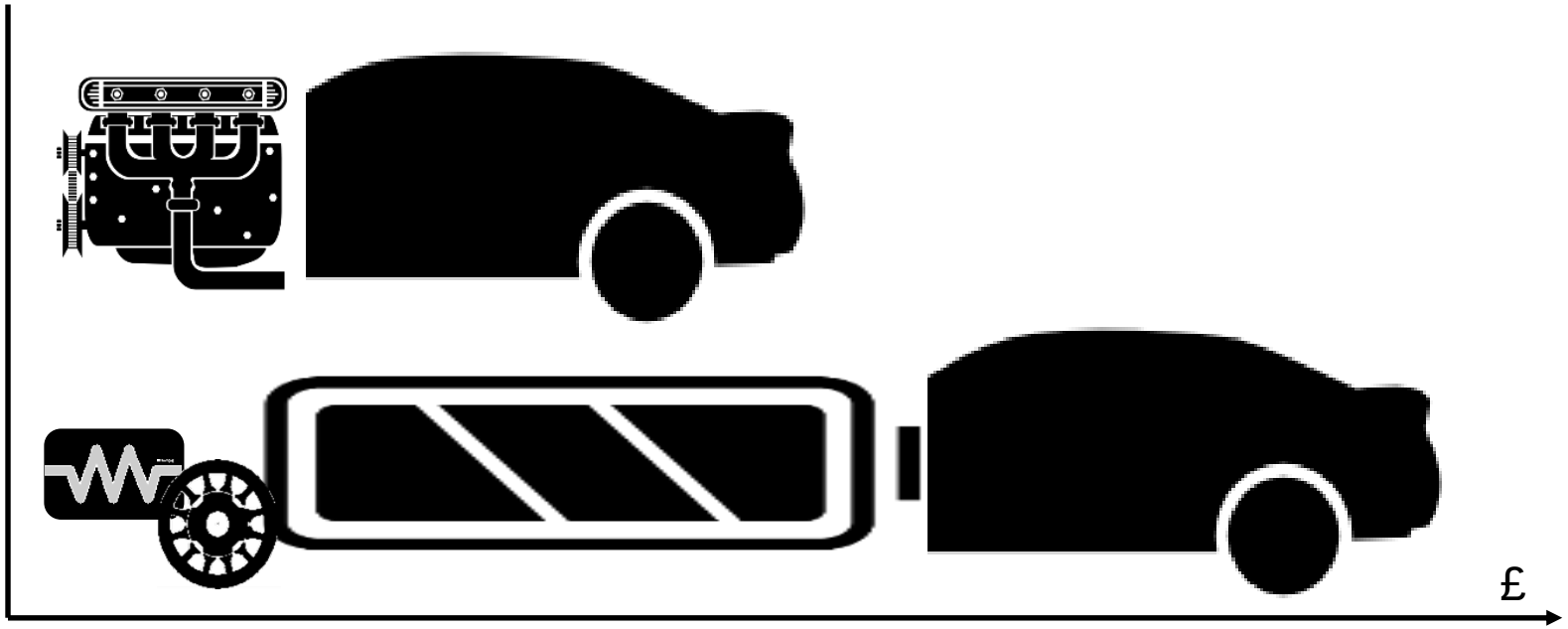
The battery is the defining component of the electric car



Batteries dominate the cost (and value) of an electric vehicle



By 2035, assuming 2M vehicles per year are made in the UK, we will need:

- £12bn/yr batteries
- £2bn/year Motors and Power Electronics
- £10bn/year vehicle components

- Motor and power electronics cost around 60% of conventional powertrain
- Battery costs around 3-5x current powertrain
- Rest of vehicle costs similar as before
- Battery is around 50% of overall vehicle value of an electric vehicle
- Price parity with ICE expected before 2030

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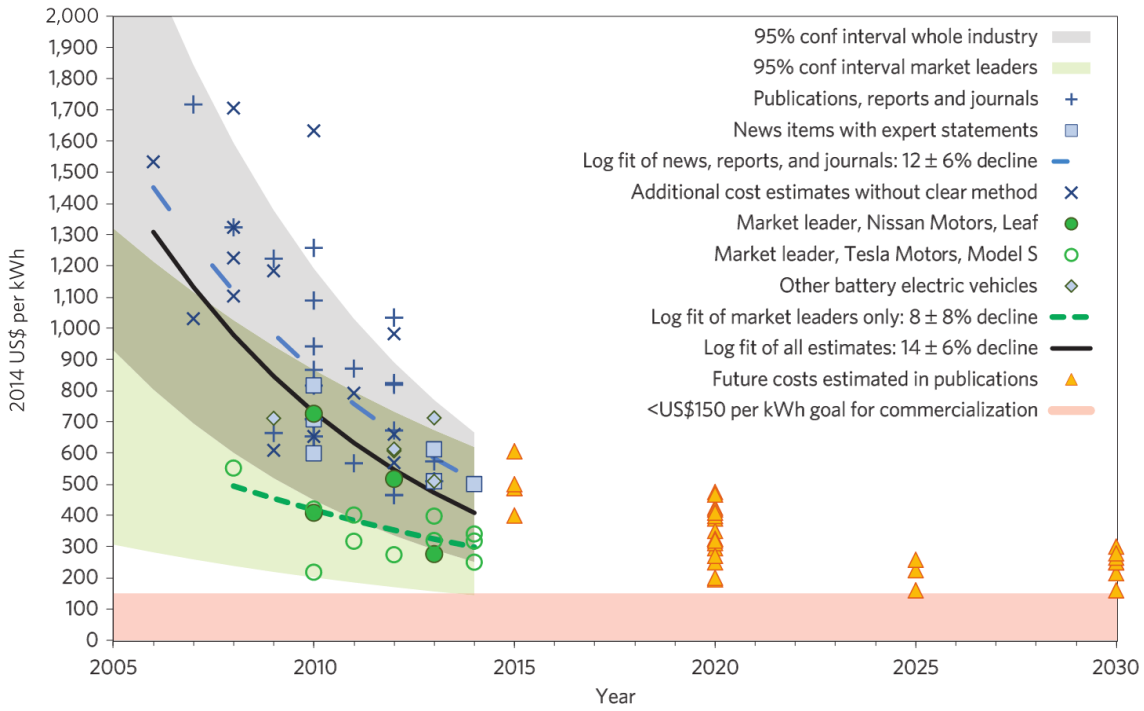
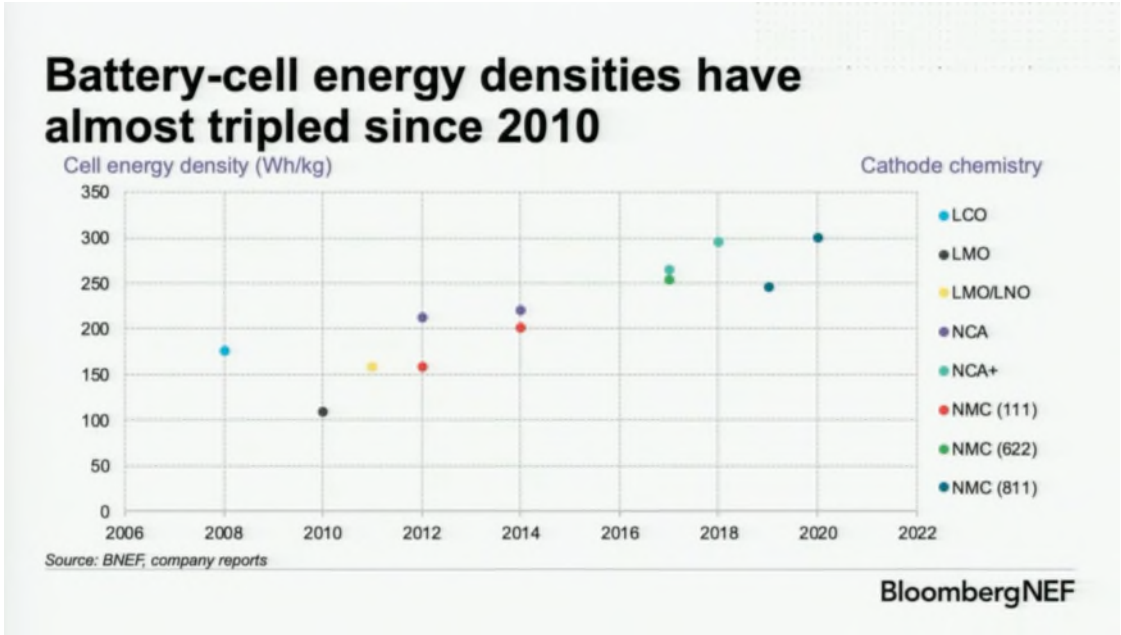
Battery improvements have made EVs increasingly feasible

- Costs have fallen dramatically due to technology, production volume and market dynamics
- Pack cost fallen from $1,000/kWh to <$200/kWh in less than 10 years- and will get below $100/kWh

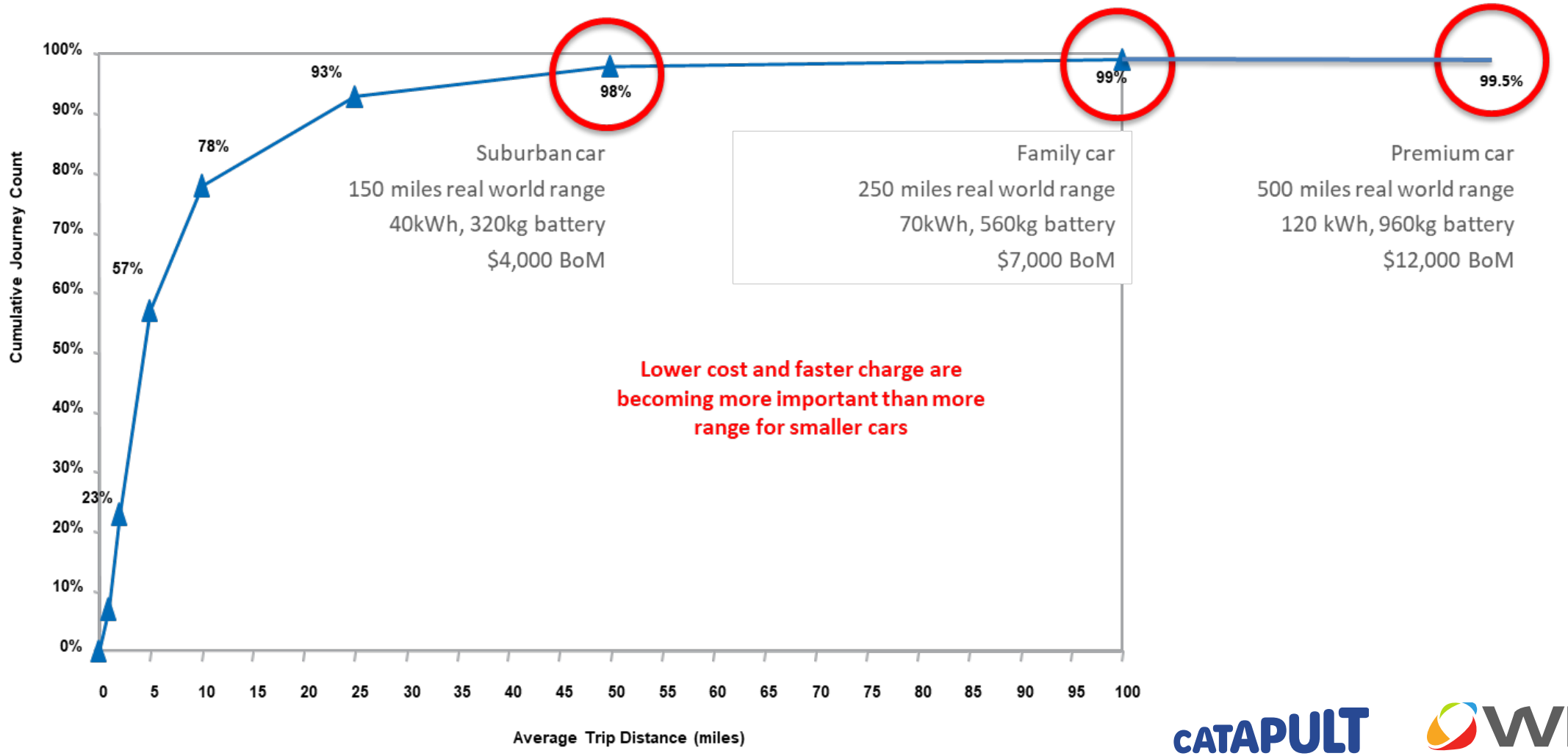


Nykvist et al 2014



- Volumetric energy density is increasing due to better materials and cell structure
- Requires continued innovation to continue

How much range (and battery cost do we need ?)



