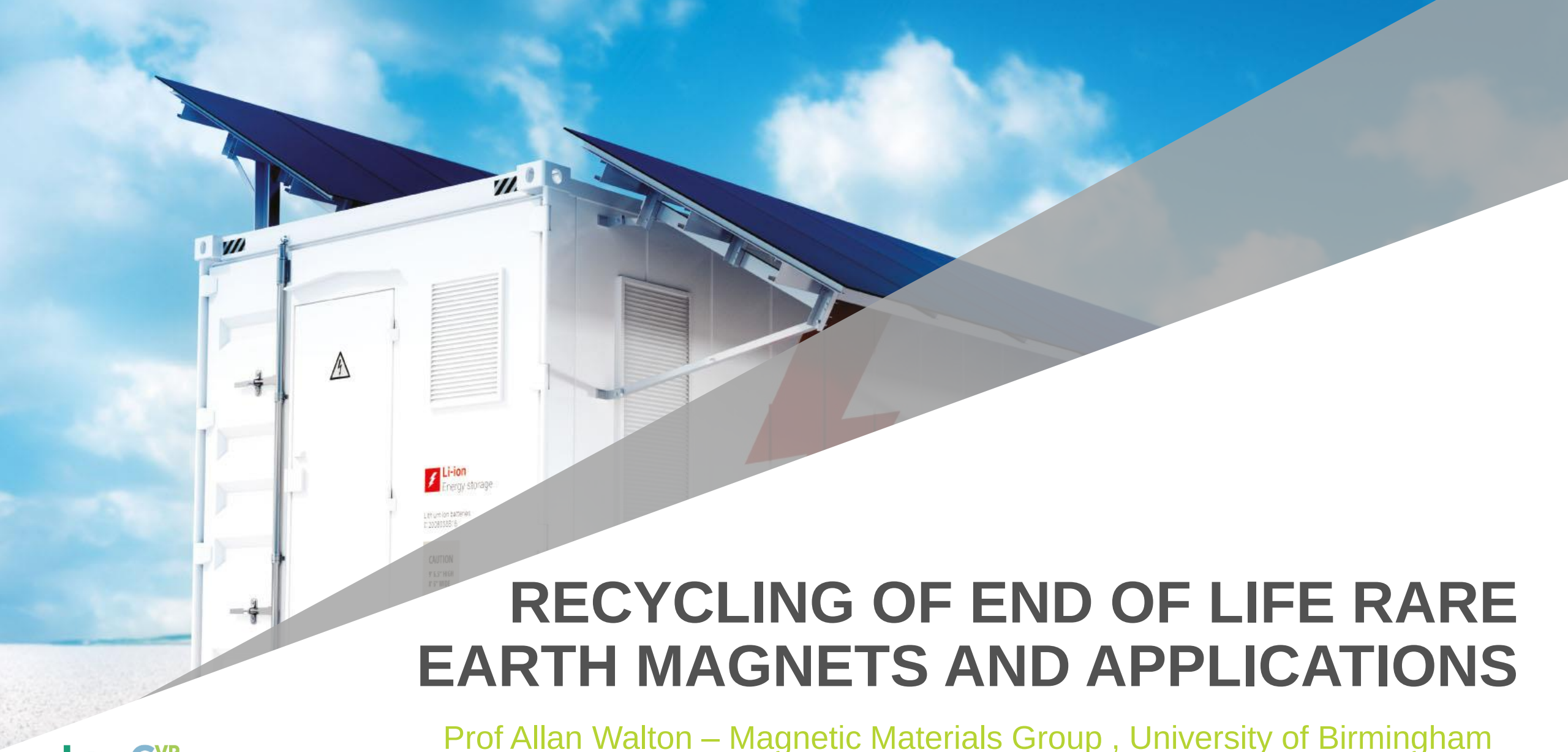
CLOSING THE END OF LIFE LOOP

9th July 2020

LowCVP
Low Carbon Vehicle Partnership

ADVANCED PROPULSION CENTRE UK



RECYCLING OF END OF LIFE RARE EARTH MAGNETS AND APPLICATIONS

Prof Allan Walton – Magnetic Materials Group , University of Birmingham

LowCVP
Low Carbon Vehicle Partnership

ADVANCED PROPULSION CENTRE UK

HYPROMAG
Magnet Recycling

UNIVERSITY OF BIRMINGHAM

WHAT ARE THE RARE EARTH MAGNETS?

4%

- $SmCo_5$
  - Sintered (powder metallurgy)
- Sm_2Co_{17} – actually $Sm_2(CoFeCuZr)_{17}$
  - Sintered (powder metallurgy) mainly used in high temp / corrosive environments

95%

- Neo (neodymium iron boron)
  - Powder for isotropic bonded magnets: compression, extruded, injection molded melt spun ribbons - Magnequench.
  - Powder for anisotropic bonded magnets – HDDR powder – Aichi Steel
  - Sintered (powder metallurgy) dominated by Chinese companies
  - Die-upset / forged, fully dense: Magnequench MQ-3 process (original and modified); Daido Electronics

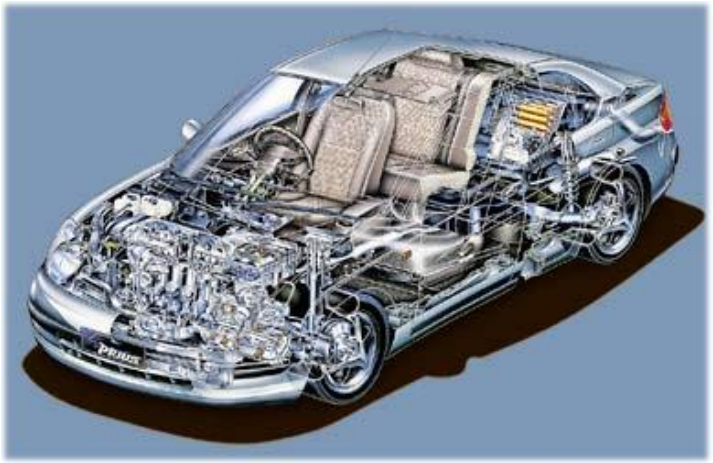
1%

- SmFeN
  - Powder metallurgy process resulting in a fine powder suitable for bonded magnets
  - Unstable above ~450 ° C – no known method for achieving a fully dense magnet

Percent by weight of commercially produced rare earth magnets

NdFeB MAGNET APPLICATIONS

Energy generation – offshore wind turbines



Automotive (Generators, motors, power steering)

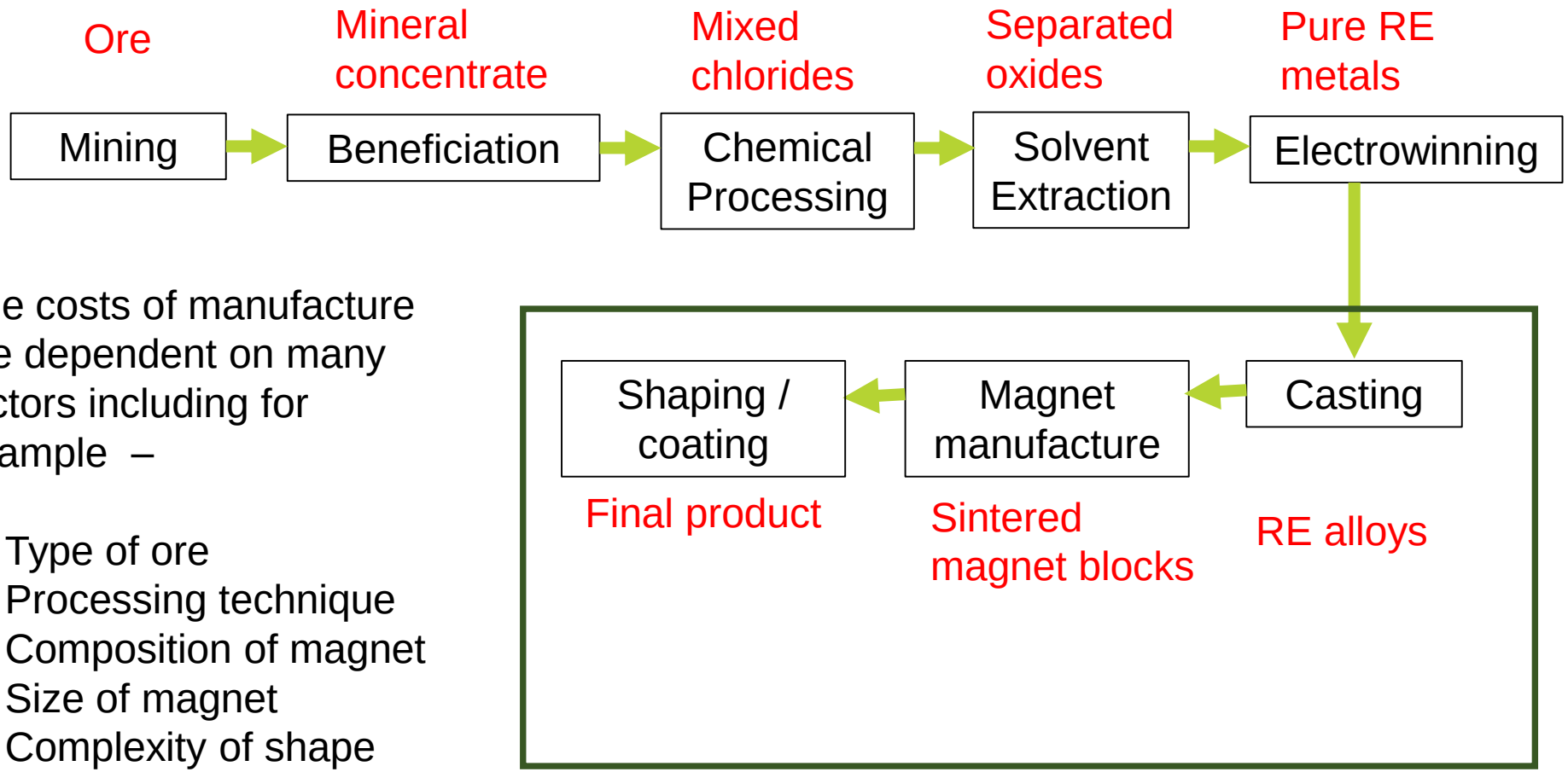
Electric bikes (motors)

Electronics - loudspeakers, vibrators, motors

FUTURE OF TECHNOLOGY SERIES

BIRMINGHAM CENTRE FOR STRATEGIC ELEMENTS AND CRITICAL MATERIALS

MINE TO MAGNET



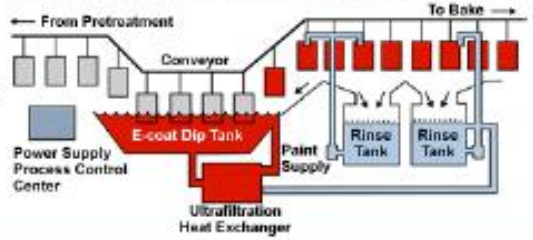
The costs of manufacture are dependent on many factors including for example –

- Type of ore
- Processing technique
- Composition of magnet
- Size of magnet
- Complexity of shape

ARNOLD MAGNETIC TECHNOLOGIES

1. Melt Alloy
2. Paddy Cast | Book Mold Cast | Strip Cast
3. Coarse Crush/Mill | Hydrogen Decrepitate
4. Jet Mill
5. Blend
6. Axial Press | Transverse Press | Isostatic Press
7. Sinter
8. Heat Treat
9. Machine
10. Coat
11. Magnetize

Typical Electrocoat System



Typical manufacturing steps for fully dense sintered NdFeB magnets

RECYCLING OF RARE EARTH MAGNETS

FUTURE OF TECHNOLOGY SERIES

Why recycle rare earth magnets

- The EU imports far more NdFeB than we manufacture
- If short loop recycling can be achieved then the economics become much more favorable
- Potentially a much smaller environmental footprint depending upon method
- Provide a secure supply of materials for the EU
- Help with the balance problem
- The costs for building a recycling plant could be a fraction of that required for primary production on a much shorter timescale.

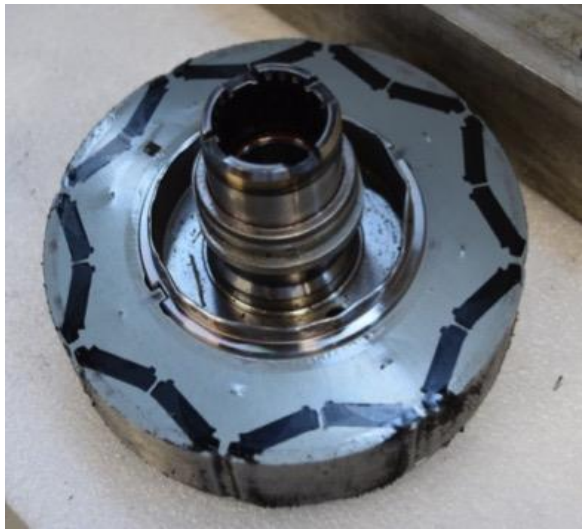
Problems for recycling of rare earth magnets

- Identification of products which contain NdFeB magnets is not easy
- NdFeB magnets are often very small (eg- 300mg in a mobile phone)
- The composition of the magnets is changing
- The final magnets are coated and have a higher oxygen content than primary alloys
- The magnets are magnetised and on shredding the magnets break apart and stick to the ferrous scrap.
- The products are not designed for disassembly
- There is no labelling of magnets
- Economics for recycling are challenging
- Supply chain is small in the EU
- A large majority of the cost for recycling is in the segregation of waste containing magnets. There is a hierarchy of difficulty of extraction based on design of product.

DESIGN FOR RECYCLE?

Generally products are not designed with recycling in mind

Hard disk drives
2-25 grams of NdFeB
Nickel plated
Glued into the assembly
Heavily embedded



Rotor from an automotive drive motor
Uncoated magnets but typically heavily embedded in epoxy resin
500g- 2kg

Mobile phones
Very small magnets (eg - 300mg)
Nickel or Zn plated
Heavily embedded

FUTURE OF TECHNOLOGY SERIES

RECYCLING OF CONVENTIONAL CARS

Prior to processing, the scrap yard would remove the following:

- Radiator – high in copper so would be sold on to IMI for example.
- Catalytic converter – contains precious metals (Platinum, Palladium etc.) which would go to Johnson Matthey for example.
- Tyres – for reuse, re-treading or recycling.
- Battery for recycling

Ferrous metal	75%
Aluminium	3%
Copper	1%
Copper wire	0.2%
Zinc	0.1%
Glass/stone/ Non-combustible waste	10%
Plastic/Rubber/Combustible waste	10%

A relatively narrow range of materials compared to an electric car. Many are single composition- video

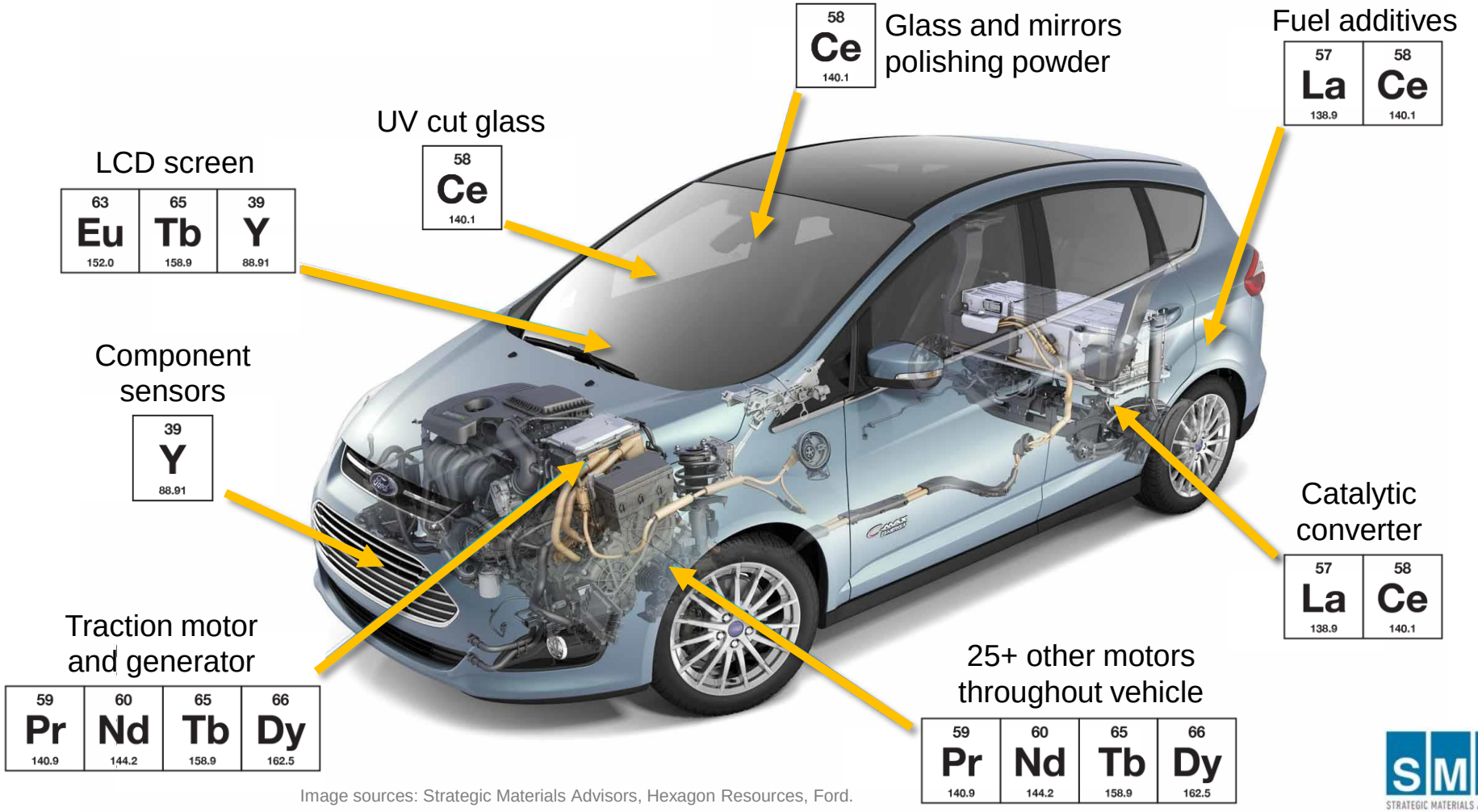


Image sources: Strategic Materials Advisors, Hexagon Resources, Ford.