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Automotive requirement will diverge

High energy density
For all EVs
NCA, NMC

Ultimate energy density
For long range premium EV
NMC -> solid state

Lowest cost / kWh
For mass market cars
LFP -> Na-Ion

High power density
To support fuel cells and hybrids
NMC, LFP,

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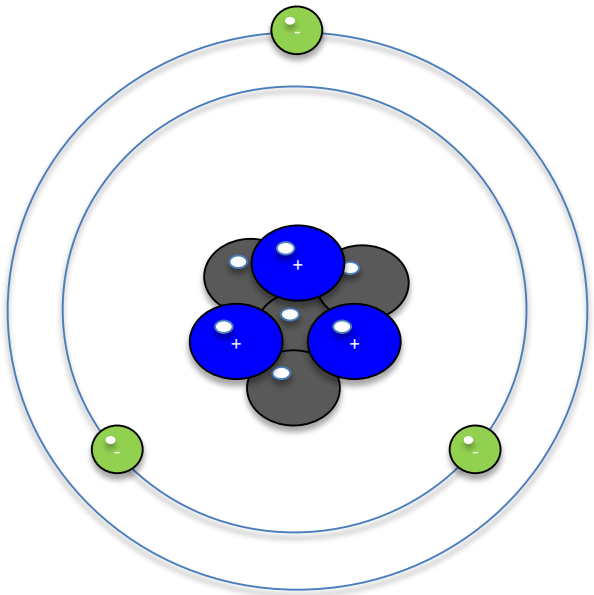
Battery 101 – How does a lithium ion battery work

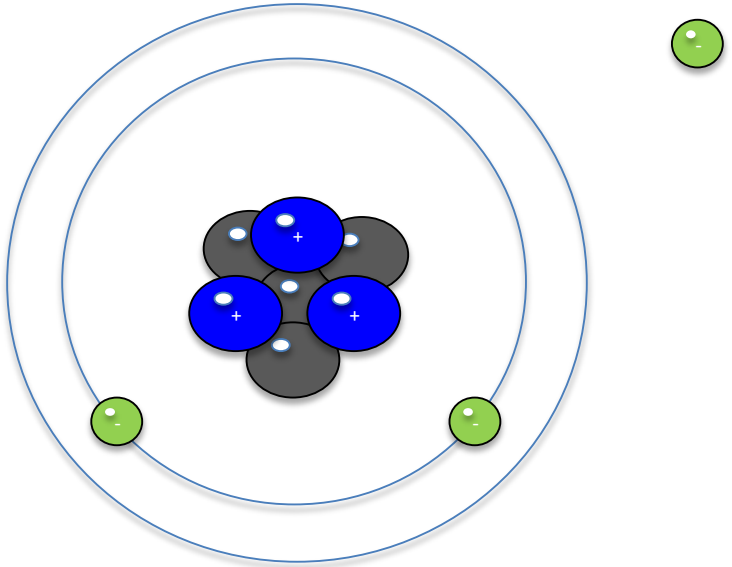
Lithium Atom comprises:

- 3 protons (+ve charged)
- 4 Neutrons (no charge)
- 3 electrons (-ve charge)



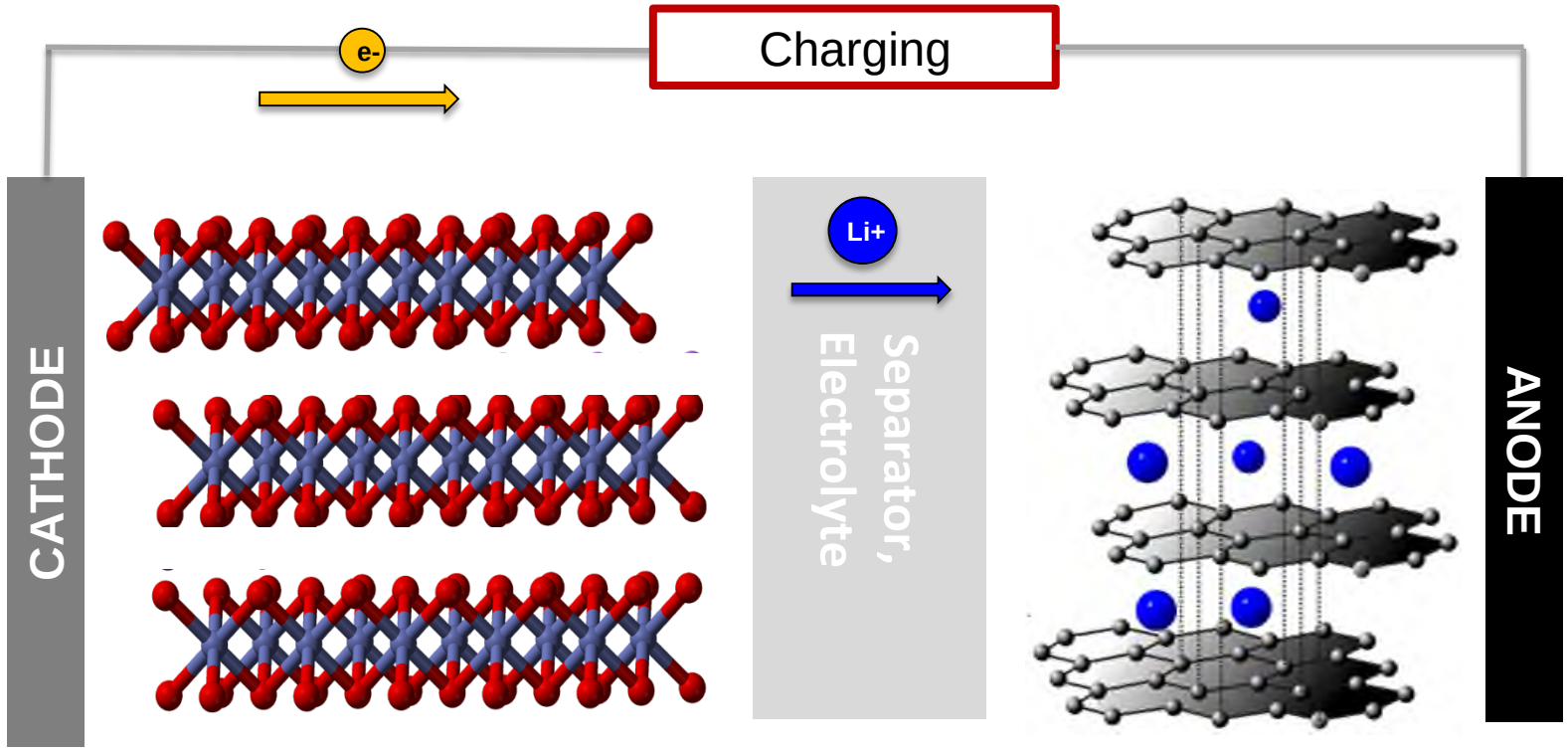
Electron in outer shell can be stripped away forming positively charged **Lithium Ion**

and a negatively charged **electron**



Battery 101 – How does a lithium ion battery work

Charging a battery turns a lithium atom into a lithium ion in the cathode, and transports it to the anode, where it meets an electron and turns back into a lithium atom

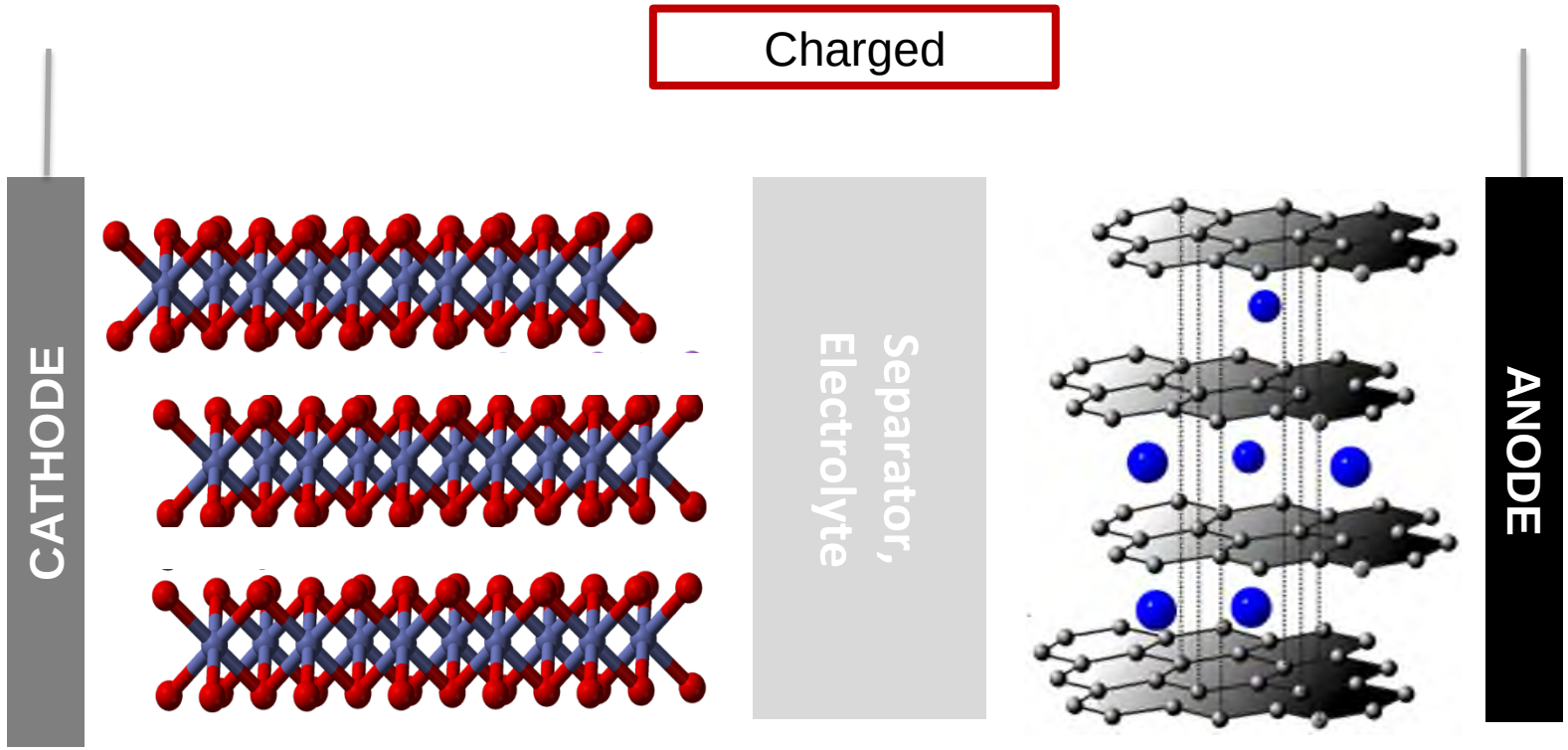


LITHIUM COBALT OXIDE – $LiCoO_2$

GRAPHITE

Battery 101 – How does a lithium ion battery work

Once charged, the separator stops the lithium atoms from passing back to the cathode