SMA STRATEGIC MATERIALS ADVISORS

Rare earths in a HEV

FUTURE OF TECHNOLOGY SERIES

SHREDDING OF MAGNETS IN THE ELECTRONICS AND AUTOMOTIVE SECTORS

- Electronic and automotive scrap is often shredded and then the ferrous, non ferrous metals are separated
- For HDDs this is used to destroy the data on the disk.
- NdFeB magnets are brittle and break up into a magnetized powder.

INDUSTRIAL SHREDDING OF HDDS

Oxidised NdFeB magnet powder

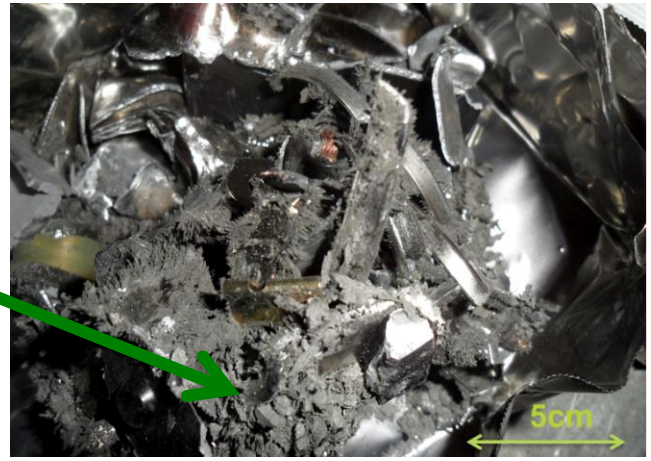
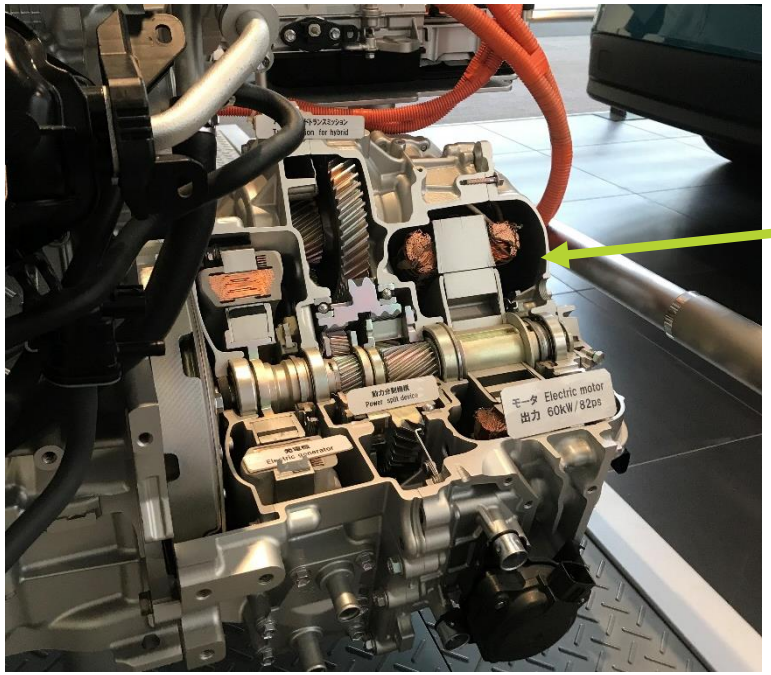


Image provided by Rene Kleijn, University of Leiden, Van Gansewinkel Group

INDUSTRIAL SHREDDING OF MOTOR

Image provided by Axion Recycling

EXAMPLES OF THE DISMANTLING CHALLENGE FOR AUTOMOTIVE COMPONENTS CONTAINING MAGNETS

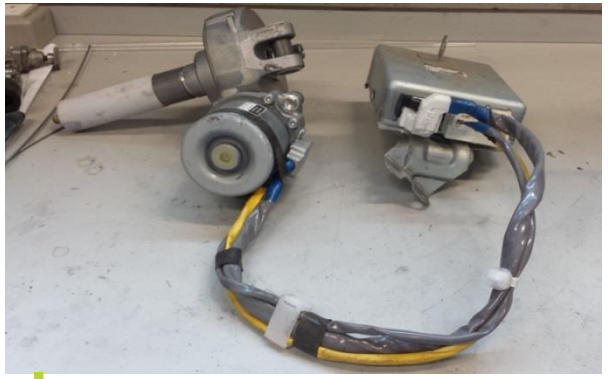


Toyota Prius

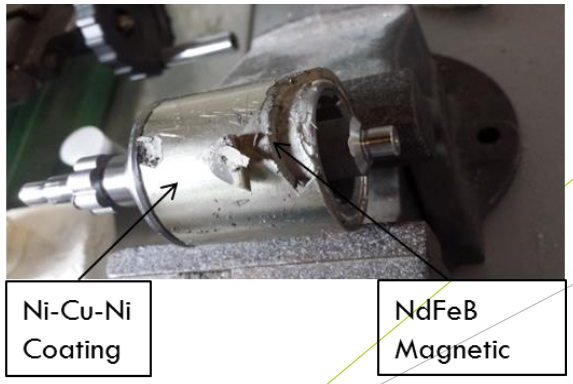
Drive motor

Rotor from an automotive drive motor

NdFeB magnets



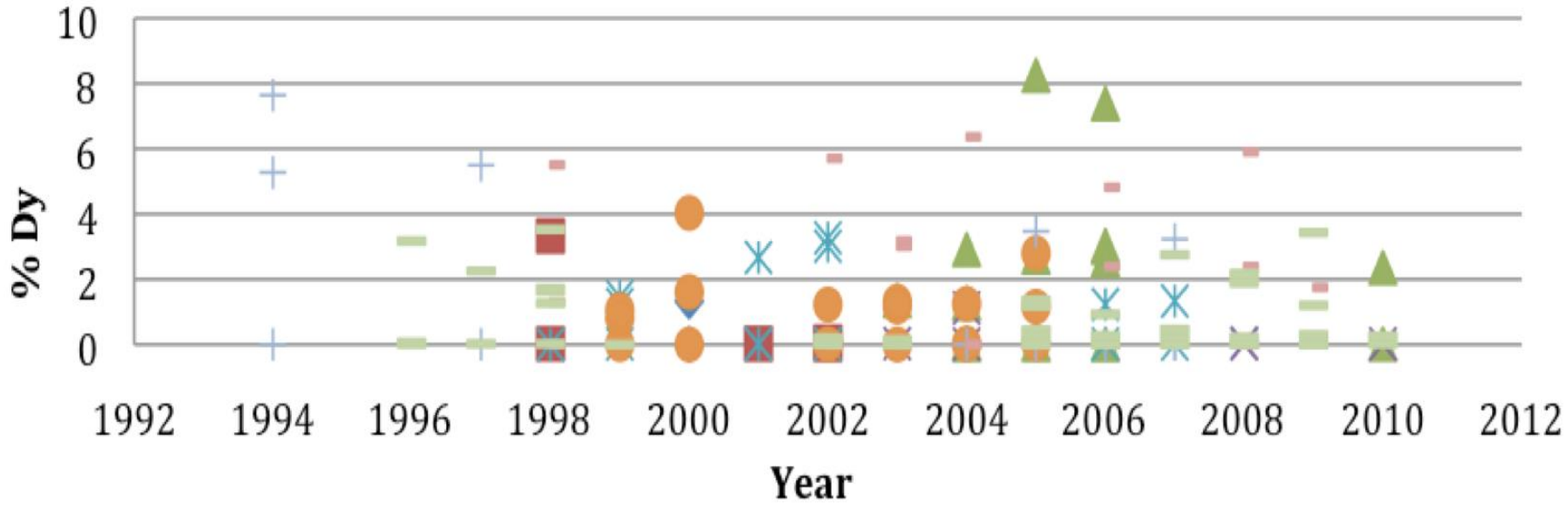
Power Steering Unit



Courtesy of Fernandho Coehlo and Mohammad Awais –
EU DEMETER project

FUTURE OF TECHNOLOGY SERIES

COMPOSITION OF HDD'S BY MANUFACTURER AND YEAR



Dy content (wt%) of sintered NdFeB magnets from HDDs (voice coil) as a function of year and manufacturer (each symbol type represents one manufacturer).

HDD's provided by Stena Technoworld AB, ICP analysis performed at Leitat Technology Centre Barcelona as part of the EU Framework 7 project Remanence.

NEW SOLUTIONS FOR SEPARATION OF COMPONENTS AND MATERIALS

FUTURE OF TECHNOLOGY SERIES

SENSING, SORTING & CROPPING

AB AUTOMOTIVE planeXt

FUTURE OF TECHNOLOGY SERIES

THE USE OF HYDROGEN TO SEPARATE AND RECYCLE NdFeB MAGNETS

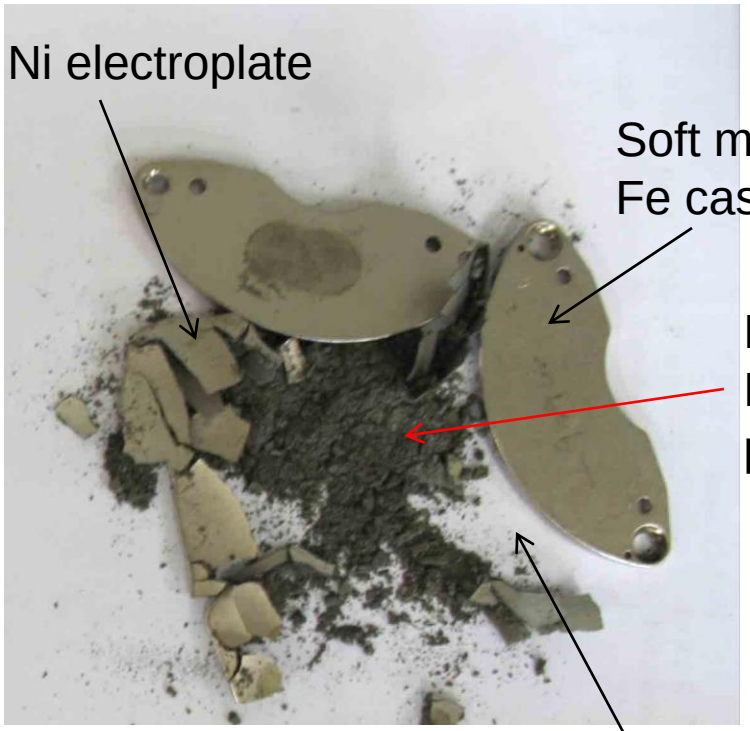
THE HPMS PROCESS

(HYDROGEN PROCESSING OF MAGNET SCRAP)

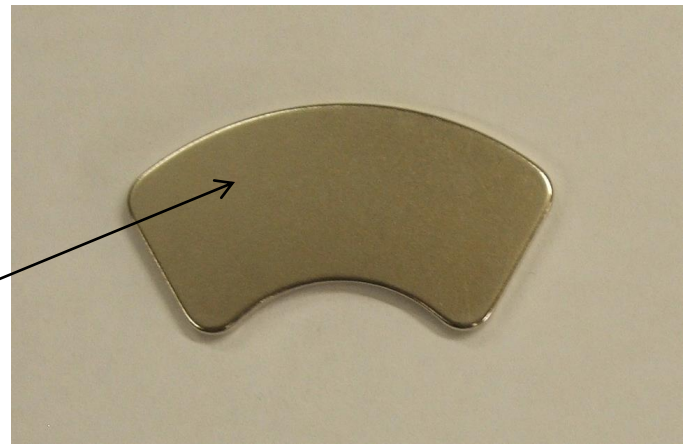
FUTURE OF TECHNOLOGY SERIES

SEPARATION OF NdFeB FROM VCM

Voice coil assembly extracted from hard drive



Voice coil assembly after HD process (RT and 1 bar pressure)

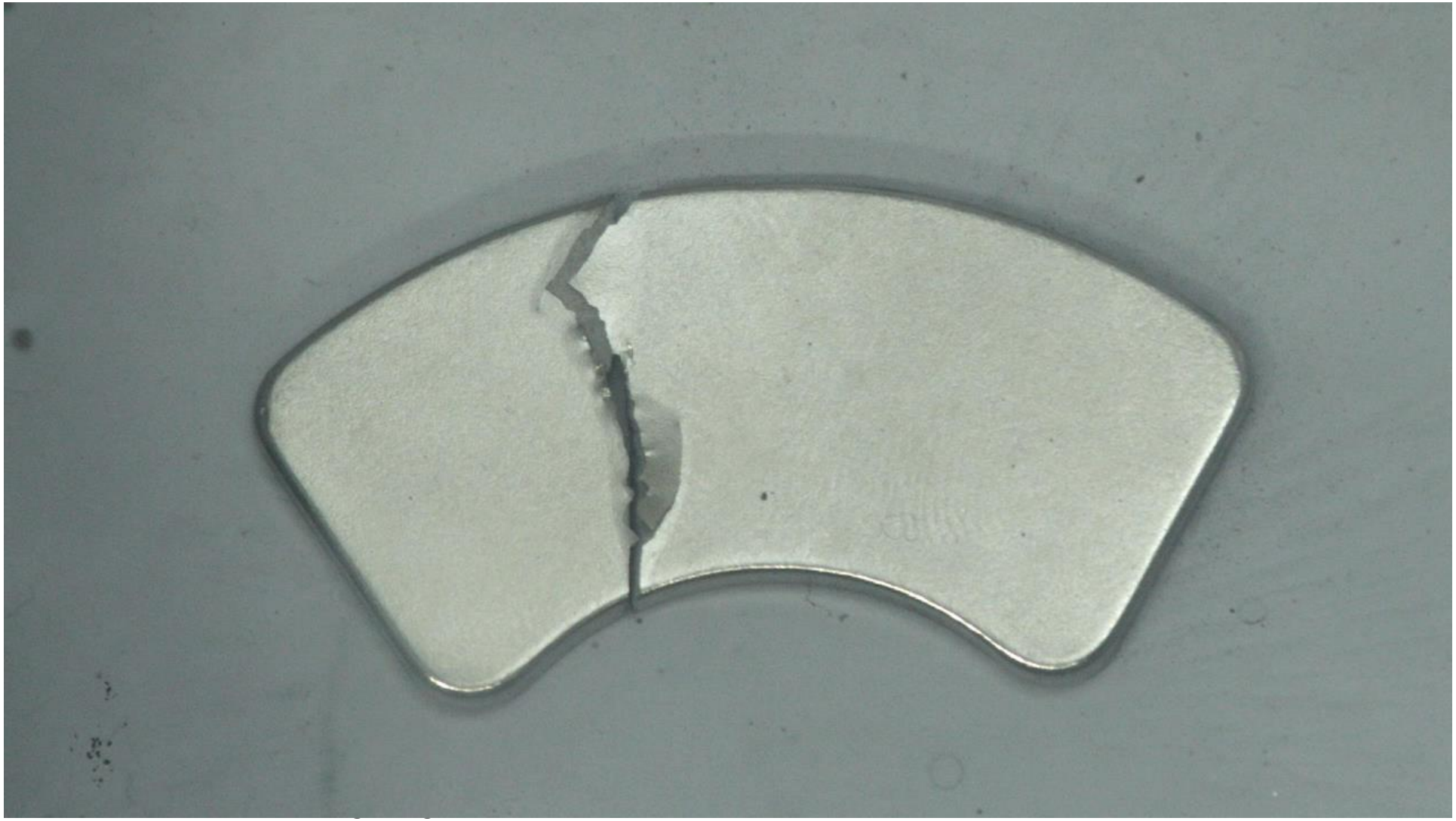


Ni electroless plated voice coil magnet

US patent – No.13/169839
HPMS process. Hydrogen Processing of Magnet Scrap

FUTURE OF TECHNOLOGY SERIES

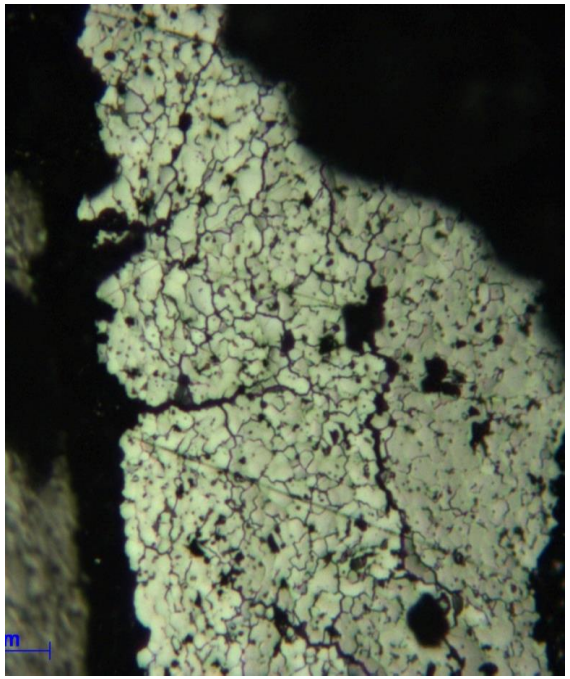
USE OF HYDROGEN FOR SEPARATION OF NdFeB



FUTURE OF TECHNOLOGY SERIES

Extracted powders

Material extracted from tumbling stage (10 sectioned HDDs).



Optical micrograph of a cross section through a HD processed sintered NdFeB magnet particle

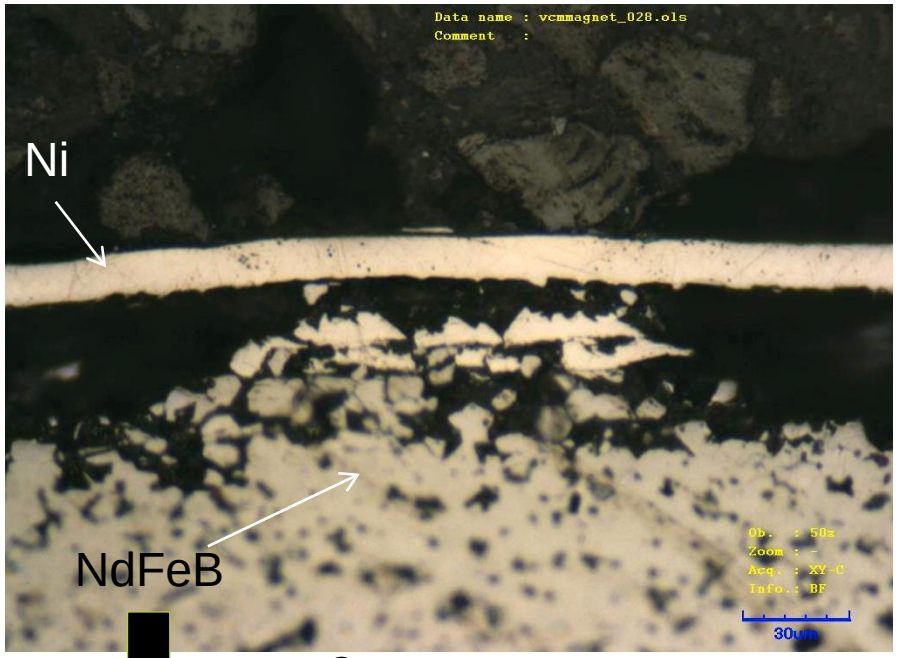
Sieving with ball bearings has been used to preferentially break down the NdFeB compared to the Ni and other impurities

The Ni content of the extracted powders for 5kg of material was around 400ppm after sieving to 90 microns

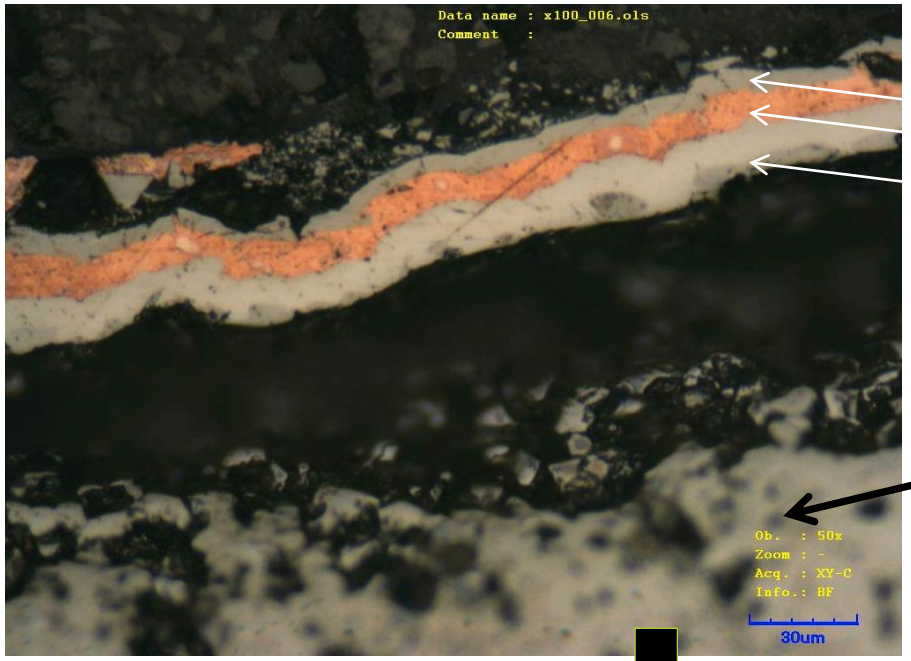
A.Walton et al - Journal of Cleaner Production 104 (2015)

FUTURE OF TECHNOLOGY SERIES

THE IMPACT OF DIFFERENT COATINGS



a



b

HD

<400 ppm Ni below 90 microns

Confocal laser microscope images of a) Ni electroplated layer on NdFeB and b) Ni-Cu-Ni layer on NdFeB

HD

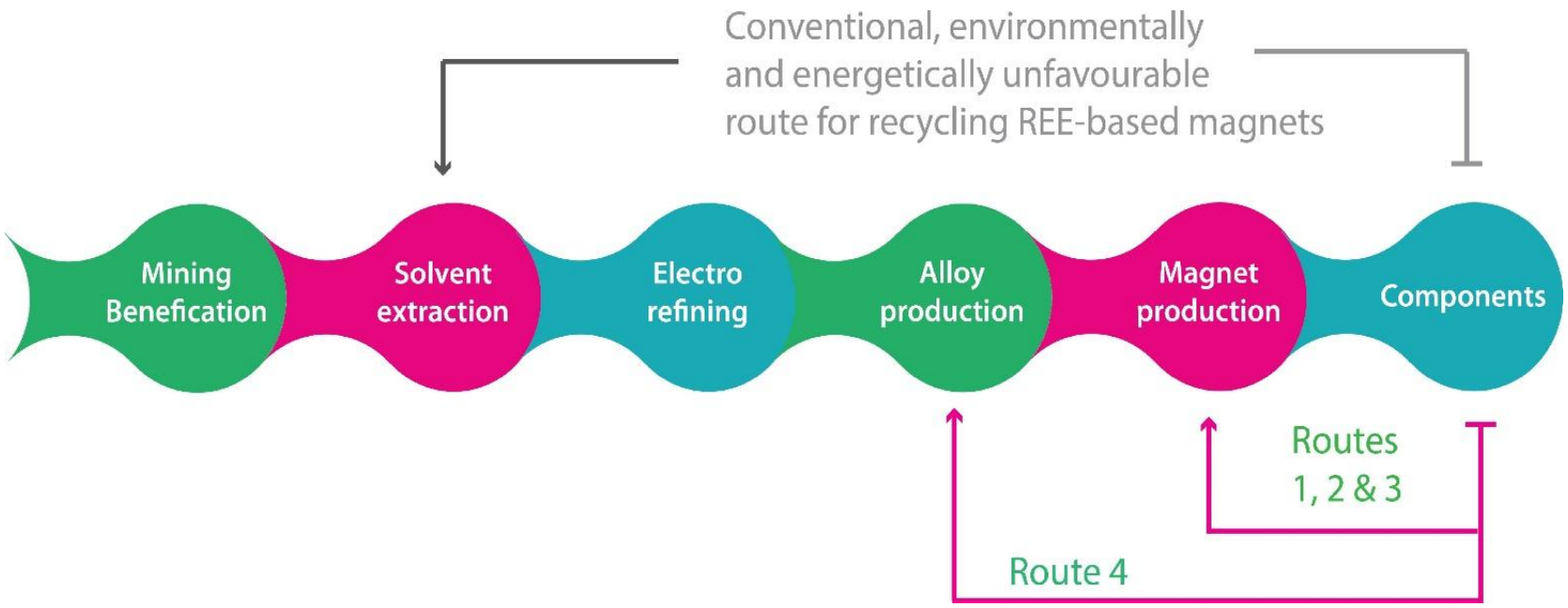
All Ni-Cu-Ni removed with 3mm sieve

FUTURE OF TECHNOLOGY SERIES

RE-PROCESSING OF EXTRACTED HYDROGENATED NdFeB POWDER INTO NEW MAGNETS

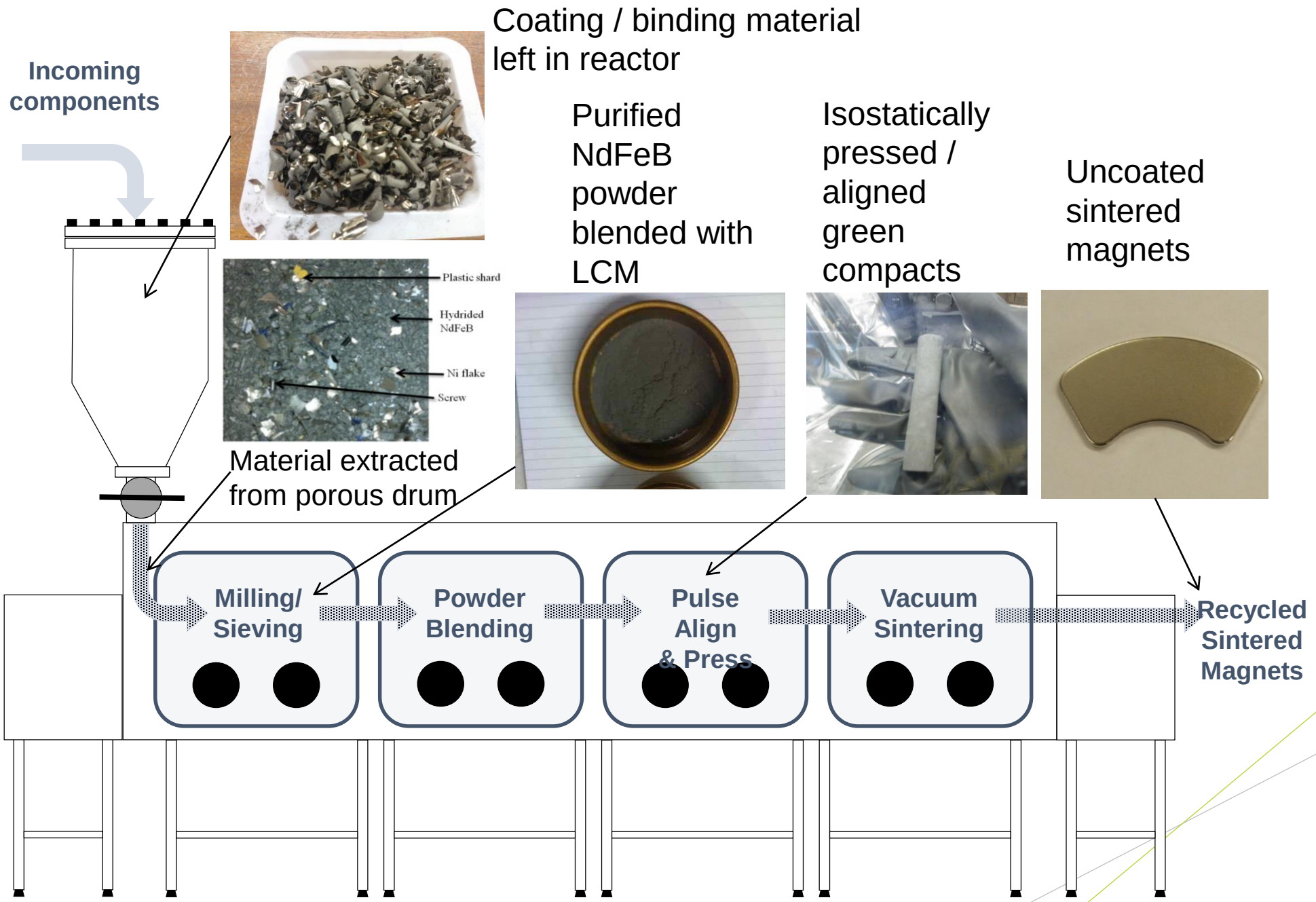
FUTURE OF TECHNOLOGY SERIES

Supply chain for rare earth magnets and where the NdFeB powder can be fed back in.