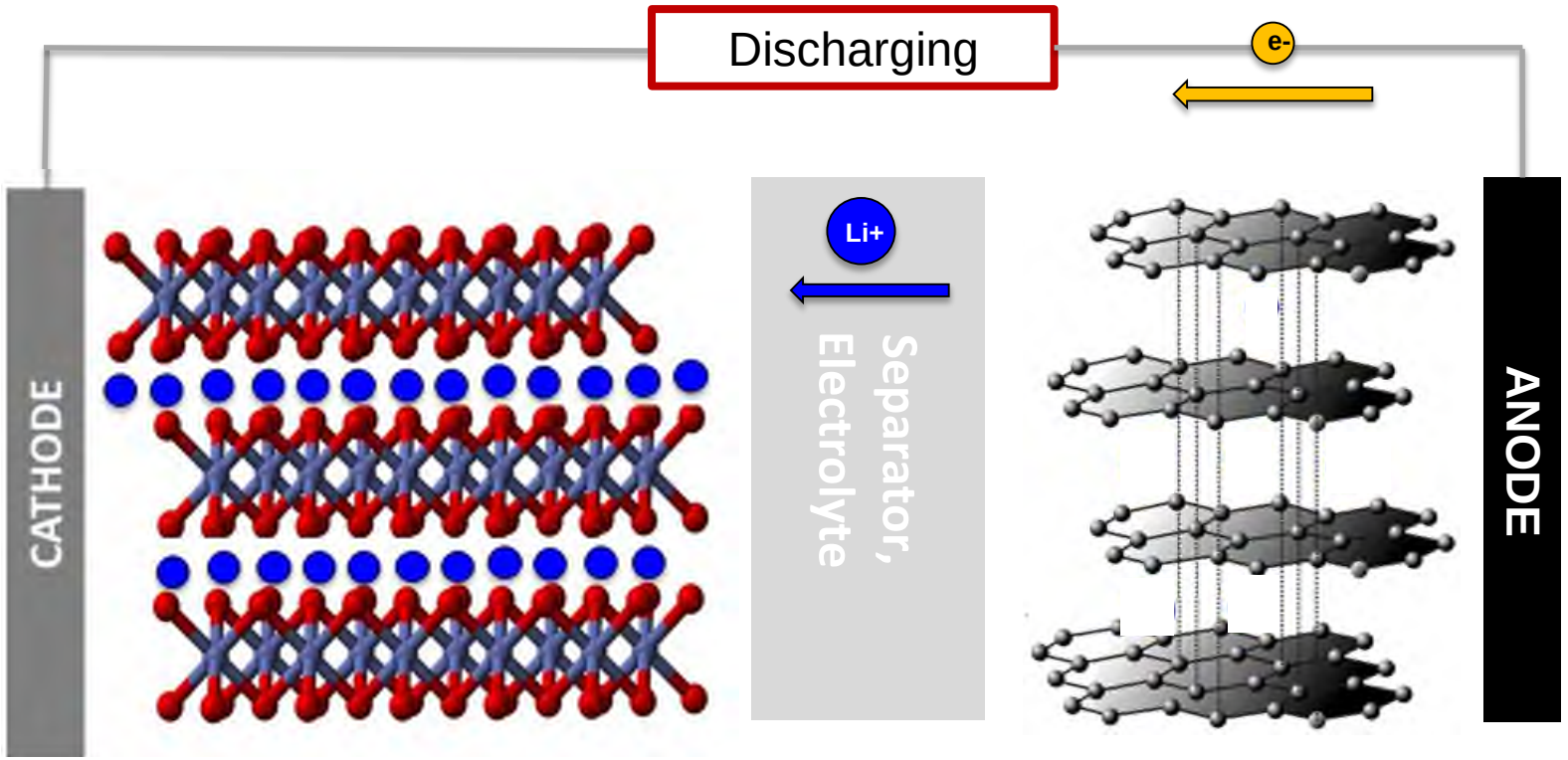


LITHIUM COBALT OXIDE – $LiCoO_2$

GRAPHITE

Battery 101 – How does a lithium ion battery work

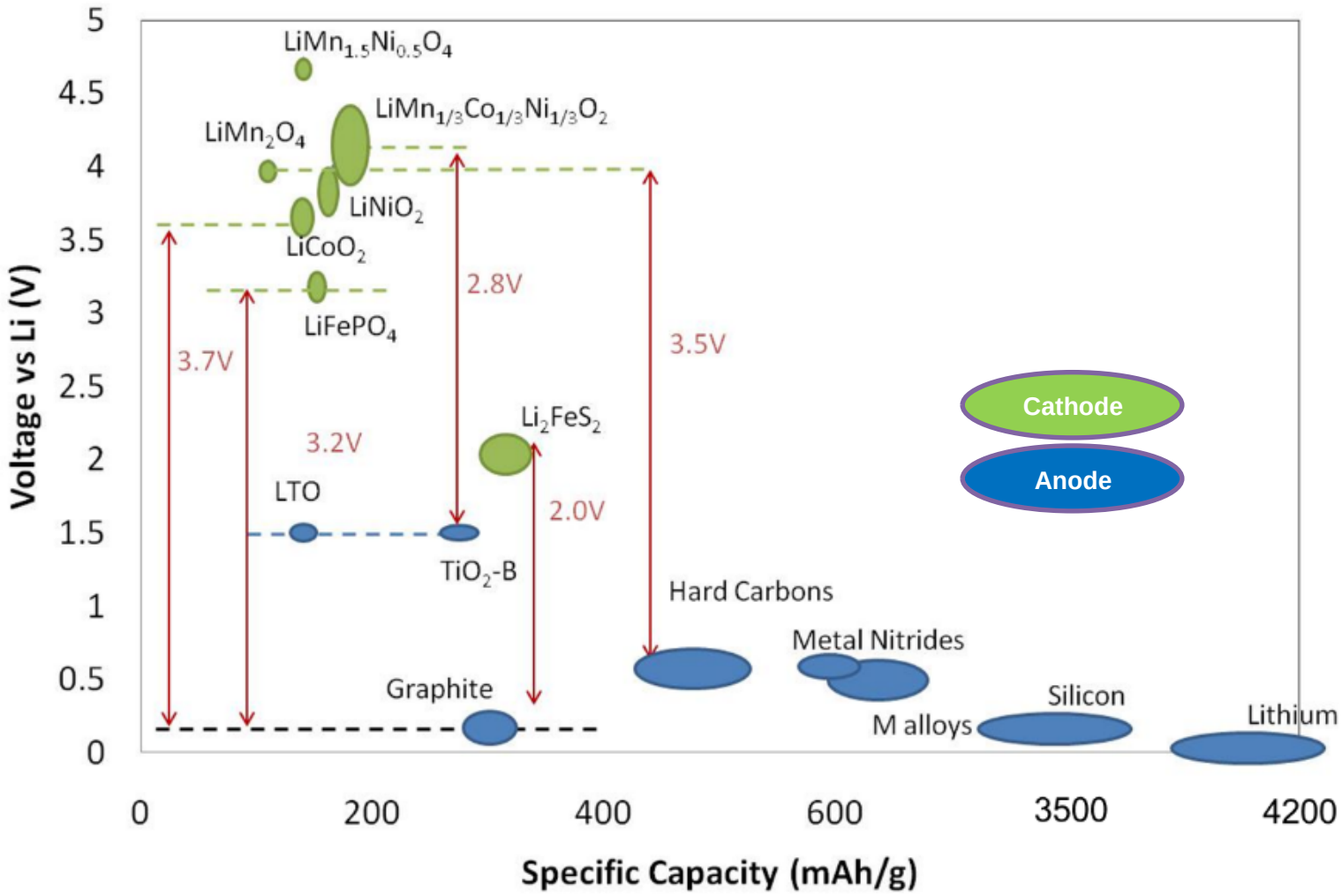
Connecting an electrical load allows the lithium atom in the anode to shed an electron and travel back to the cathode, where it meets an electron and turns back into a lithium atom.



LITHIUM COBALT OXIDE – $LiCoO_2$

GRAPHITE

Battery 101 – Different materials store lithium atoms at different electrochemical potentials



Anode / cathode materials: specific capacities and operating voltages vs pure lithium

Different chemistries suit specific requirements

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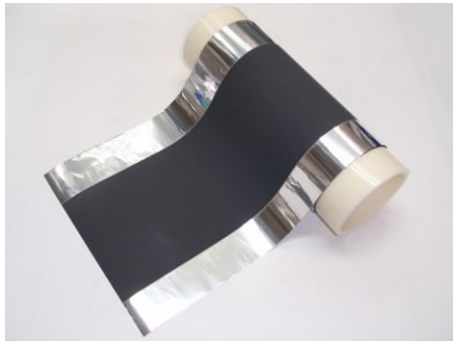
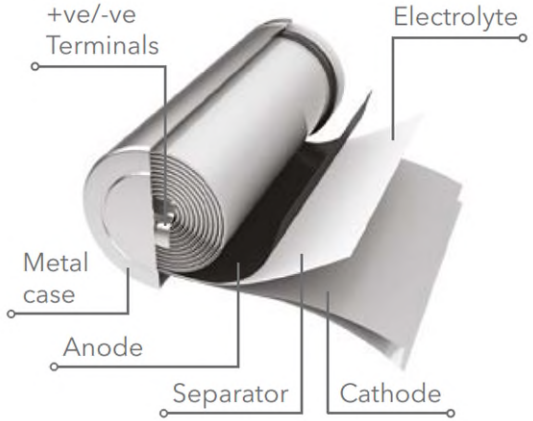
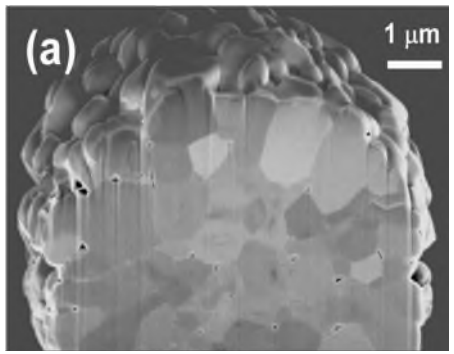
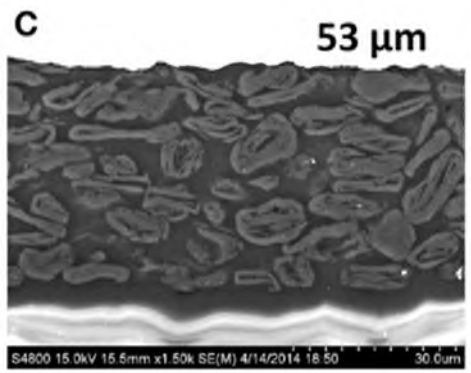
Battery 101 – What does that look like in real life ?



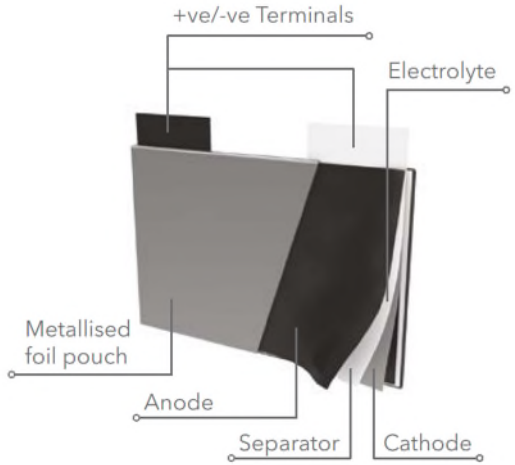




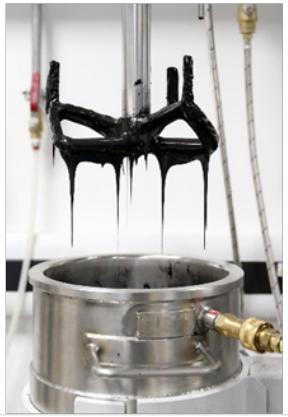
Gilbert et al.
Journal of The
Electrochemical Society
January 2017,
164(2):A389-A399

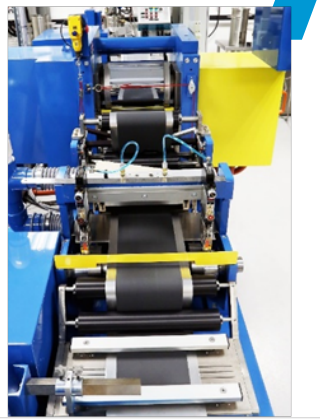


Sheng et al. Front Energy Res 5 December 2014



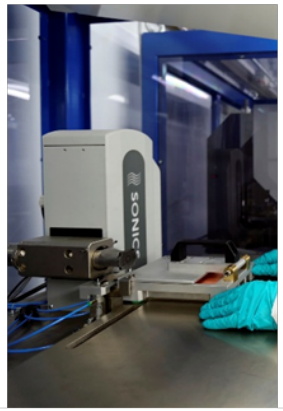
Battery 101 – The manufacturing process





Powder → Mixing → Coating → Evaporating → Calendering → Slitting

Electrode Manufacturing



Cell Stacking → Tab Welding → Packaging → Electrolyte Filling → Formation / Ageing → EOL Testing

Cell Assembly / Electrical Formation

Manufacturing will be as important as chemistry

“Gigafactories” make GWh capacities of cells per year

10GWh factory equates to:
- 1 large, or 15 small cells per second
- 160,000 cars
- 250,000m2
- 1000 workers
- £1.2bn Capex, £1bn turnover per year