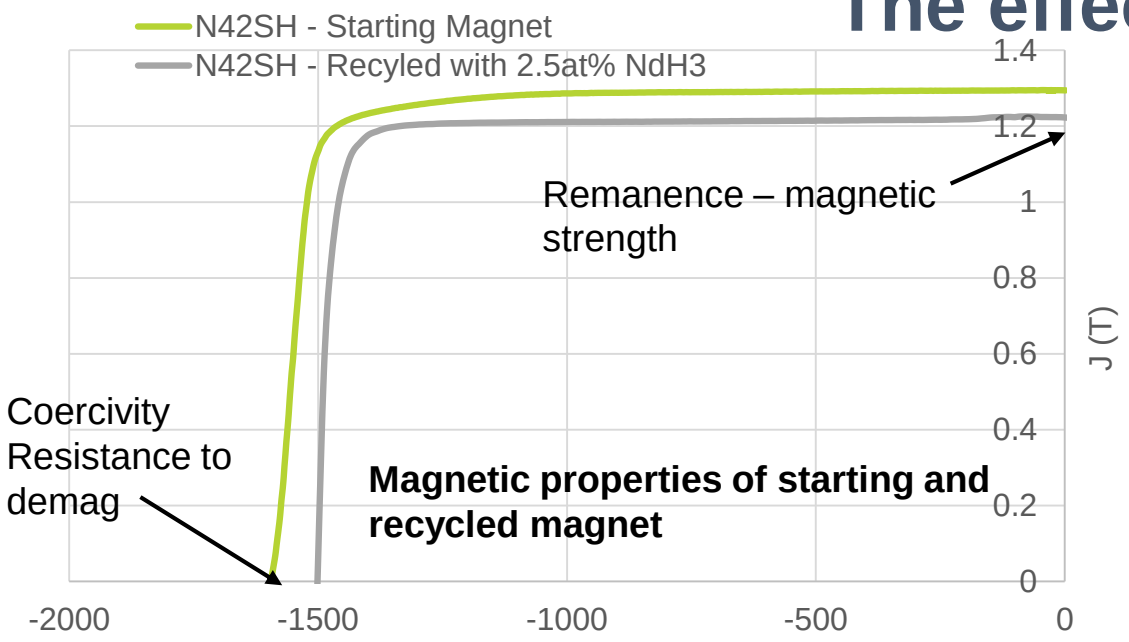
Conventional production route for Nd-Fe-B magnets and the SUSMAGPRO "Short-Cycle" route

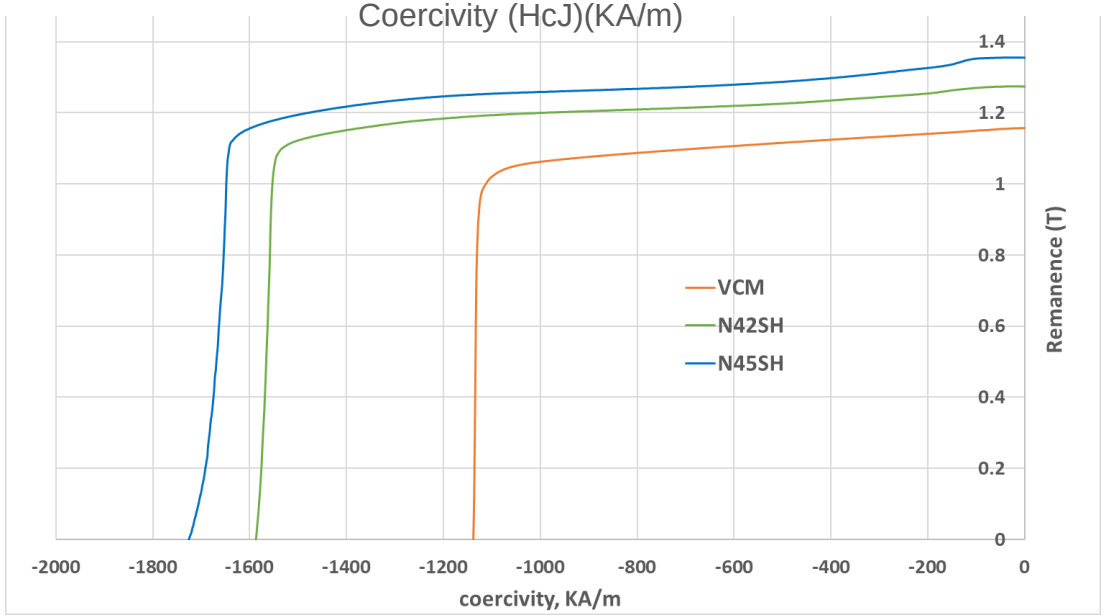
RE-SINTERING OF RARE EARTH MAGNETS



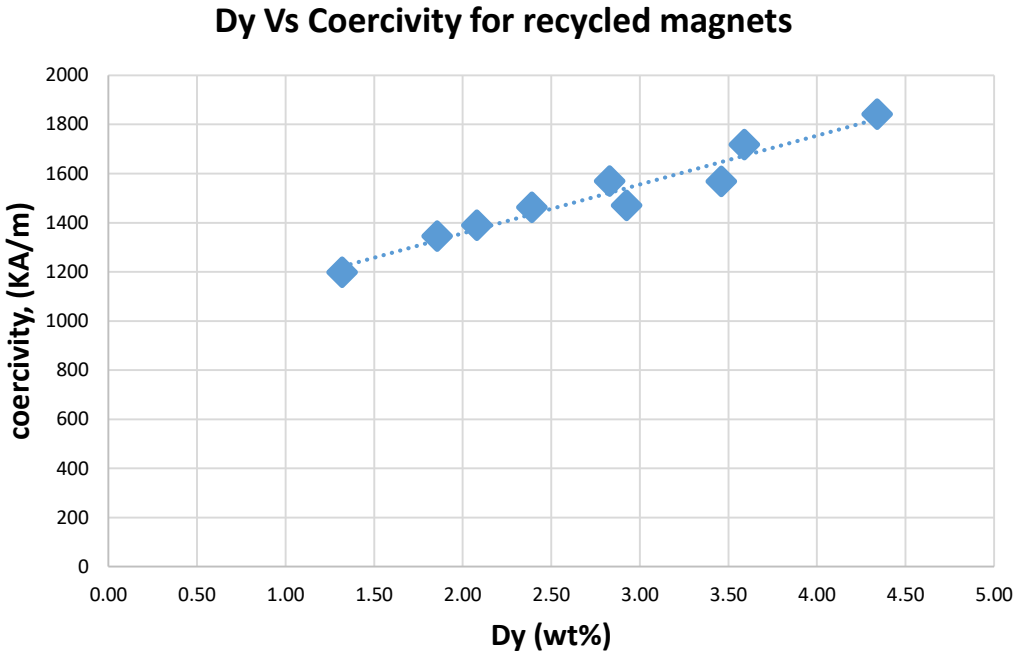
FUTURE OF TECHNOLOGY SERIES

The effect of composition





Magnetic properties of VCM and two different grade automotive scrap magnets



Type of Scrap	Al (%)	B (%)	Co (%)	Cu (%)	Dy (%)	Fe (%)	Ga (%)	Nd (%)	Pr (%)
VCM	0.30	1.02	1.30	0.10	1.32	Bal	0.12	25.59	3.42
N42SH	0.44	0.97	0.65	0.13	3.46	Bal	0.10	20.22	5.69
N45SH	0.32	0.96	1.97	0.17	4.34	Bal	0.10	20.89	3.48

Composition of different magnet grades

HOW COULD THE CIRCULAR ECONOMY IN RARE EARTH MAGNETS BE ENCOURAGED

- Labelling of magnets in waste streams (Maxcycle and SUSMAGPRO)
- Provide information to recyclers on products which contain magnets, dismantling advice etc…
- Eliminate glue or change the binding material
- Encourage end users to buy magnets based on composition and not grade. Ie- keep to a few grades
- Design the product so that the magnet containing components can be removed more easily.
- Change the coating materials so that they are easier to remove.
- Standardisation for magnets would help and this is being developed.

The SUSMAGPRO project is developing a database which will provide advice to machine designers on best practice for recycling of magnets. https://www.susmagpro.eu

CONCLUSIONS

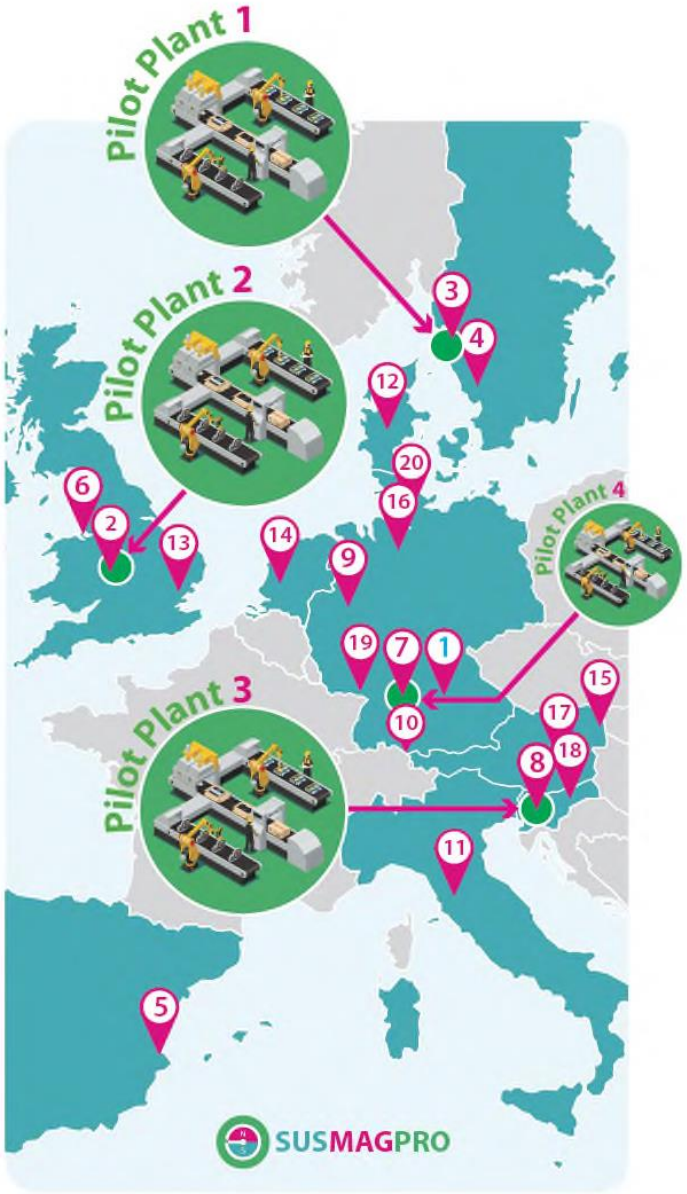
- We have unique IP in the UK which we could capitalize upon.
- To take this to scale requires significant capital investment in an immature market which is challenging. This needs support.
- The UK is unique in having certain parts of the supply chain already. Ie- Less Common Metals who cast rare earth alloys.
- We need to integrate magnet and motor manufacturing.

- The main barrier to developing LCA models in this area is a lack of good quality data.
- As the critical materials are often a small fraction of the overall weight of a car then wt% based recycling targets do not drive this market.

Scale up

SusmagPro (EU project) €14 million

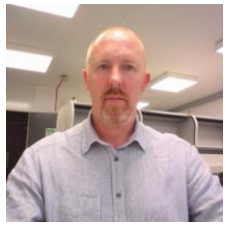
1 Pforzheim University (HSPF) Coordinator
2 University of Birmingham (UOB)
3 Stena Technoworld AB (STNA)
4 RISE Acreo (ACR)
5 Inserma Anoia S.L. (INS)
6 Less Common Metals Ltd (LCM)
7 OBE Ohnmacht & Baumgärtner GmbH & Co KG (OBE)
8 Magneti Ljubljana (MGI)
9 Kolektor Magnet Technology GmbH (KMT)
10 ZF Friedrichshafen AG (ZF)
11 B&C Speakers (B&C)
12 Grundfos (GBJ)
13 Bunting Magnetics Europe (BME)
14 Universiteit Leiden (UL)
15 FOTEC GmbH (FOTEC)
16 Sennheiser GmbH (SHR)
17 Montanuniversität Leoben (MUL)
18 Jožef Stefan Institute (JSI)
19 Steinbeis Europa Zentrum (SEZ)
20 Siemens Wind Power A/S (SIE)



Plasma building is being converted into a pilot magnet manufacturing facility

SCALE UP THOUGH HYPROMAG

New company set up (2018) – Hypromag Ltd, with investment from Mkango Ltd



Mr Nick Mann
Hypromag Ltd

Mr Rob Arnold
Rare Project

Prof Rex Harris
Emeritus Professor

David Kennedy
Honorary Research Fellow

Dr John Speight
Honorary Research Fellow

Prof Allan Walton
Head of the MMG

Innovate UK

Rare project (Rare Earth Recycling for E-Machines) aimed at scaling the downstream re-sintering processes for NdFeB magnets

BENTLEY

UNIPART

HYPROMAG Magnet Recycling

Advanced Electric Machines

UNIVERSITY OF BIRMINGHAM

Intelligent Lifecycle Solutions

FUTURE OF TECHNOLOGY SERIES

INDUSTRIAL STRATEGY

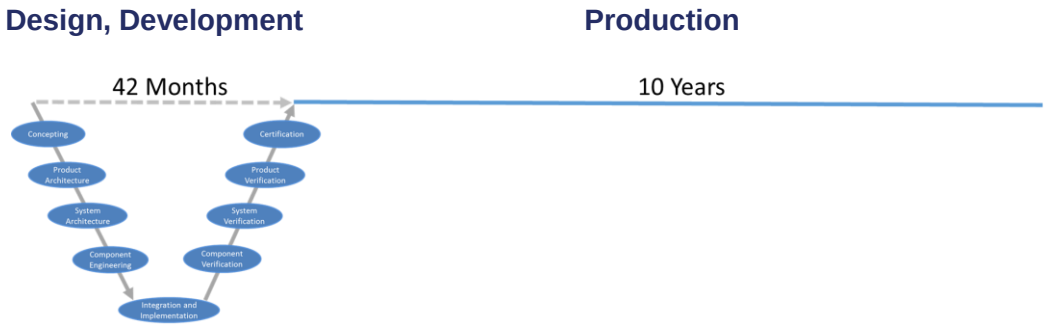
UK Research and Innovation

ISCF Faraday Battery Challenge

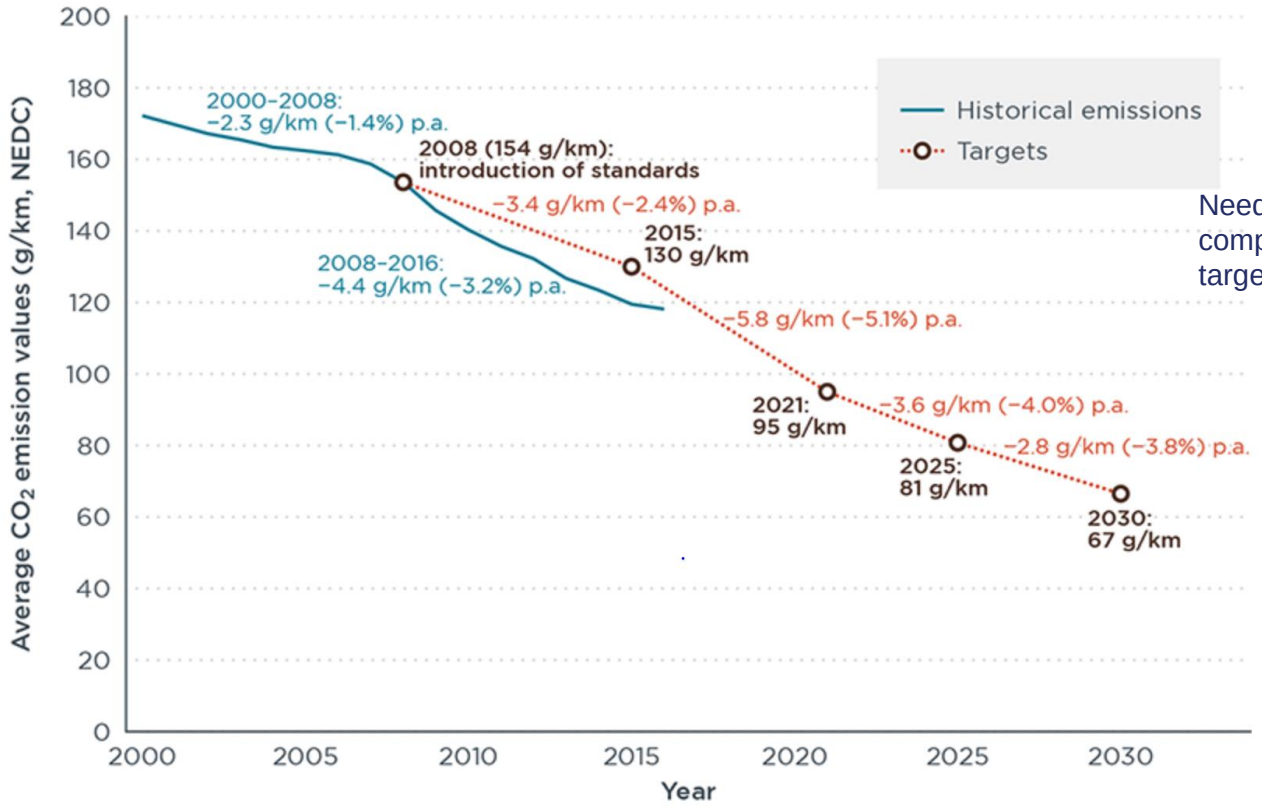
Jacqui Murray, Deputy Challenge Director

Batteries are coming. Why?

Automotive technology decisions for 2030s **must be made today**!