They need large amounts of
- Land
- Power
- Capex

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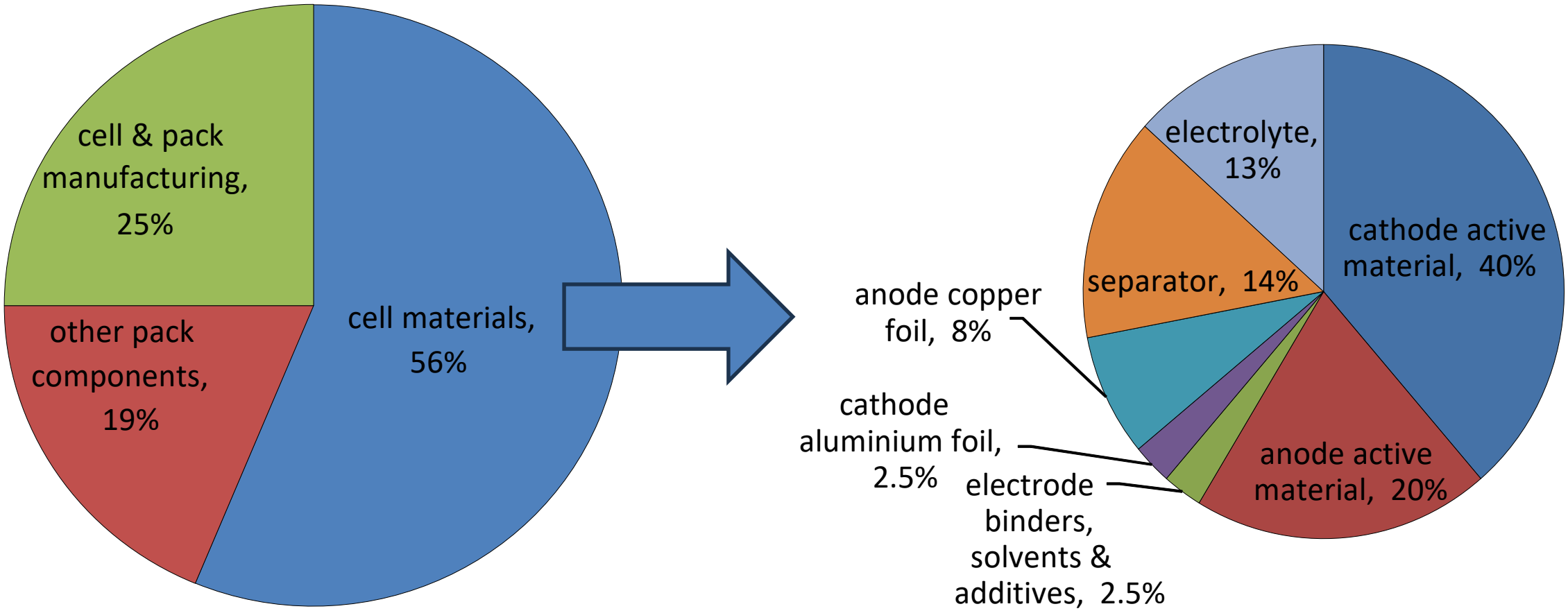
Battery 101 – where is the money ?



Future Technologies - Cells

Li-Ion family

Iron Phosphate (cost)

High Nickel (weight, volume)

Increasing Silicon in anode

Electrolytes for higher voltage (weight, volume, cost)

Sodium Ion family (Cost)

Lithium Sulfur family (weight, cost)

Solid State (volume, weight)

Lithium Air, Mg ?, Ca ?...

Manufacturing and process improvements

Increased line speed and yield

Elimination of NMP / solvent, reduction of energy usage

Structured, thicker electrodes

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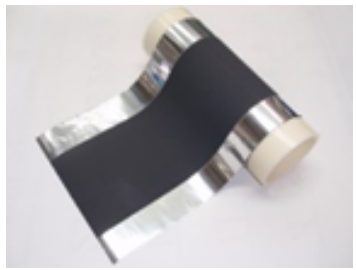
Cell / module / pack engineering will save cost and weight

- **The Russian Doll**





Packaging Packaging Packaging Packaging

- **“Onion to Apple”**
  - Bigger cells, multiple cells per package
    - Larger modules, structural modules
      - Vehicle structure = pack structure

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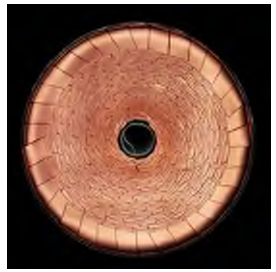
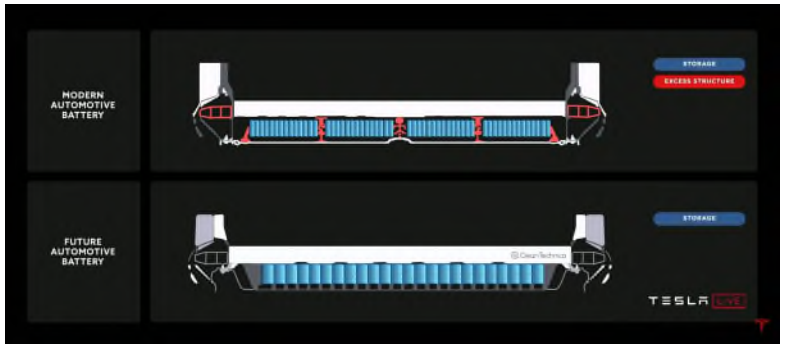
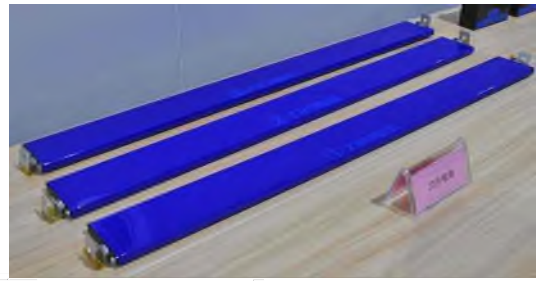
Future Technologies – Cells get bigger and better integrated

Tesla – bigger cells, better integration

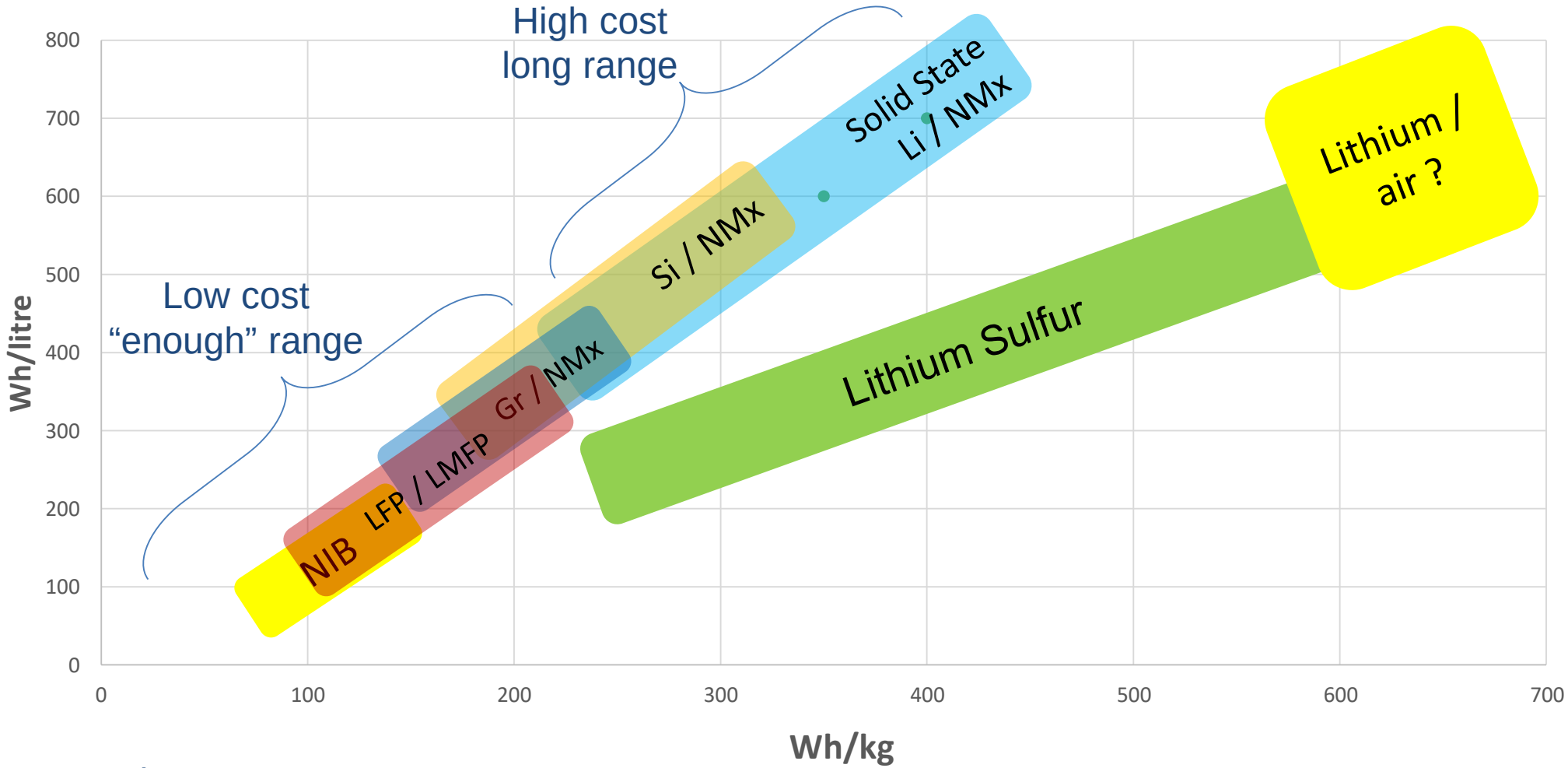




BYD – bigger cells, better integration



Likely pack level capabilities up to 2035 / 40



Pack assumptions

Gravimetric cell to pack efficiency	Gctp (range) 60% - 85%
Volumetric cell to pack efficiency	Vctp (range) 40% - 65%

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UK Policy context for Electric Vehicles
EU Trade and Co-operation Agreement

Trade and Co-operation Agreement (TCA) governs tariff free trade between UK and EU. Agreed in December 2020

To qualify for tariff free trade between EU and UK, EVs must have at least following % content from UK or EU

Otherwise 10% tariff on vehicle applies

Neither EU nor UK ready for 2024 date
10% Tariff will apply to EVs (not ICEs !)
…"Under negotiation…"

	2024	2027
Vehicle	>45%	>55% + battery must be UK/EU
Battery pack	>60% *	>70% *
Cells	>50% *	>65% *

* Or CTH with UK/EU cathode material

2024 date scrapped as UK and EU not ready 2027 remains
- UK must have a battery industry by 2027 or face tariffs

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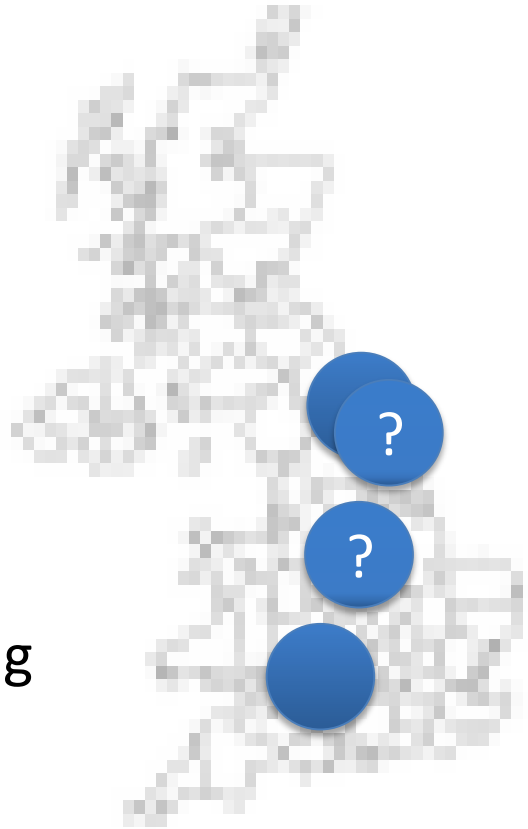
How is the UK doing today ?

- UK OEMS committed to EV (JLR, BMW, Nissan, Stellantis…)

- 1 gigafactory operational and expanding (AESC)
- 1 gigafactory announced (Tata)
- Further gigafactory discussions underway

- Upstream and downstream supply chains incomplete
- Lithium, anode material and electrolyte looking good
- Cathode material needs strong focus
- First stage recycling looks good, but need black mass processing

- World class R&D structure
- Joined up policies (for the most part)



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EV Mythbusting

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My favourite myths:

- EV sales have slumped
- The batteries will need replacing and they cost a fortune to maintain
- EVs are worse than diesel because all our electricity is made from coal
- Embedded carbon in batteries is never recovered over vehicle life
- EVs catch fire all the time
- There aren't enough rare earth materials – and they are all mined by children
- We're going to be left with a mountain of dead batteries
- There isn't enough electricity to power it all
- EVs are so heavy that they cause potholes / car parks to collapse /
- EVs have higher brake and tyre dust emissions
- All of this will be overtaken by Hydrogen / fuel cells in the future

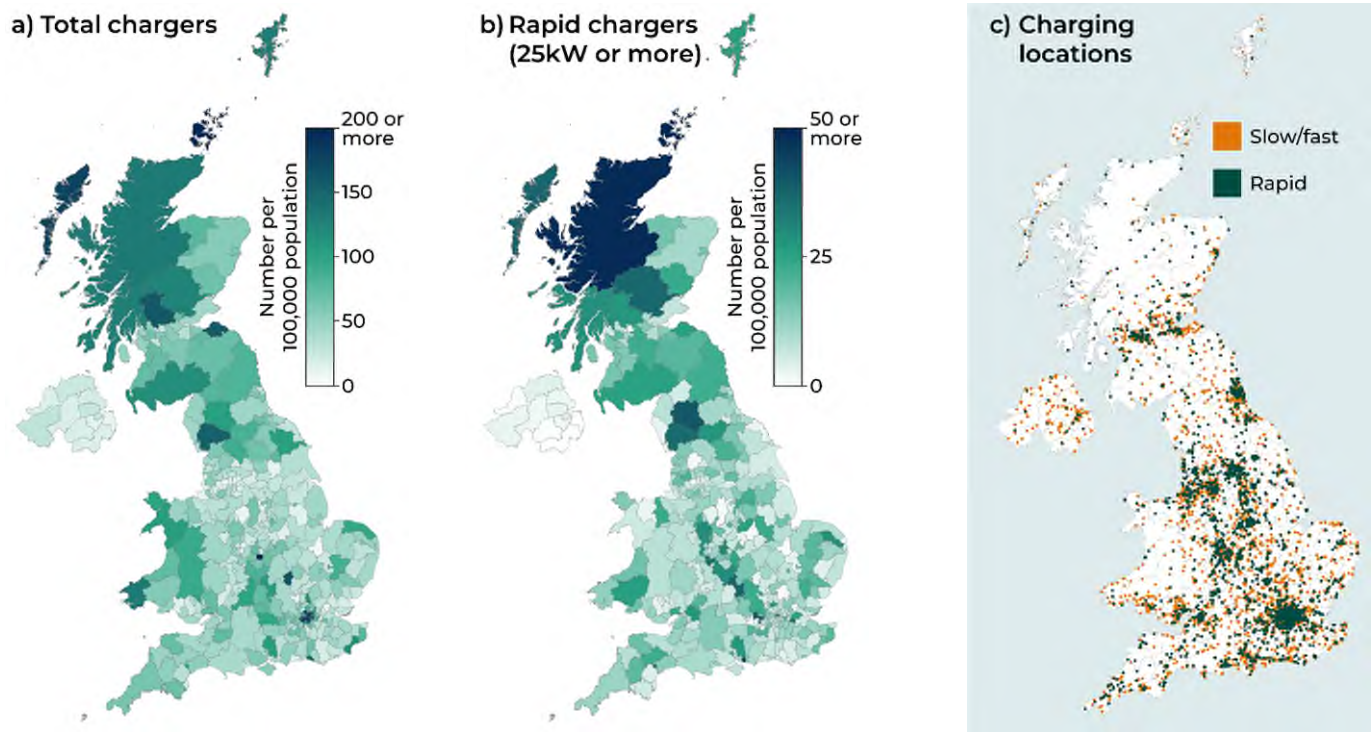
FALSE

- There isn't enough charging infrastructure
- Insurance is ridiculously expensive
- Residual values are terrible

Partly True

Myths: There isn't enough charging infrastructure

- UK motorway charging infrastructure best in EU
  - 220 fast chargers per 100km
  - EU average of 70
- Now commercially viable as investment proposition – so race for profitable sites
- But rural areas not profitable
- And planning, and grid connection can cause major delays
- Cost of charging (VAT charged) can be higher than cost of diesel. Home charging much cheaper



Source: DfT, National Chargepoint Registry

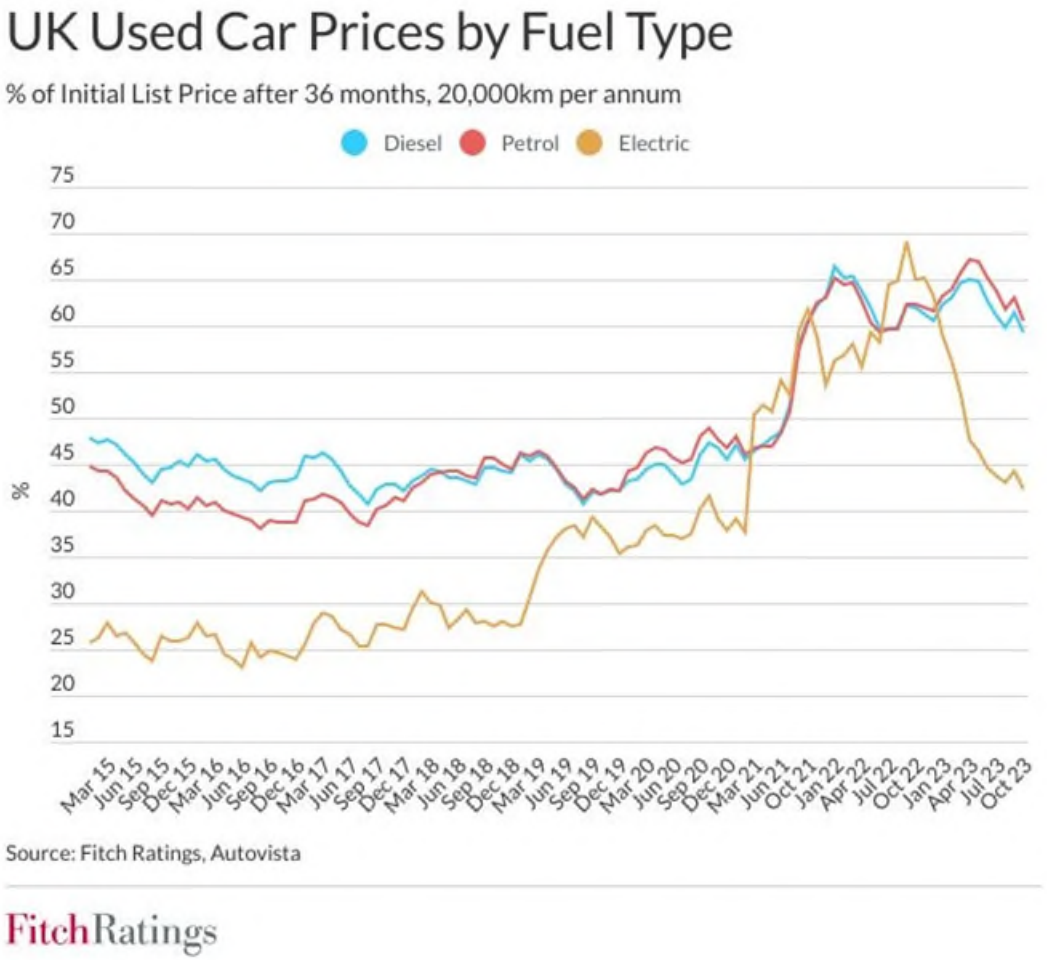
Myths: Insurance costs are ridiculous

Confused.com 2024

- Average electric car £910
- Average Hybrid £790
- Average ICE £670

- EVs are more expensive vehicles
- Performance often higher than ICE equivalent
- Thefts lower (by 50%)
- Repair costs higher (by 29%) if battery damaged

Myths: residual values are terrible



Why ?:

- Tesla dropped new EV prices as competition increased in market
- 3 year old lease cars from 2020 tax schemes flooded 2nd hand market
- No buyer incentives for 2nd hand EVS (and absolute price still high)
- Lower cost new EVs appearing on market

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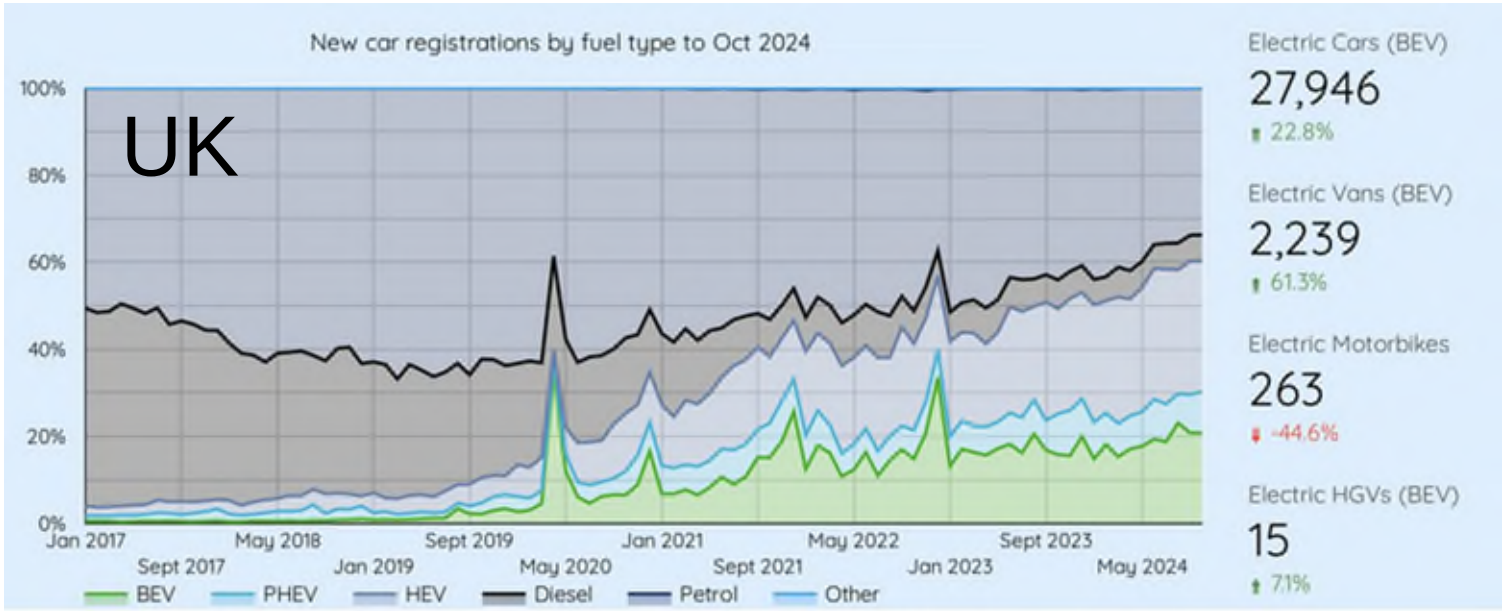
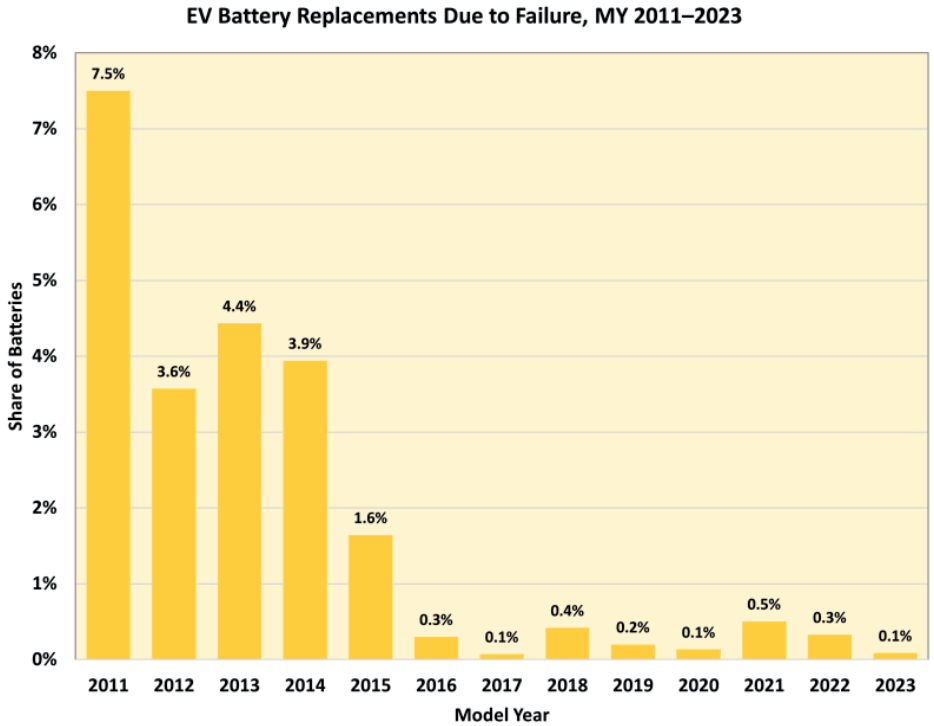
Myths: EV Sales have slumped