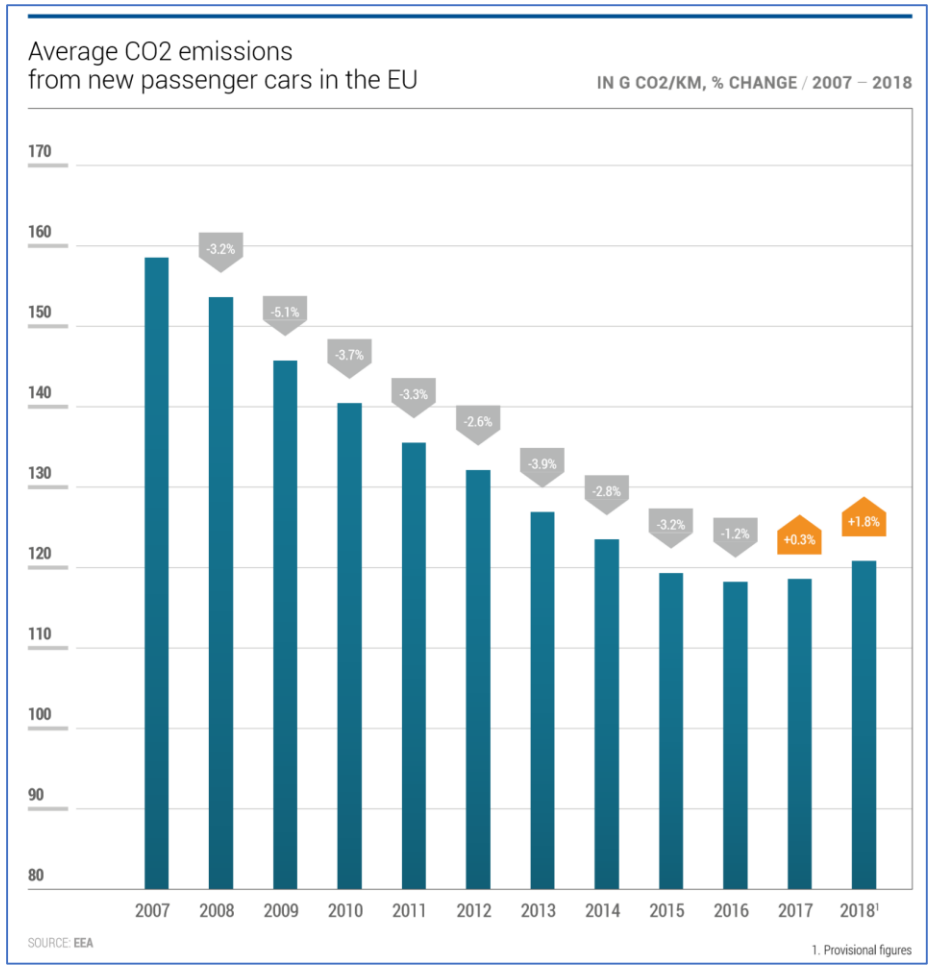


Development of average CO2 emission level for new passenger cars in the EU and current as well as proposed regulatory target values.



Need to be compatible with targets in 2035

We have reached the limits of ICE to reduce CO2 emissions.



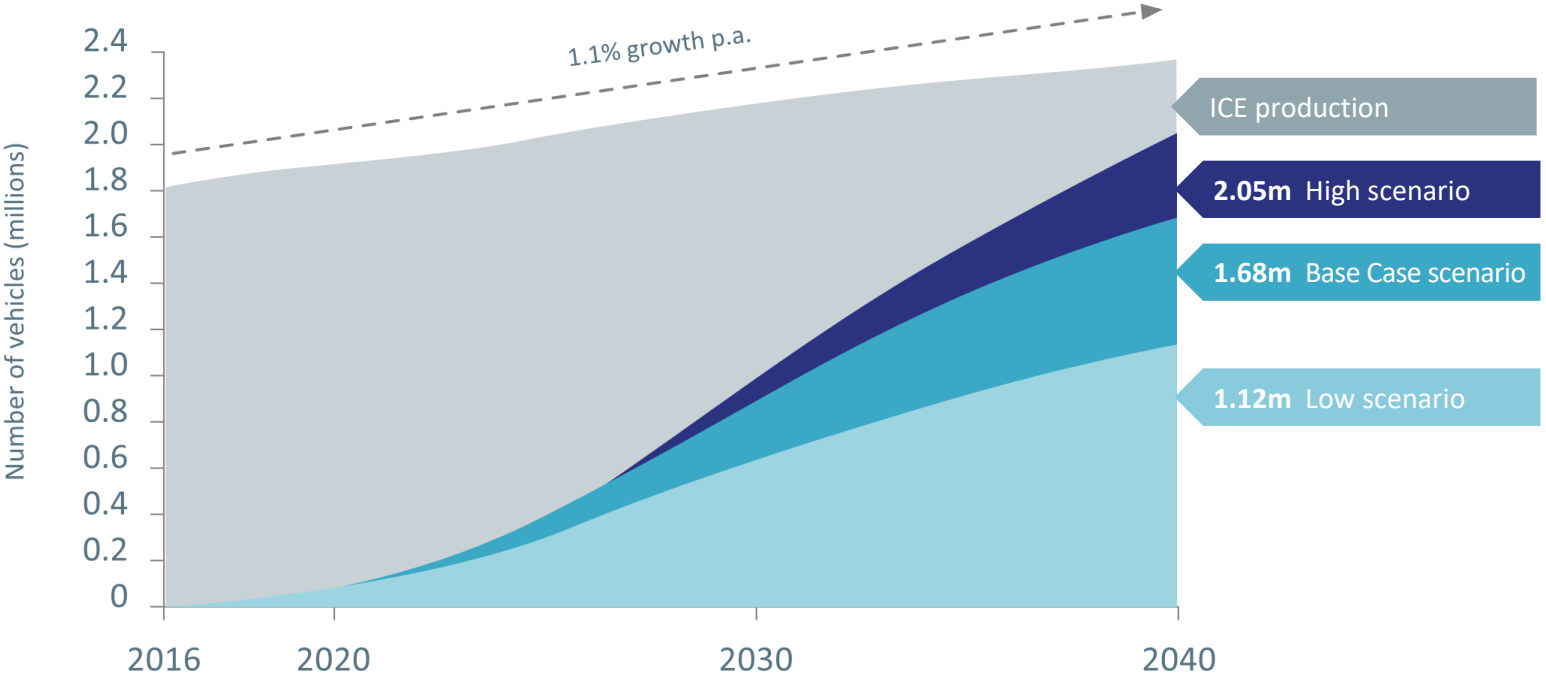
EU Fleet average CO2 has increased in the last 2 years after a prolonged period of steady decline.

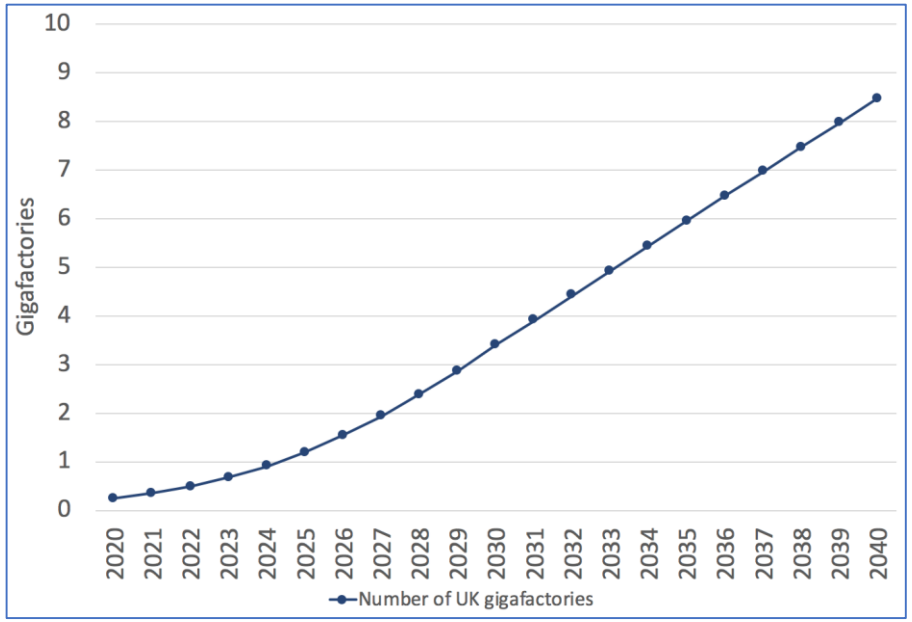
The main factors are:

- Reaching the limit of ICE-based technology
- The shift from Diesel to Petrol
- The shift to “real-world” test drive cycles

A technological transition involving 15m passenger cars is required!

If decisions must be made now, **batteries are the only realistic technology**.





EV vehicles produced in the UK

Maintaining current market shares in its key markets allows UK-based EV manufacturing to capture 1.1 to 2.0m EVs by 2040

https://faraday.ac.uk/publications/ev-economics-study/

Technical/Commercial/Customer Targets Moving Faster Than Predicted at Programme Start!!

INDUSTRIAL STRATEGY

UK Research and Innovation

Cost

NOW: $130/kWh (cell) $280/kWh (pack)
2035: $50/kWh (cell) $100/kWh (pack)

Energy Density

NOW: 700Wh/l, 250Wh/kg(cell)
2035: 1400Wh/l, 500Wh/kg(cell)

Power Density/ Fast Charging

NOW:
3 kW/kg (pack)
2035:
12 kW/kg (pack)

Safety

2035:
Eliminate thermal runaway at pack level to reduce pack complexity

1st Life

NOW: 8 years (pack)
2035: 15 years (pack)

Temperature

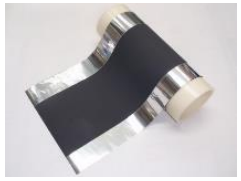
NOW: -20˚ to +60˚C (cell)
2035: -40˚ to +80˚C (cell)

Predictability

2035:
Full predictive models for performance and ageing of battery

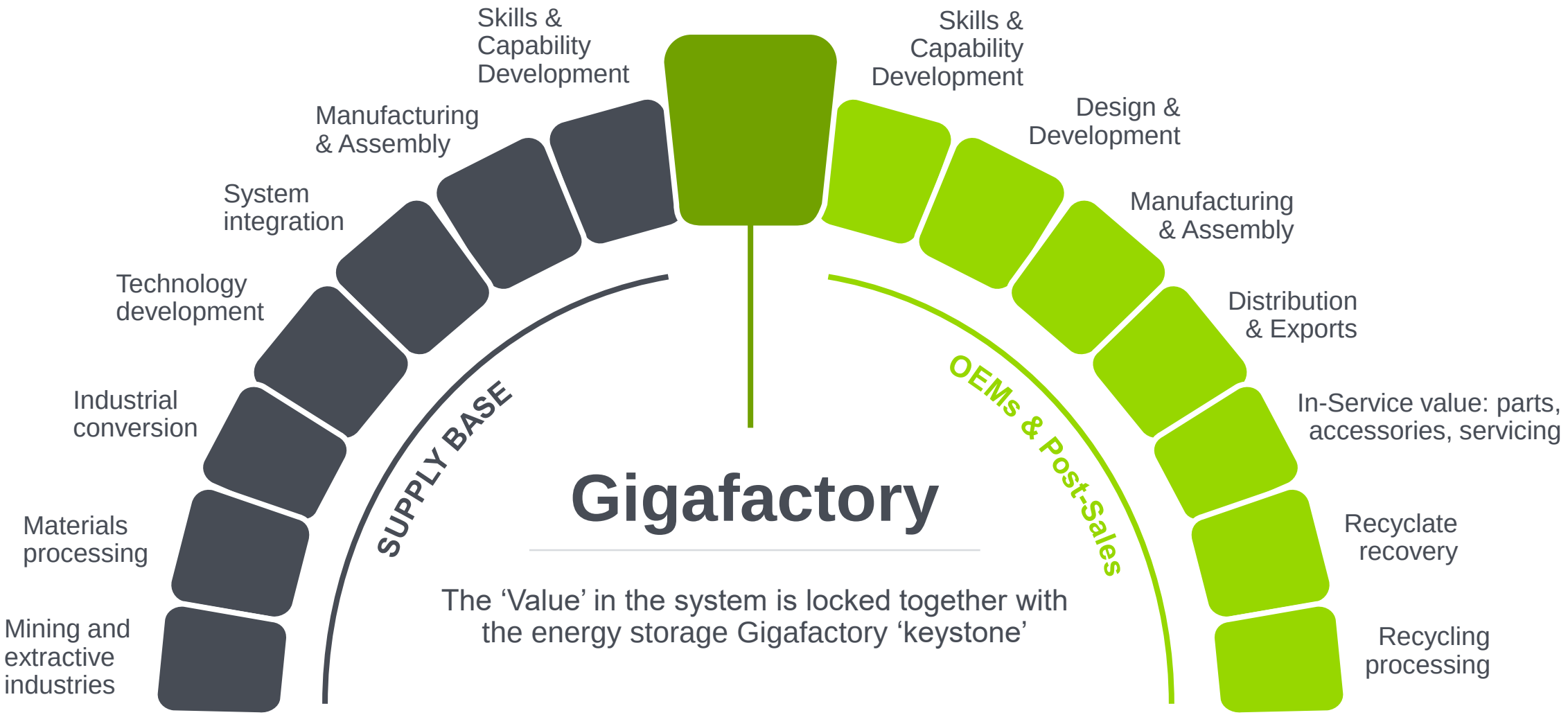
Recyclability

NOW:
10-50% (pack)
2035:
95% (pack)



Raw Materials → Materials and Electrochemistry → Electrode, electrolyte, separator, etc. → Cell Manufacture → Module, Pack and BMS → Vehicle Application → 2nd life / Recycling

VALUE OF A GIGAFACTORY TO THE UK



Faraday Battery Challenge is addressing these challenges.

INDUSTRIAL STRATEGY

UK Research and Innovation

£78m

The Faraday Institution

Harnessing the strengths of the UK research base

THE FARADAY INSTITUTION

£108m

UK Battery Industrialisation Centre

Open access, scale up centre, rapidly moving products to market

UK BATTERY INDUSTRIALISATION CENTRE

ADVANCED PROPULSION CENTRE UK

£88m

Collaborative R&D

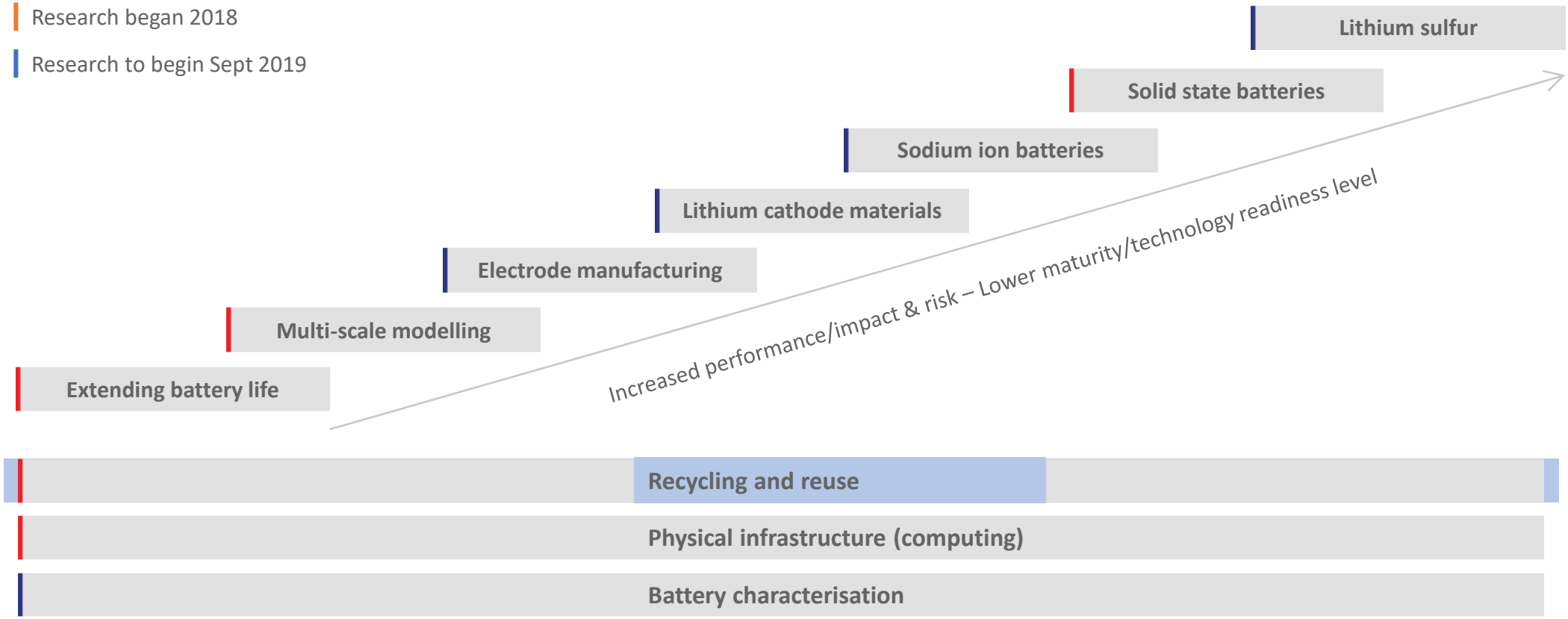
Creating new solutions and demonstrations

Innovate UK | UK Research and Innovation

Scientific research

Application-inspired research to address known technical performance gaps

- Research began 2018
- Research to begin Sept 2019



20+ Academic Partners

40+ Industry Partners

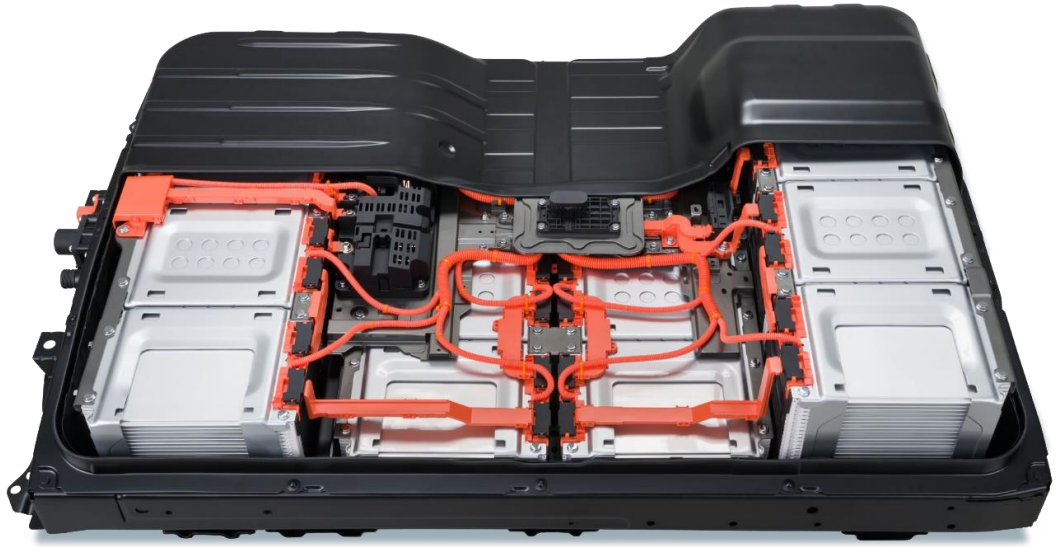
Innovate UK Collaborative R&D

By the Numbers

- £114 million invested in 62 projects
  - £82 million in innovation funding
  - £32 million investment from industry
- 124 organisations funded
  - Academic (20%)
  - Micro companies (42%)
  - Small companies (5%)
  - Medium companies (10%)
  - Large companies (23%)

Project Technical Areas

- Cells and cell materials (54%)
- Modules and packs; BMS, thermal (28%)
- Recycling and reuse (9%)
- Safety (7%)
- Diagnostics (2%)



UK Battery Industrialisation Centre

UKBIC

DE-RISKING GROWTH

TO HIGH VOLUME MANUFACTURING

STEPS IN CELL DEVELOPMENT

Gramme Scale
University scale
Research

Kilogramme Scale
Corporate R&D
or specialist Uni facilities

Tonne Scale
Manufacturing process
development at industrial rates

Kilotonne Scale
Full scale, high
volume manufacture

Winning and winning again

Frances Wall

LowCVP
Low Carbon Vehicle Partnership

ADVANCED PROPULSION CENTRE UK

UNIVERSITY OF EXETER

Winning and winning again

We need a mixed economy of raw materials supply - with mining driving sustainable development **(first win)** and then excellent materials stewardship, including recycling to keep our materials in use **(win again and again)**

Frances Wall

UNIVERSITY OF EXETER

LowCVP
Low Carbon Vehicle Partnership

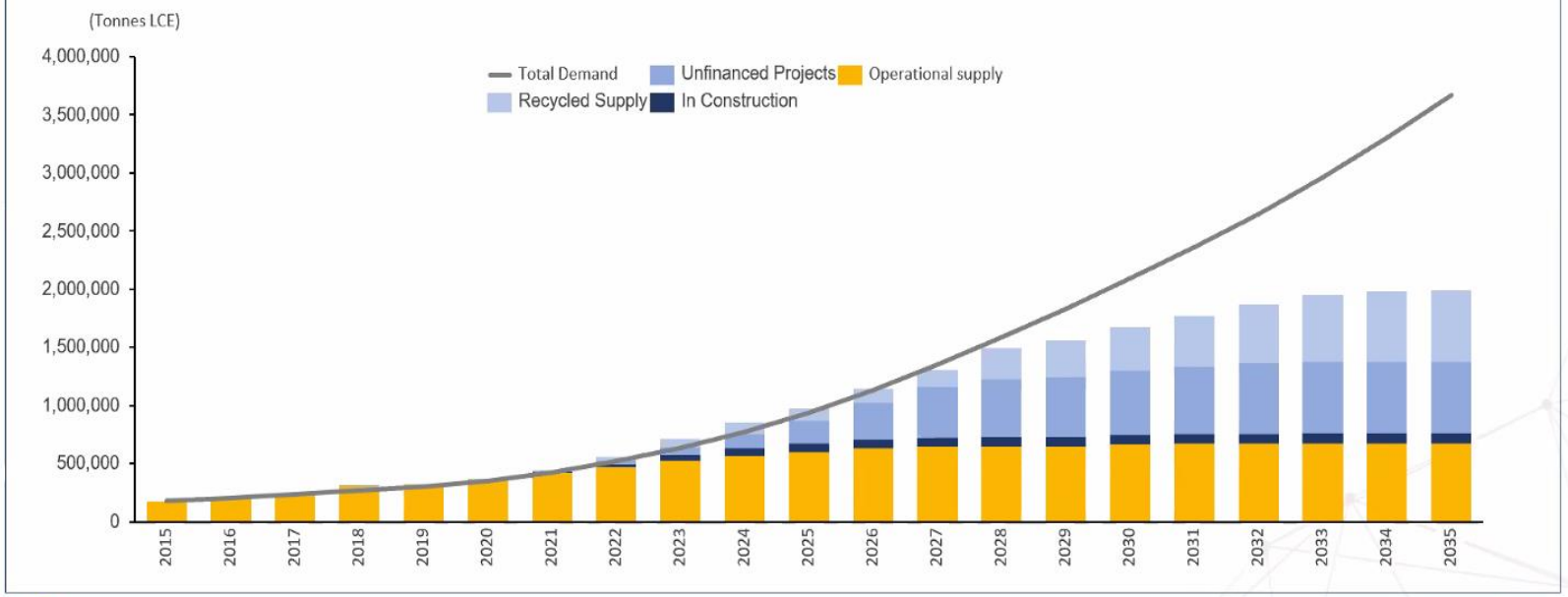
ADVANCED PROPULSION CENTRE UK

Zoom Webinar

Andy Leyland

All major battery raw materials face impending shortages due to drastically increasing demand, and industry is looking for new material sources

Lithium Demand Vs Financed and Unfinanced Supply (MT LCE)



BENCHMARK MINERAL INTELLIGENCE

Source: Benchmark Mineral Intelligence, Bolivian estimate

Zoom Webinar Chat

If you have a question for our speakers, please utilise the Q&A box available at the bottom of your screen. We will aim to get through as many of these as possible. You may be contacted to ask if you are happy to ask these questions live, so please keep an eye on your chat box.

From Philippa Oldh... to All panelists and attendees:
Please let us know if you have questions for Darryn in the Q&A box

From Alex Voss to Me, All panelists:
Hi Frances,
Thanks for you question! Are you happy to ask this live?

From Me to All panelists:
Yes ok

From Ileana Lupsa to All panelists and attendees:
You can also register to the LowCVP Annual Conference here: https://www.lowcvp.org.uk/events/conference/2020.htm
The 2020 LowCVP Annual Conference will focus on how the UK can seize the opportunity for an investment-led green recovery in road transport as we emerge from the pandemic.

To: All panelists

Your text can only be seen by panelists

11:12
07/07/2020

Exploring for rare earths in Malawi

f.wall@exeter.ac.uk

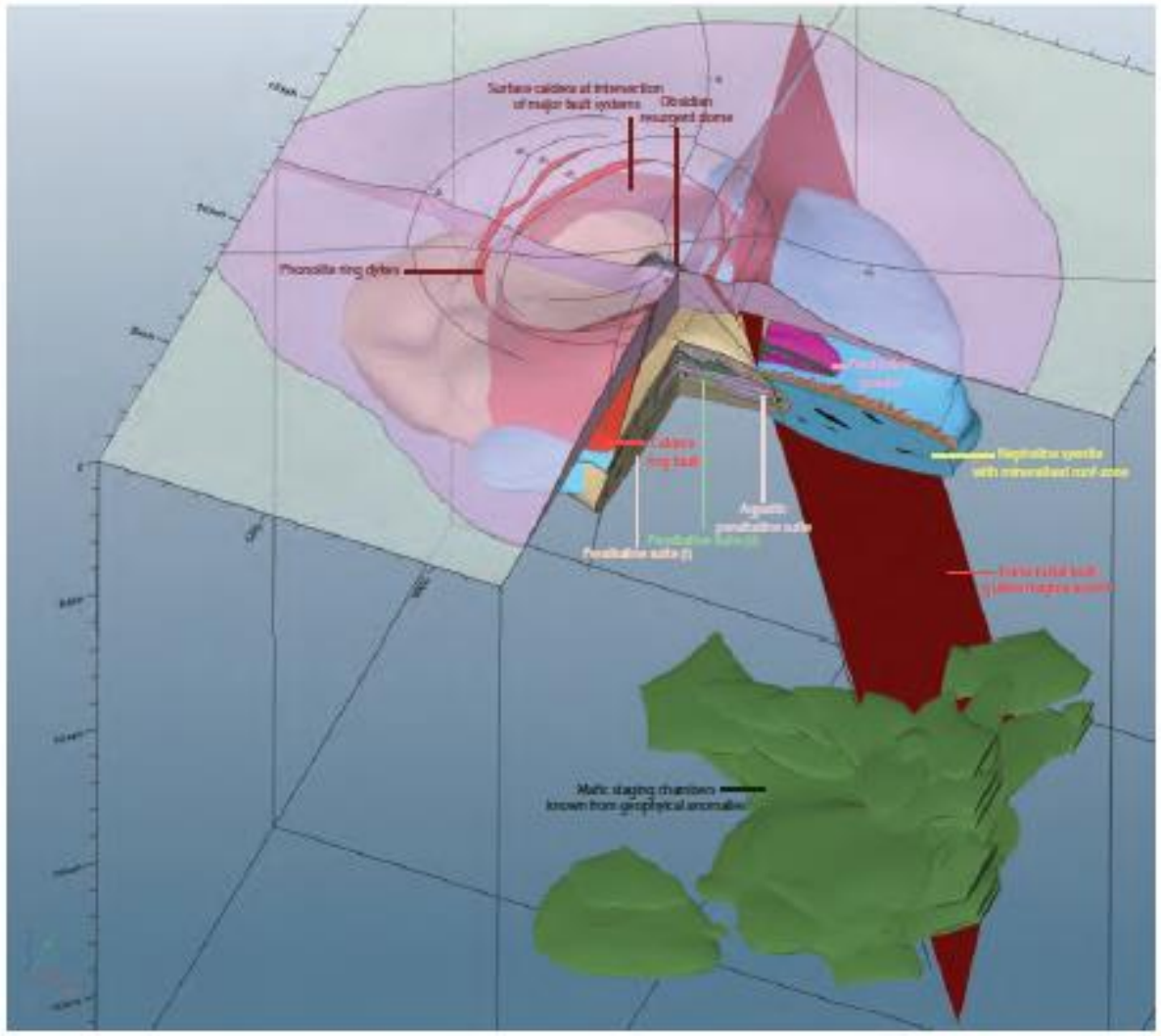
#LCAweek

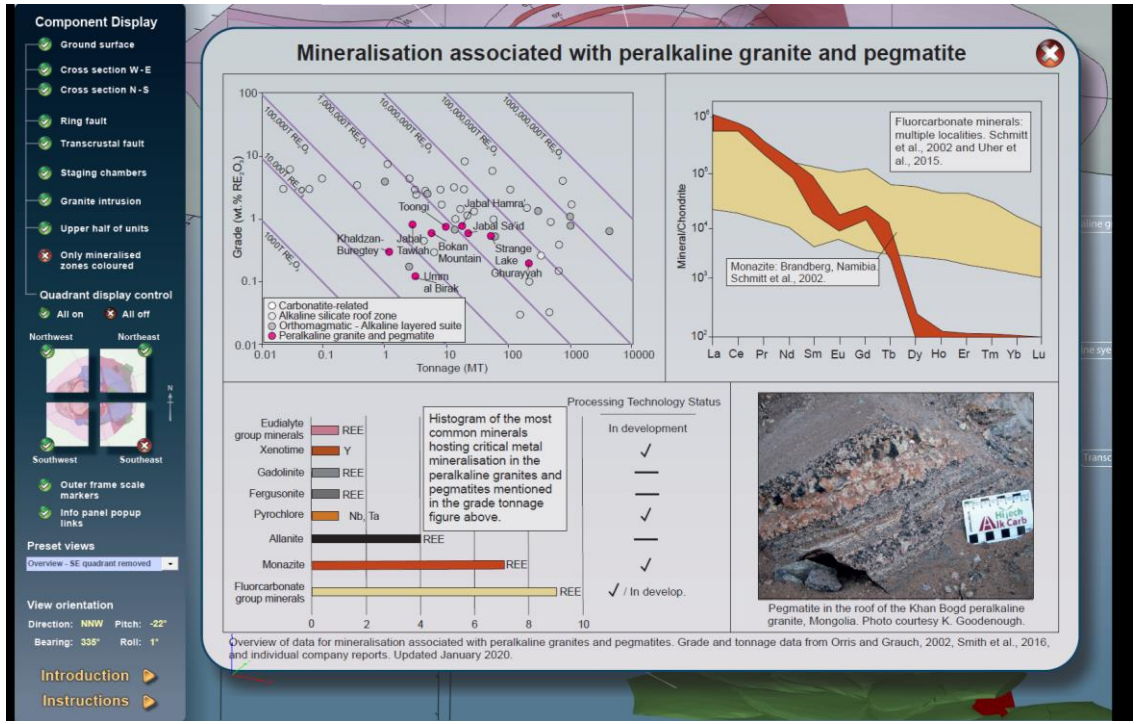
Photo Sam Broom-Fendley

Exploration - geomodels for REE in alkaline rocks and carbonatites

This project has received funding from the European Union's Horizon 2020 research and innovation programme (grant agreement No 689909)

www.carbonatites.eu

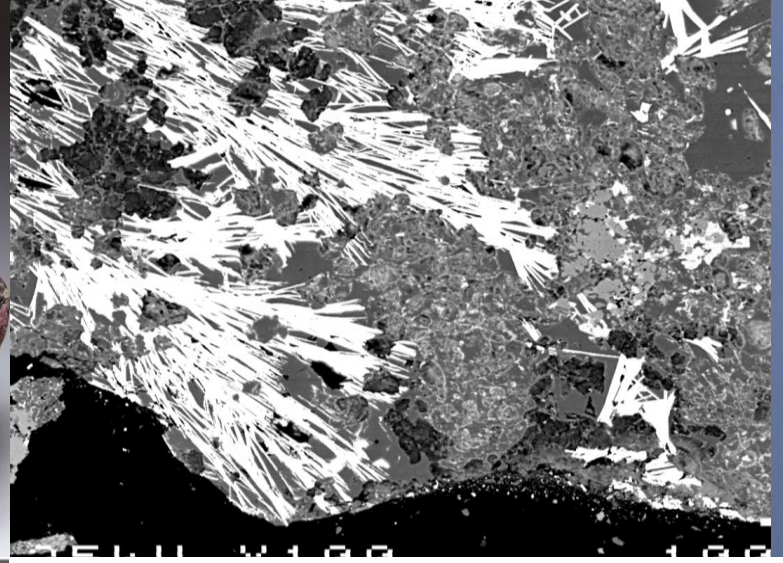


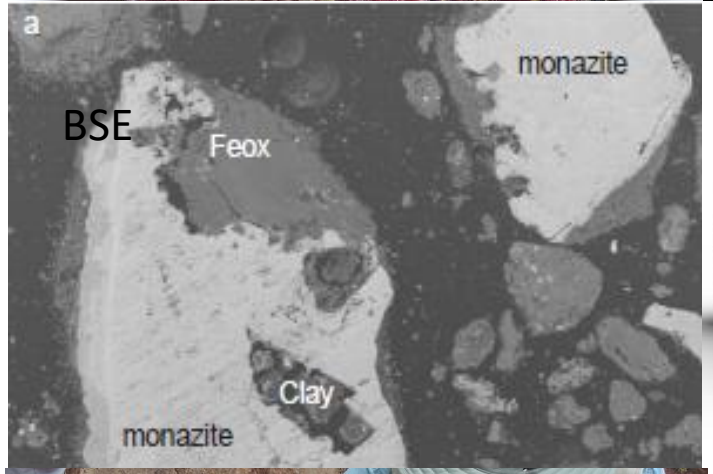


Charlie Beard, Kathryn Goodenough, Eimear Deady, Frances Wall et al (in preparation from project deliverable)

f.wall@exeter.ac.uk

#LCAweek





‘Rare earth ores’