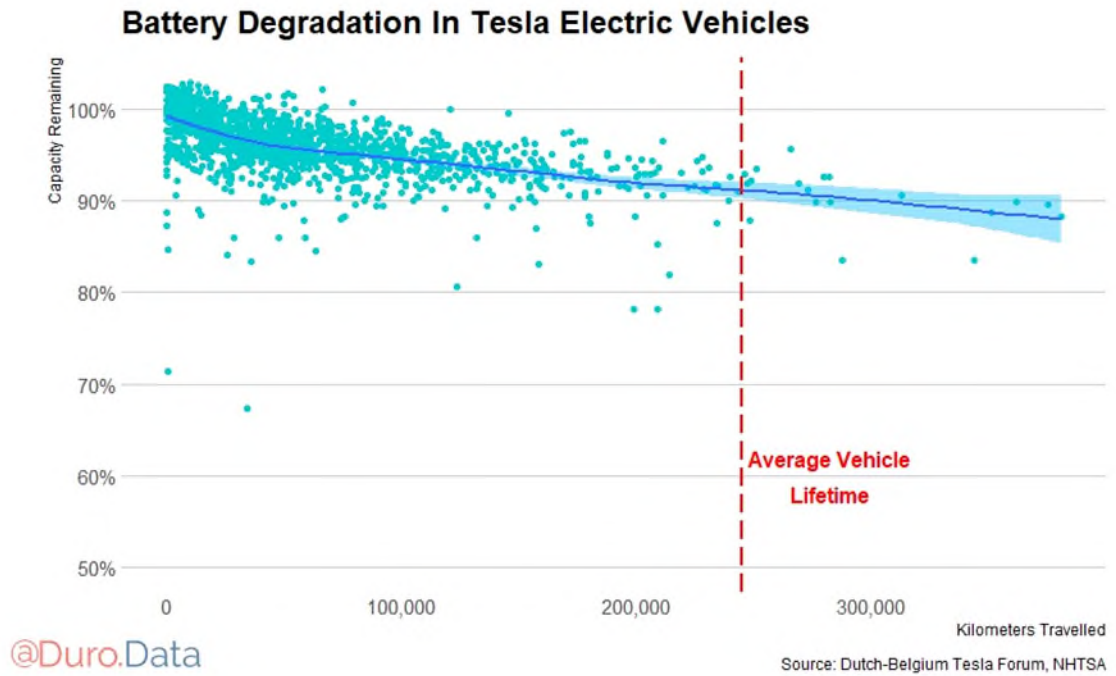
Source: New AutoMotive
Electric Car Count October 2024

Source: SMMT, September 2024

Myths: EV batteries will need replacing / EVs are expensive to maintain



Source: Recurrent Motors 2023



Electric Vehicle Service Intervals (e.g. – BMW)

- Pollen Filter and Air Filter: Every 20,000 miles or 2 years
- Brake Fluid: Every 20,000 miles or 2 years
- Battery Coolant: Lifetime change if replaced

Electric Vehicle Service Costs (e.g. Motability)

- EV - £103 every 2 years
- ICE - £175 every year

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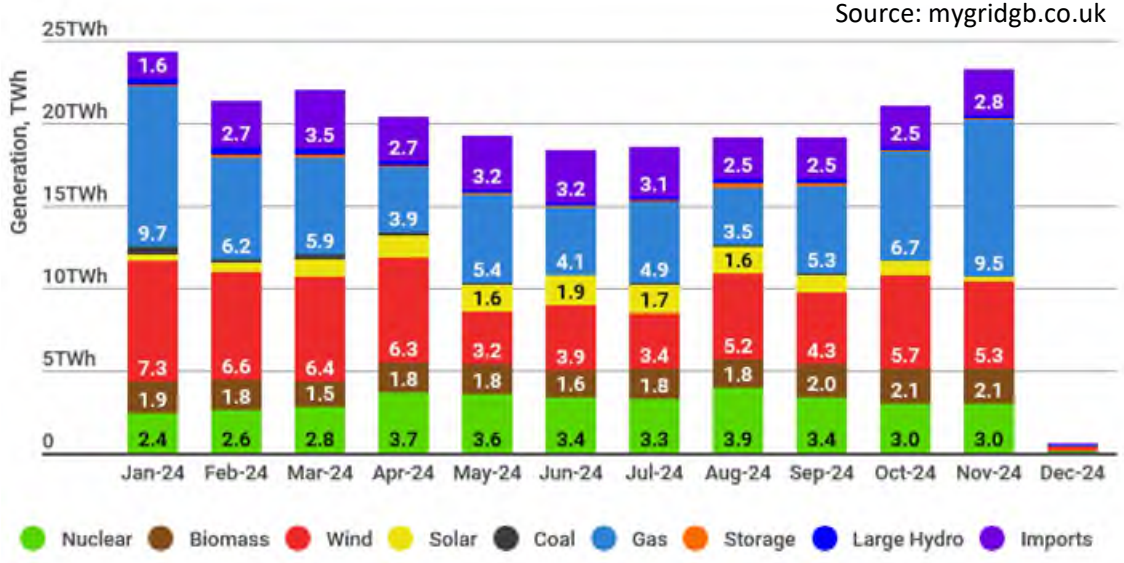
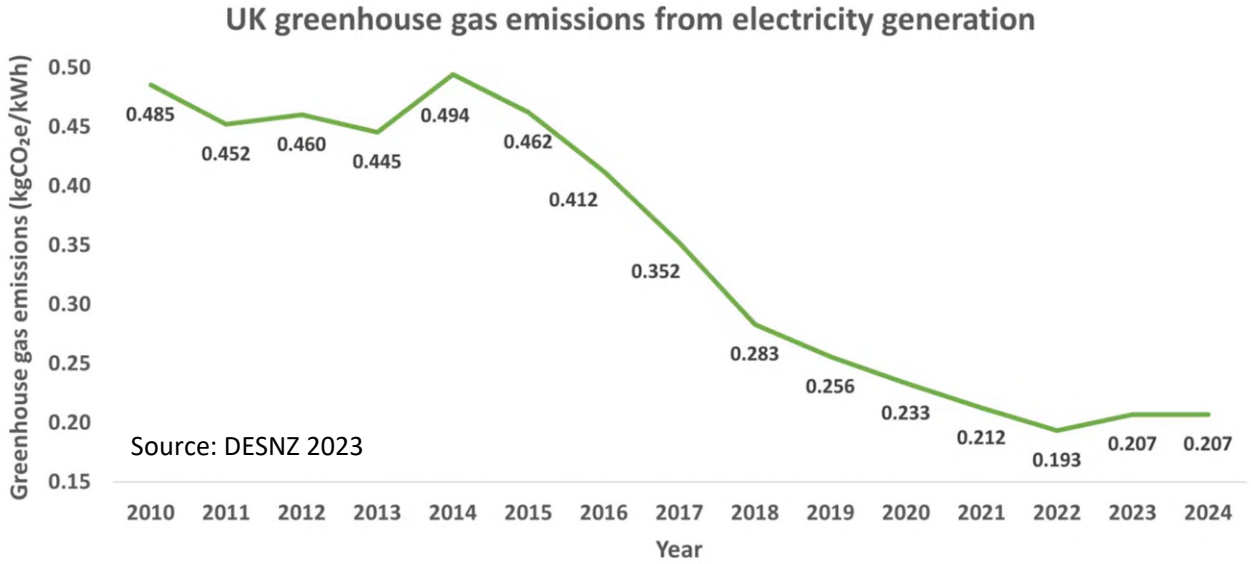
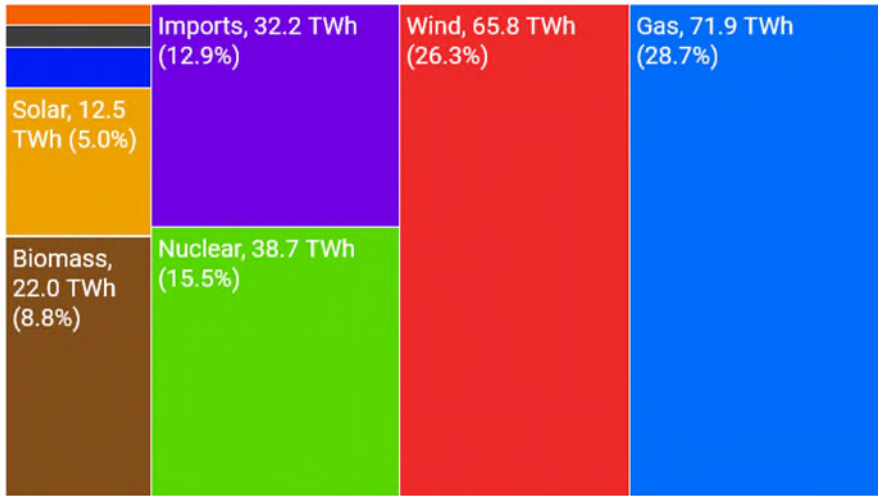
Myths: EVs are worse than diesel as all our electricity comes from coal

Source: mygridgb.co.uk

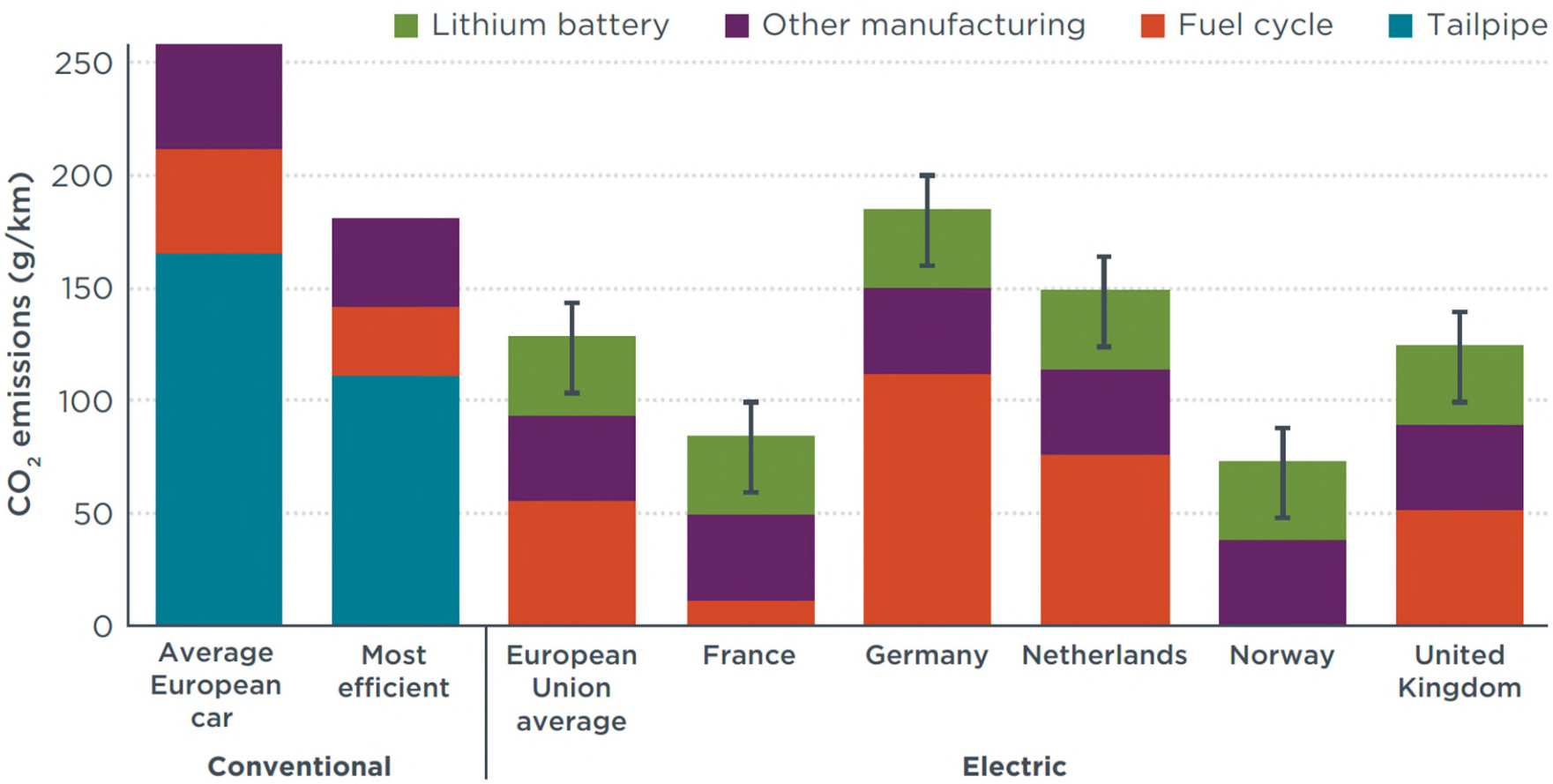




Source: DESNZ 2023



Myths: Embedded CO2 means EV is worse than Diesel



Source: ICCT – Effects of battery manufacturing on electric vehicle lifecycle greenhouse gas emissions– Feb 2018