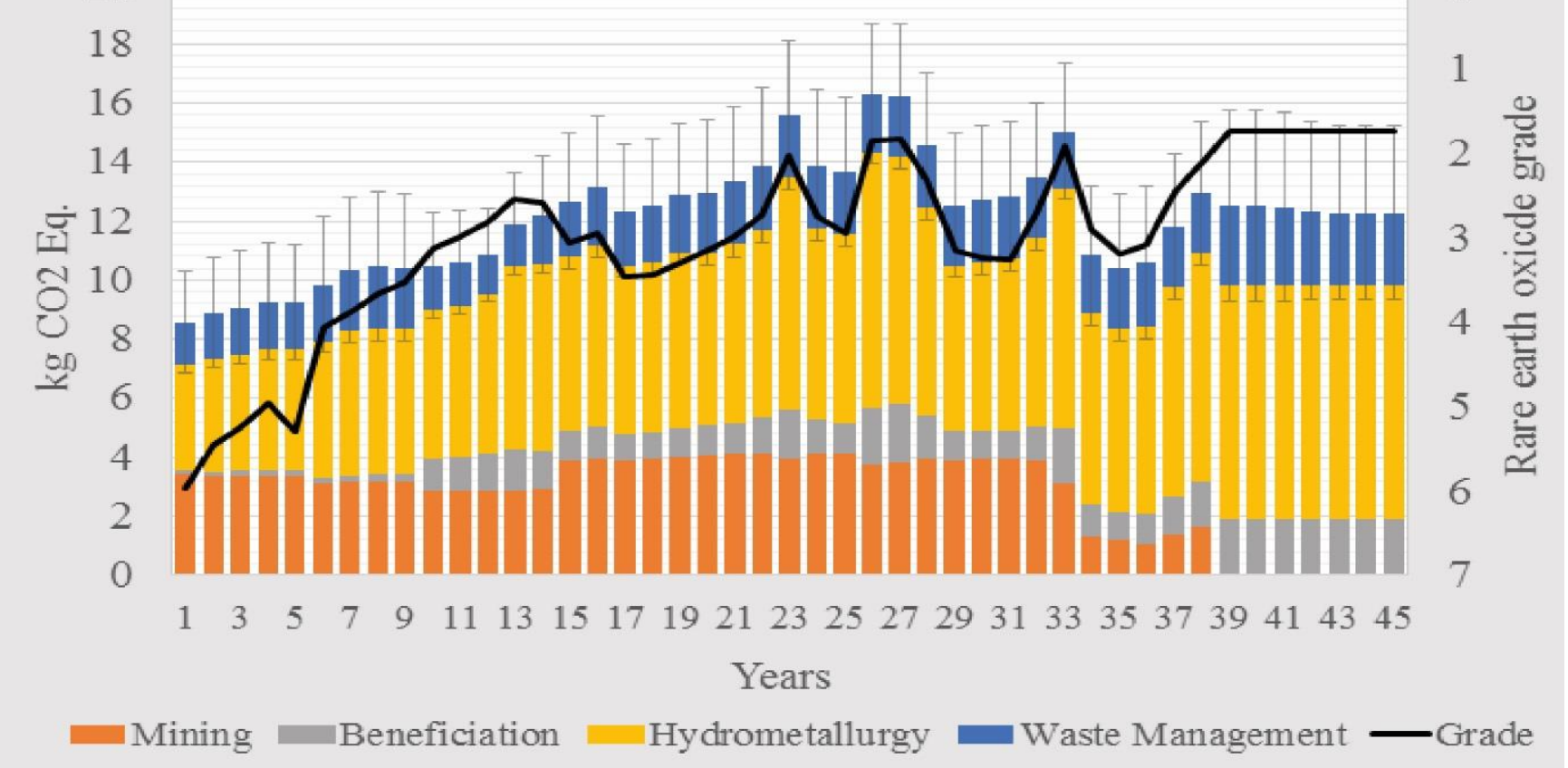
f.wall@exeter.ac.uk

#LCAweek

Life Cycle Assessment - good tool to join up the value chain

Bear Lodge REE project assessed early in development

Lower grade = Higher global warming potential



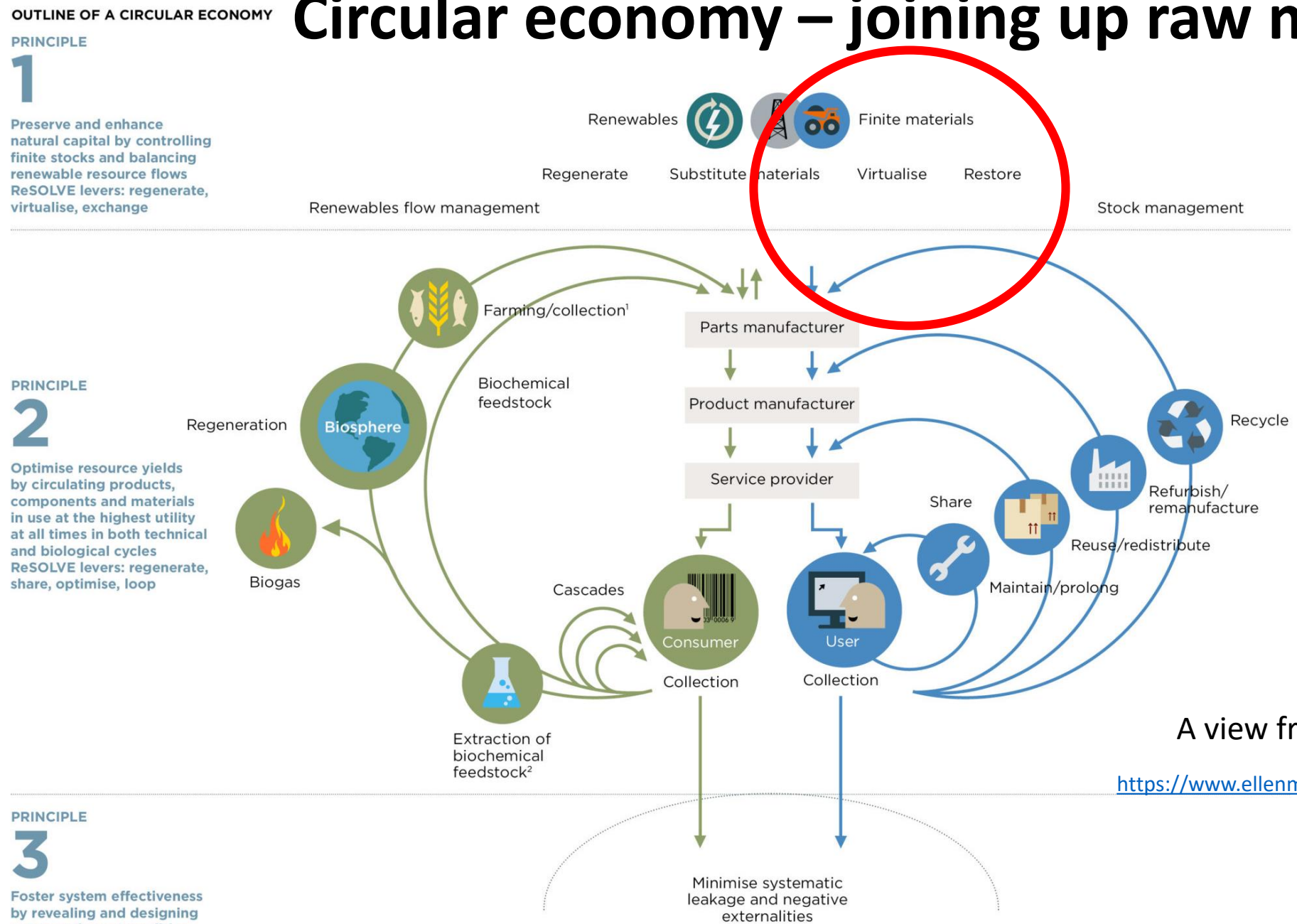
SoS RARE

using data from Dahlberg, P. Bear Lodge Project Canadian NI 43-101 On the Reserves and Development of the Bull Hill, **2014**.

Pell R, Wall F, Yan X, Li J, Zeng X. 2019. Temporally explicit life cycle assessment as an environmental performance decision making tool in rare earth project development, *Minerals Engineering*, volume 135, pages 64-73, DOI:10.1016/j.mineng.2019.02.043.

#LCAweek

Circular economy – joining up raw materials



A view from Ellen Macarthur Foundation

https://www.ellenmacarthurfoundation.org/circular-economy/infographic

#LCAweek

Chromite mine in Finland, mines new ore to combine with scap iron to make stainless steel

f.wall@exeter.ac.uk

#LCAweek

Kemi chromite mine, Photo F. Wall

Responsible Sourcing Choices

Recycled

Re-used

Economic development and secure supply from new UK extraction

Responsible supply from large mines

Helping developing countries

Helping marginalised artisanal miners

f.wall@exeter.ac.uk
www.exeter.ac.uk/csm

How do we help artisanal miners? – we *do* want cobalt from DRC!

Amnesty International image

https://www.amnesty.org/en/latest/news/2016/01/child-labour-behind-smart-phone-and-electric-car-batteries/

‘Elon Musk's worst nightmare: child labor and cobalt supply’

http://www.mining.com/web/elon-musks-worst-nightmare-child-labor-cobalt-supply/

But better to help than avoid -

Pact expands fight against worst form of child labor in Africa. October 11, 2017 WASHINGTON, D.C., USA Support from Google http://www.pactworld.org/news/pact-expands-fight-against-worst-form-child-labor-africa

Much could change around ownership and traceability

Blockchain traceability initiatives:

https://sustainability.google/projects/traceability/

https://www.rcsglobal.com/wp-content/uploads/2018/09/ICMM-Blockchain-for-Traceability-in-Minerals-and-Metal-Supply-Chains.pdf