Myths: There aren't enough rare earth materials, and they are mined by children

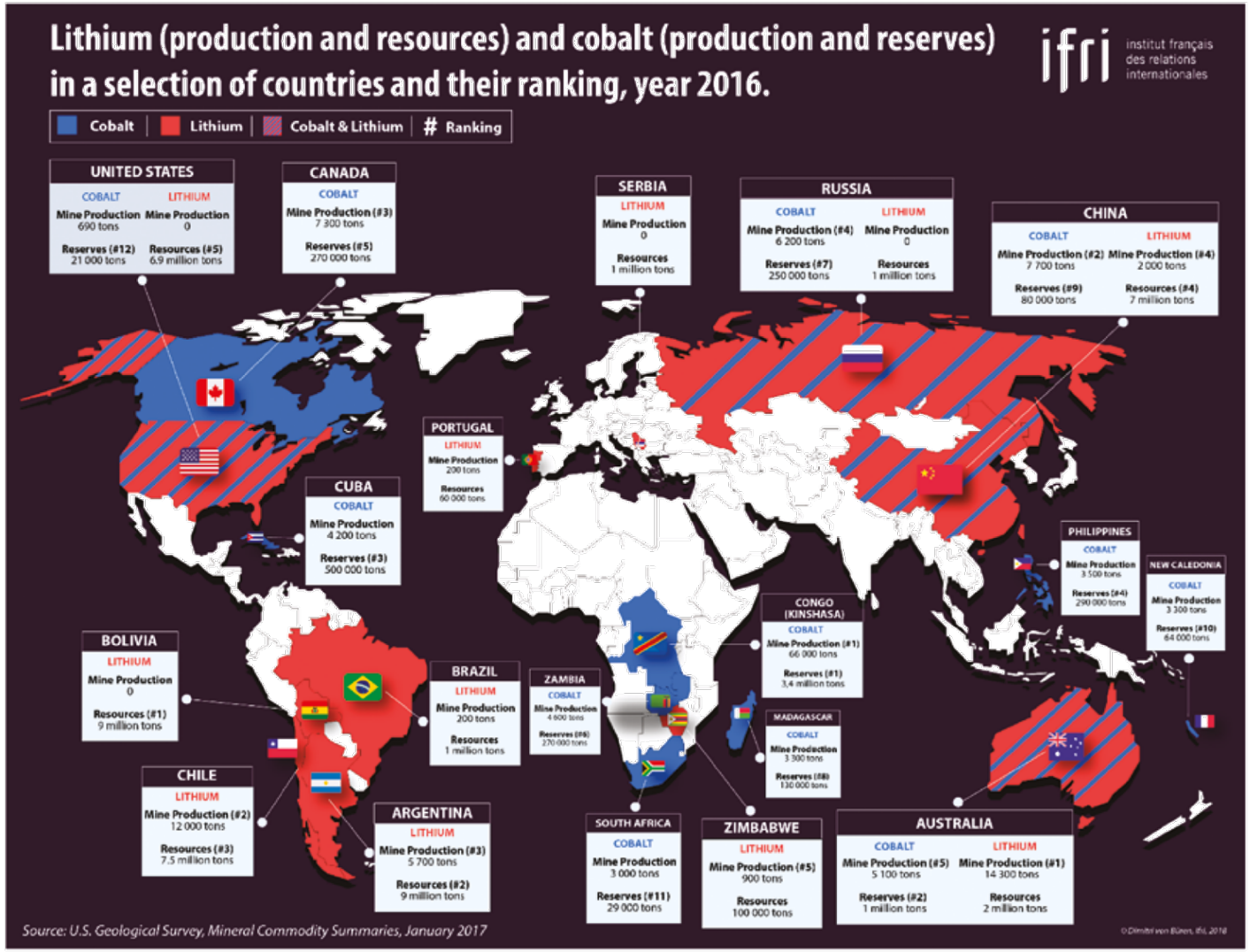
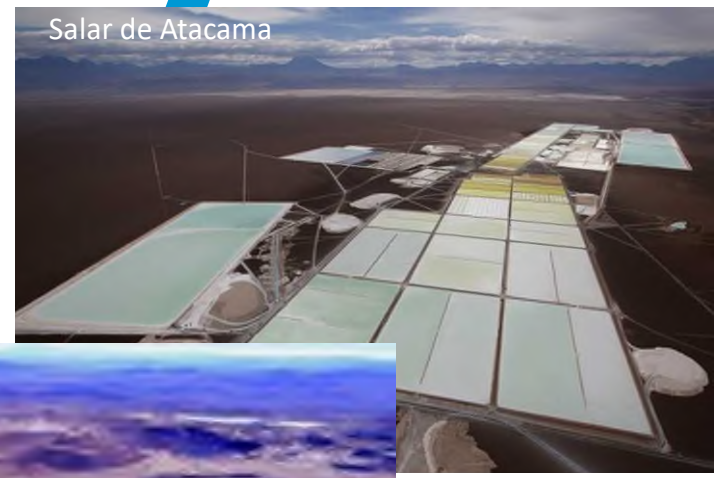
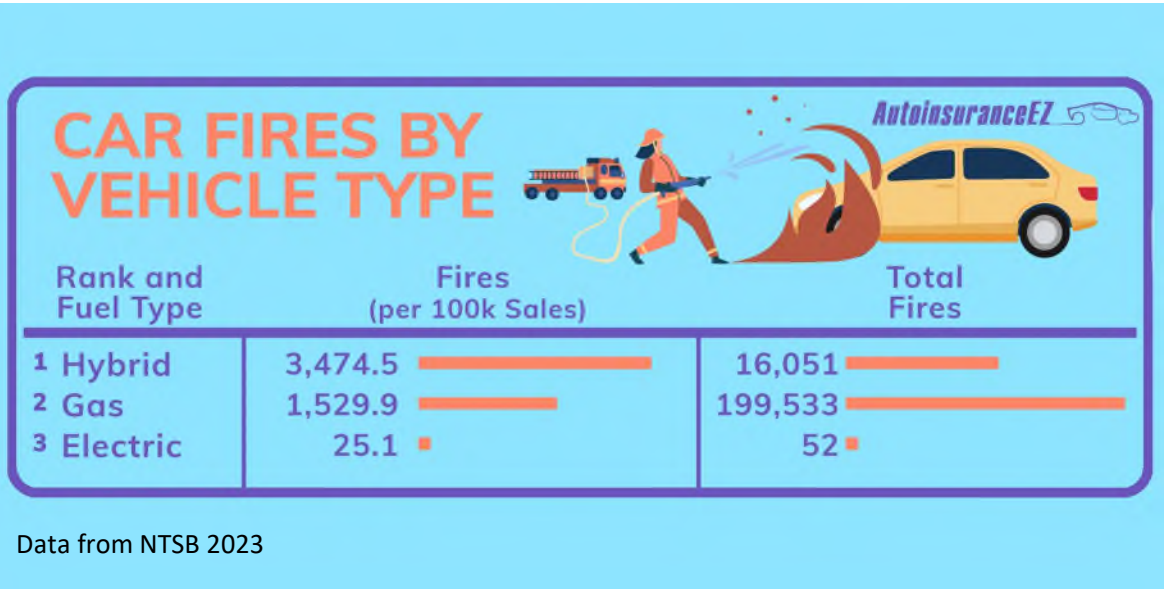


Image credit: Institut francais des relations internationales (ifri)

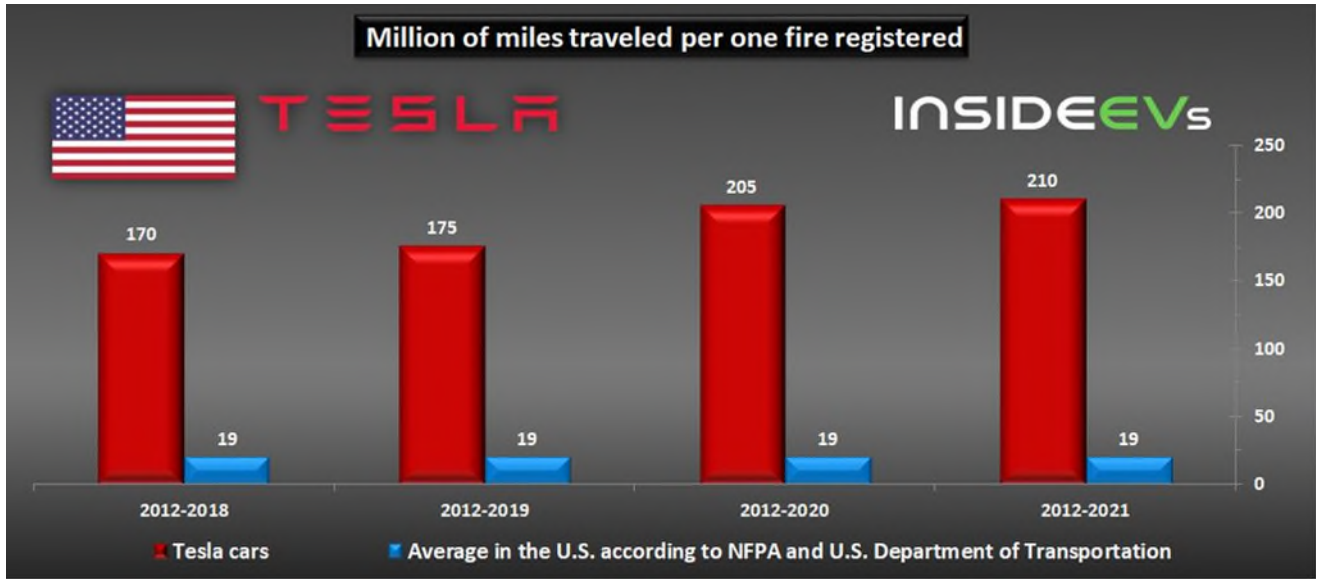


Myths: EVs catch fire all the time



Data from NTSB 2023

- Includes arson, house fires etc as well as “EV fires”
- US data used as EU data has anomalies resulting in over index for diesel vehicle fires



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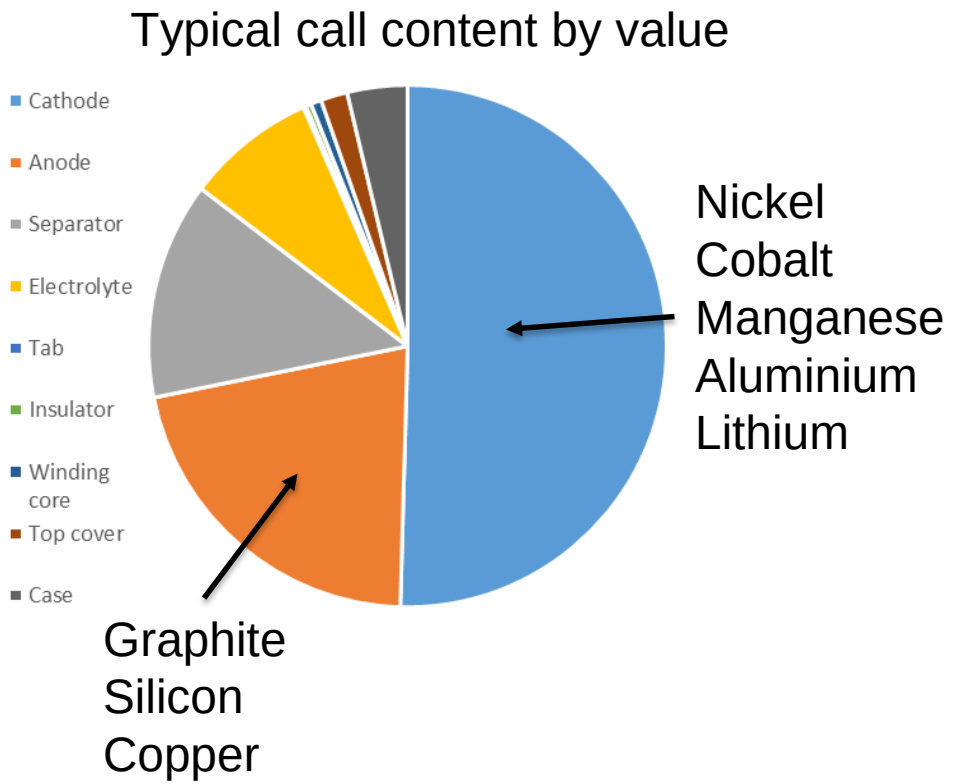
Myths: We're going to be left with a mountain of dead batteries (1/2)

EV batteries contain valuable and recoverable materials

Pack component	% Mass
Cells	60%
Pack Casing	30%
Wiring	4%
Electronic components	1.5%
Cooling tubes, casing parts	1.5%
Busbars	1.5%
Screws, metal parts	1%
Rubber, tape, etc	0.5%
Total	**100%**



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Myths: We're going to be left with a mountain of dead batteries (2/2)

EU Regulations dictate that greater proportions of the battery must be recycled

- And specific requirements for key elements

Year	Average LIB Recycling Target
2021 (current)	50%
2025	65%
2030	70%

Year	Specific Target per Metal			
	Li	Ni	Co	Cu
2021	N/A	N/A	N/A	N/A
2026	35%	90%	90%	90%
2030	70%	95%	95%	95%

And cell manufacturers must incorporate recycled content

- Creates market for recyclate (potentially at the expense of second life uses)

Year	% Recycled Metal in New Cells			
	Li	Ni	Co	Cu
2021	N/A	N/A	N/A	N/A
2026	4%	4%	12%	N/A
2030	10%	12%	20%	N/A

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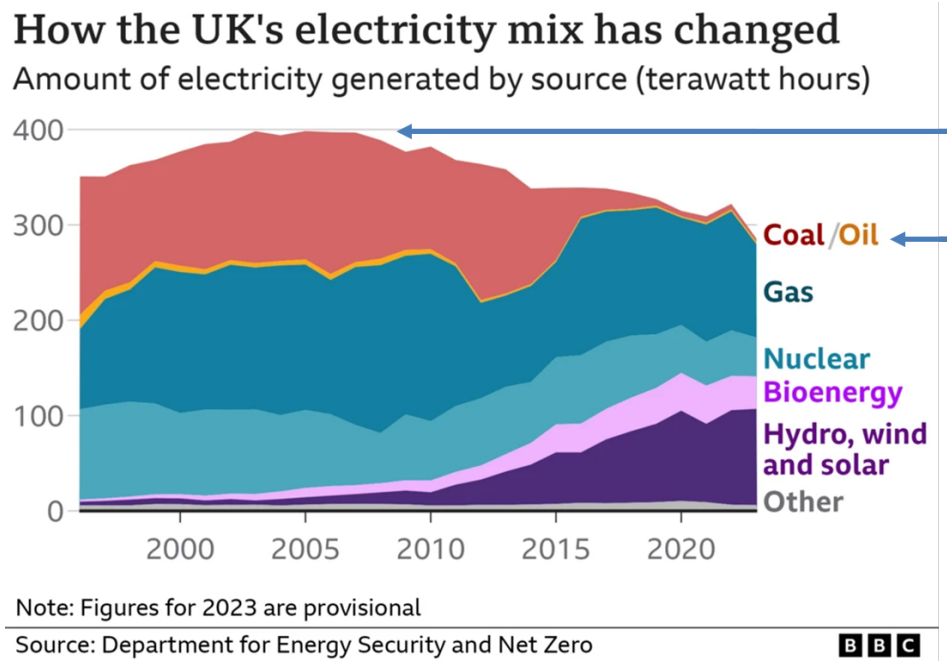
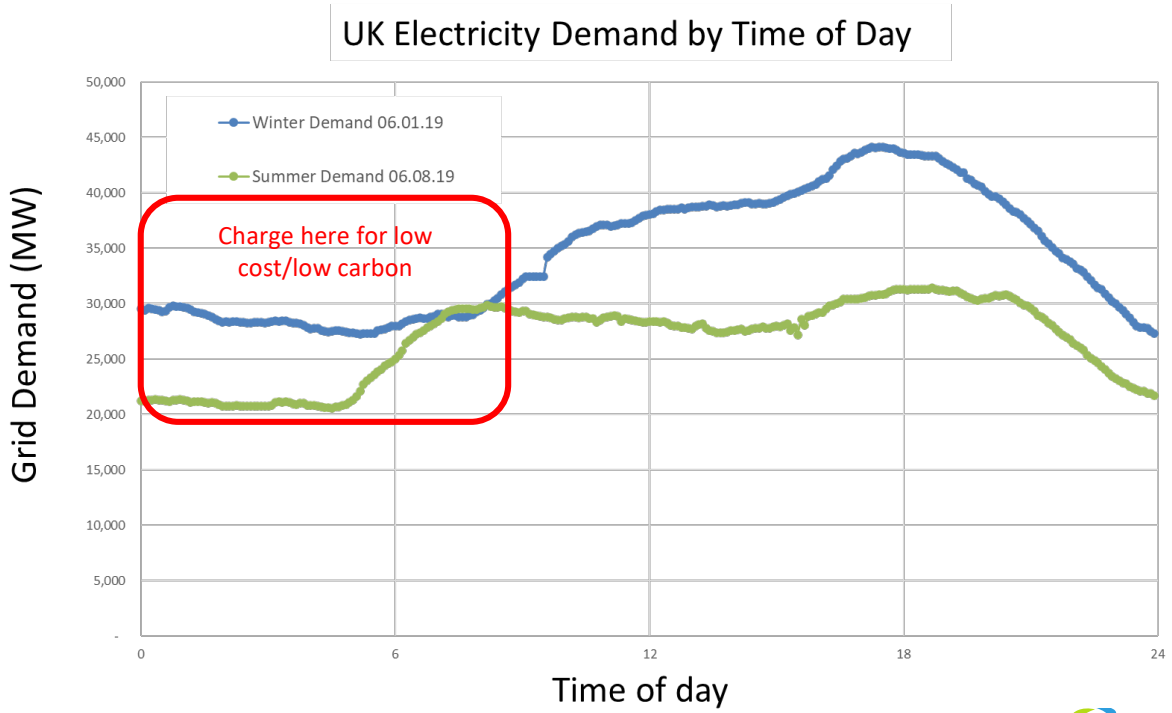
Myths: There isn't enough electricity for us all to use EVs



Peak generation was in 2006. Grid designed for >this

Currently operating at 75% of 2006 peak demand – Grid has capacity



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Myths: EVs are so heavy they cause potholes / car park collapse

Road damage is proportional to axle weight to the power of 4

(squared, then squared again)

Vehicle type	Axle load (kg/axle)	Relative damage
40T Truck	8000	17059
18T Truck	9000	27326
Ford Transit	1650	31
BMW I4 M50	1150	7.3
Range Rover (Petrol)	1100	6.1
Nissan Leaf	900	2.7
Ford Puma	700	1

EV weights

- 1200 kg (Mitsibushi i-Miev)
- to 2960 kg (Mercedes EQV)

ICE weights

- 900 kg (Suzuki Ignis)
- to 2800 kg (Mercedes Maybach)

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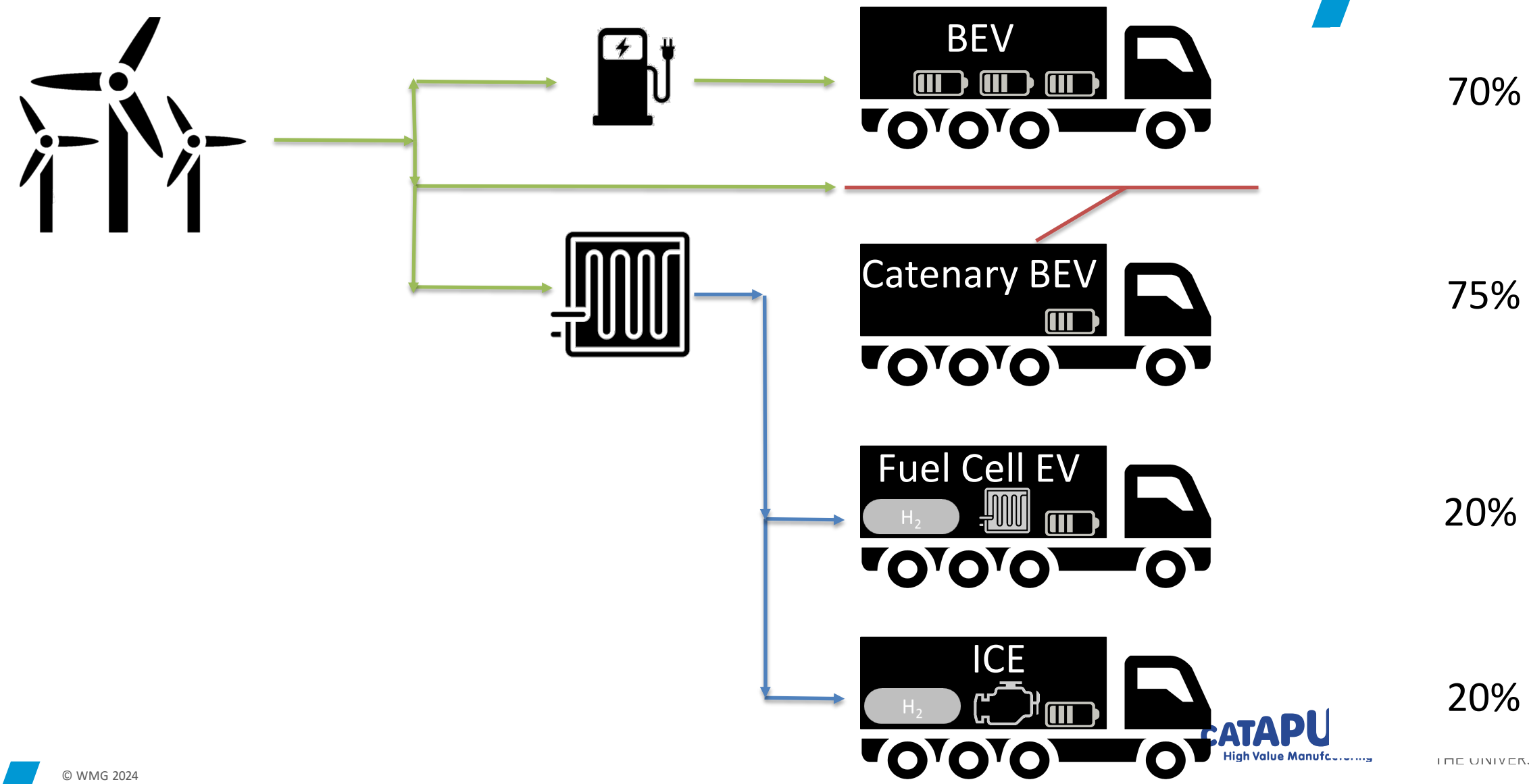
Myths: All of this will be overtaken by hydrogen / fuel cells



In Conclusion

Pretty much all cars (vans and motorcycles) will go electric – driven by CO2 and Air Quality

- Timing depends on government policies, but likely 2035-2040
- By that time it will be as much consumer pull as technology push
- ICE will still exist – it will be the 2040 equivalent of today's horses (or expensive mechanical watch)

Batteries are the critical enabling technology

- They are a **materials challenge**, a **manufacturing challenge** and a **recycling challenge**
- They are improving rapidly and will continue to do so for at least another decade

The UK has work to do to onshore the supply chain for batteries and EVs

- We're off to a decent start, but there's a way to go yet

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Thank you – Questions welcome !

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