RECLAMATION AND RECYCLING OF LITHIUM ION BATTERY MATERIALS

Prof Emma Kendrick

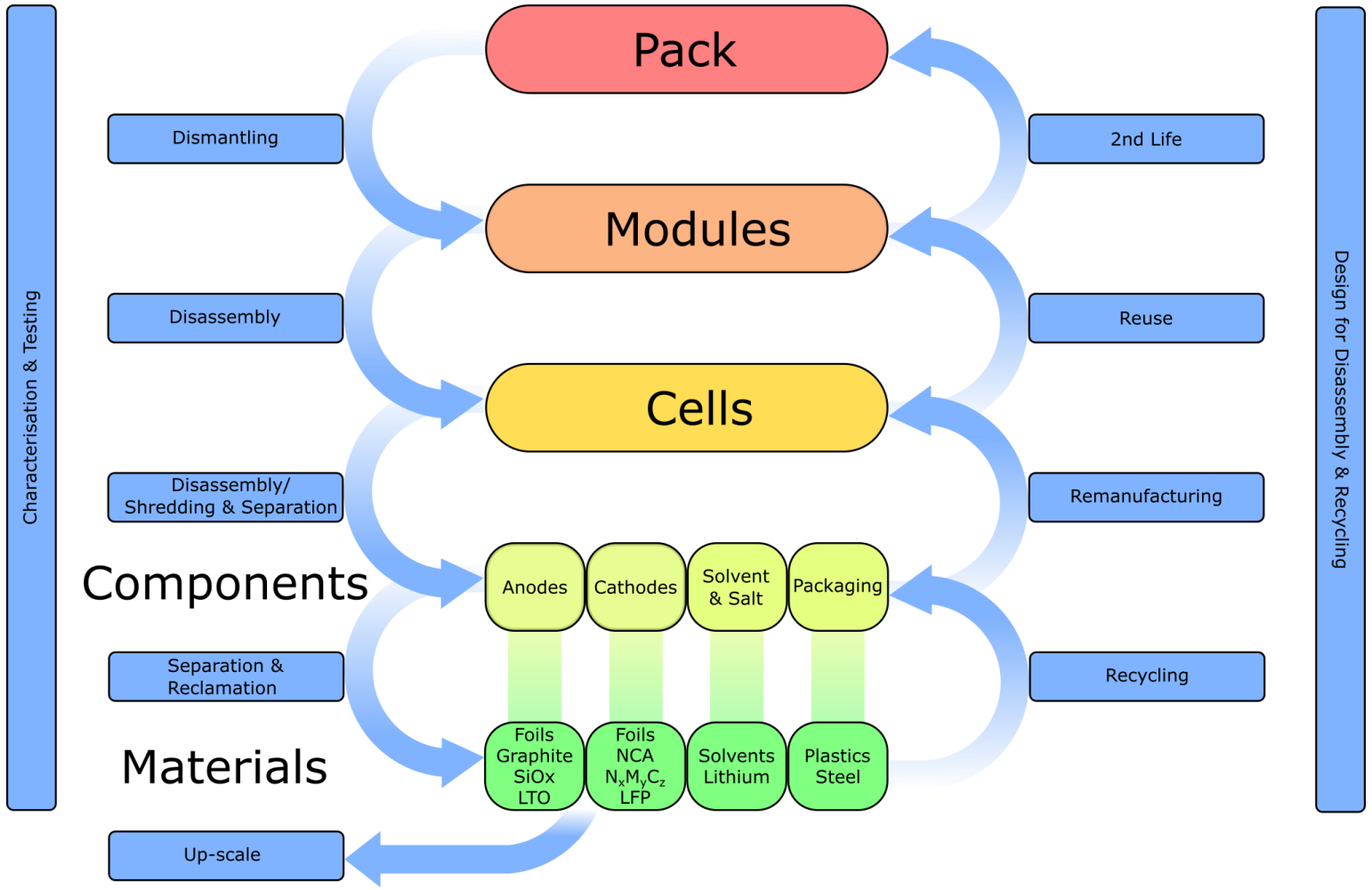
LowCVP
Low Carbon Vehicle Partnership

ADVANCED PROPULSION CENTRE UK

UNIVERSITY OF BIRMINGHAM

THE FARADAY INSTITUTION ReLiB

RELIB PROJECT

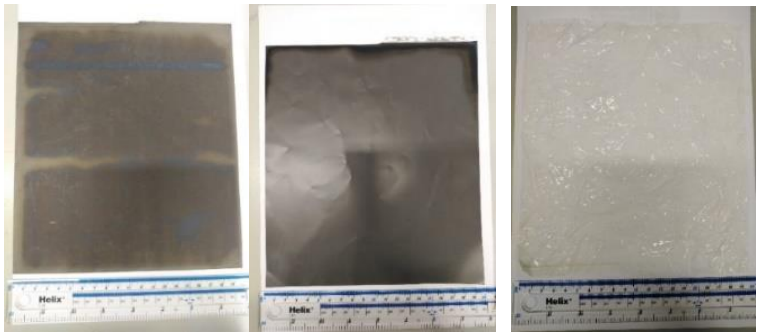


Recycling

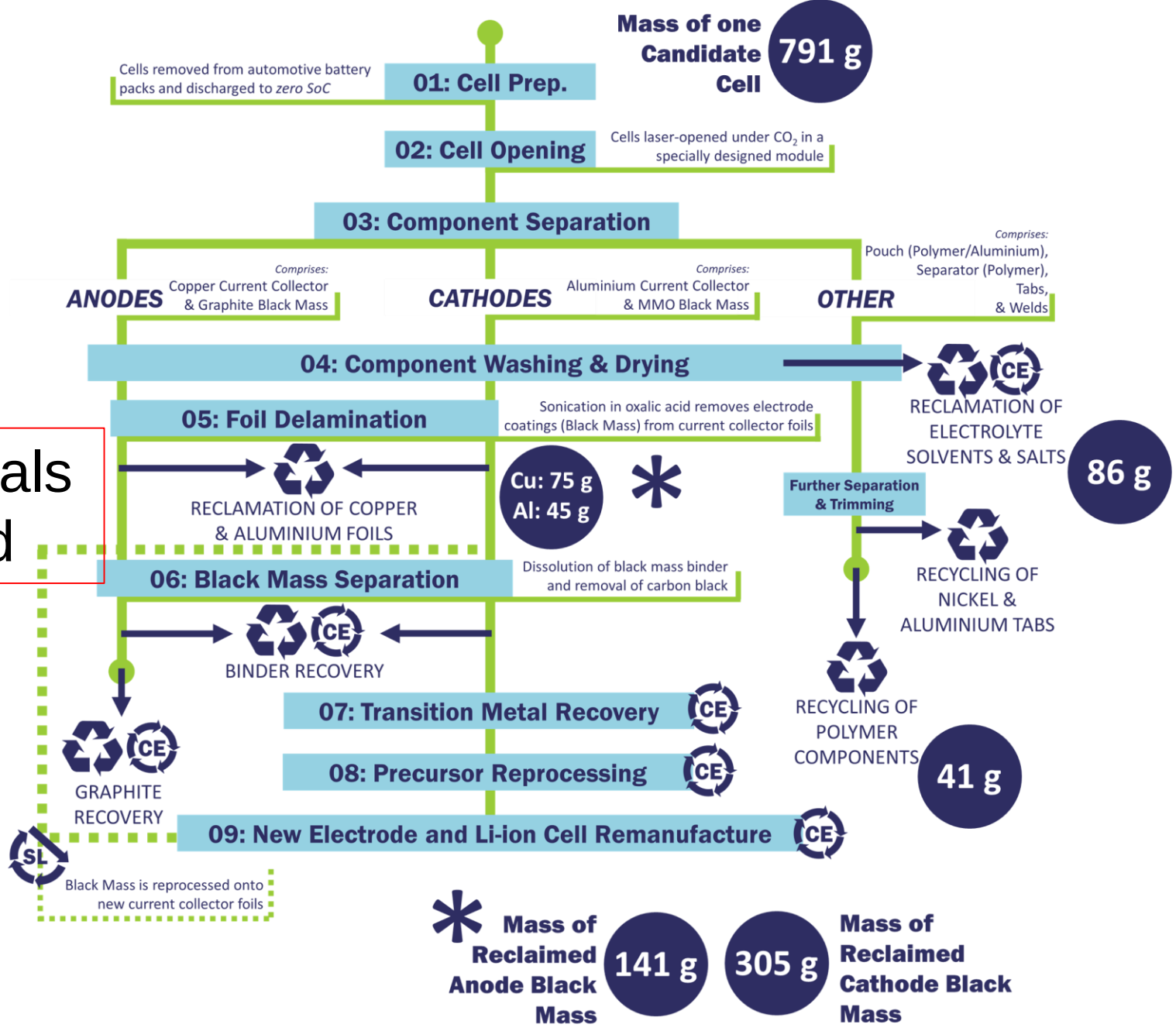
R2LIB – IUK Faraday Challenge

87% materials reclaimed

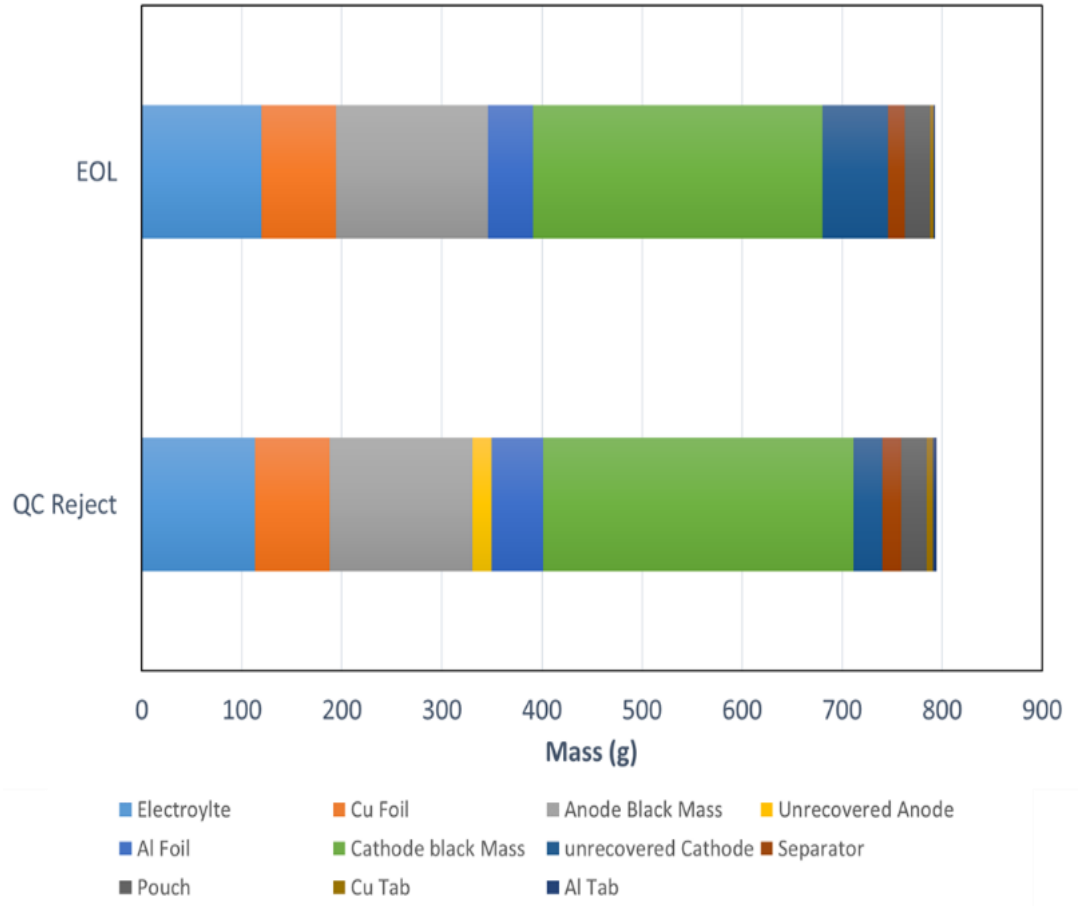
Electrolyte Not

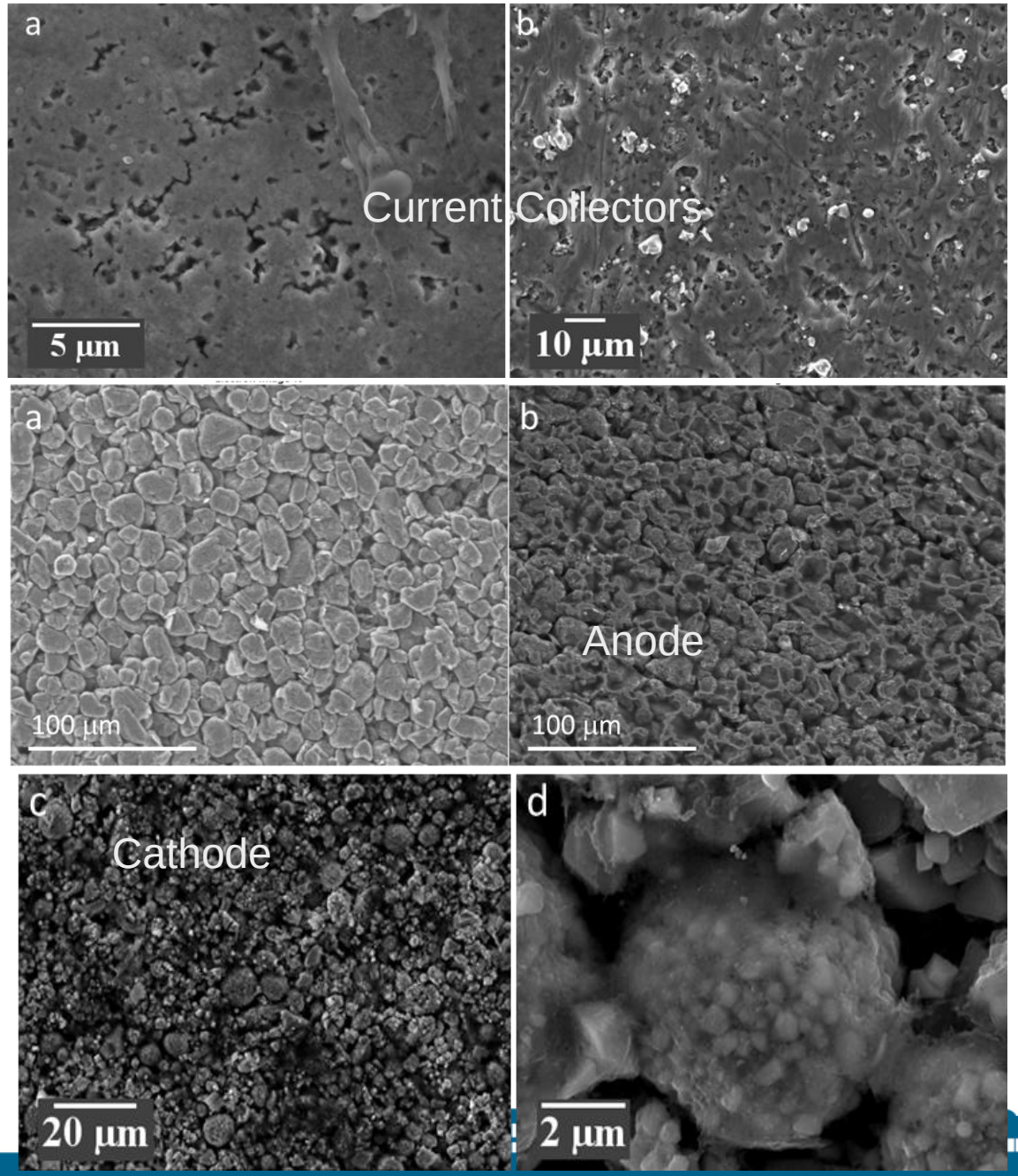


Anode Cathode Separator



Reclaimed materials from End of Life and QC Rejects!





Reclaimed black mass

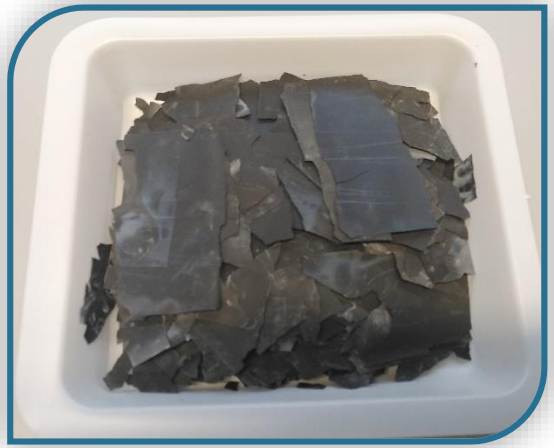
sent

sent

sent

Reclaimed material at the University of Birmingham

Cathode black mass delivered to partners
4325.8 g



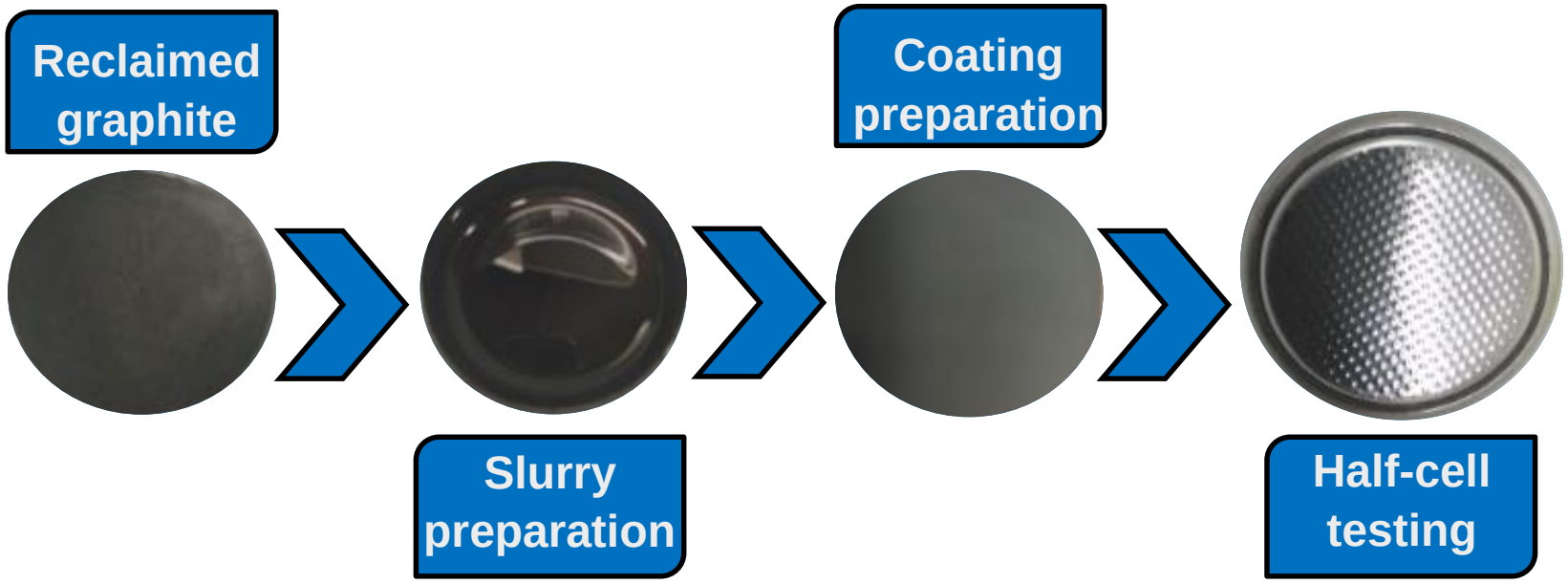
Anode black mass delivered to partners
469.3 g

Total number of opened cells
29

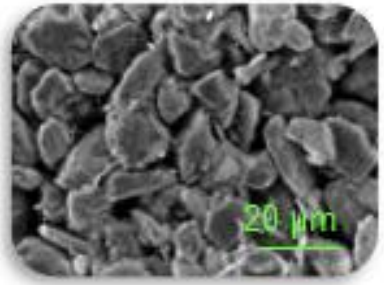
Short Loop recycling of Anodes and cathodes

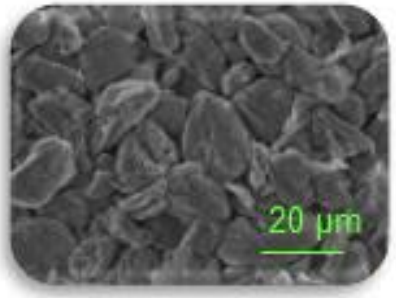
- Removal of binder and carbon black required
- Direct loop recycling, metals leached from cathodic black mass (binder-carbon doesn't dissolve)

Short-Loop Recycling



QC failed



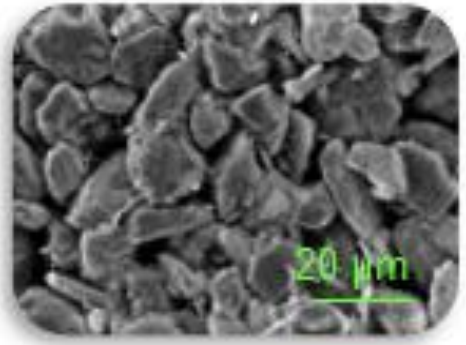


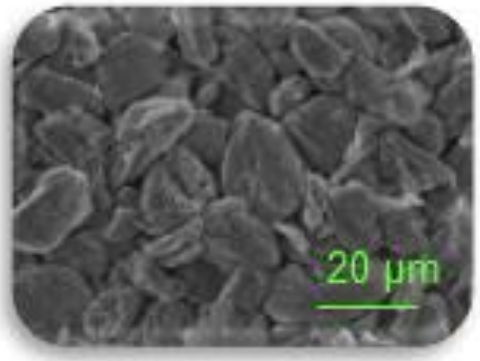
End of life

Graphite Short-Loop Recycling

QC Rejected

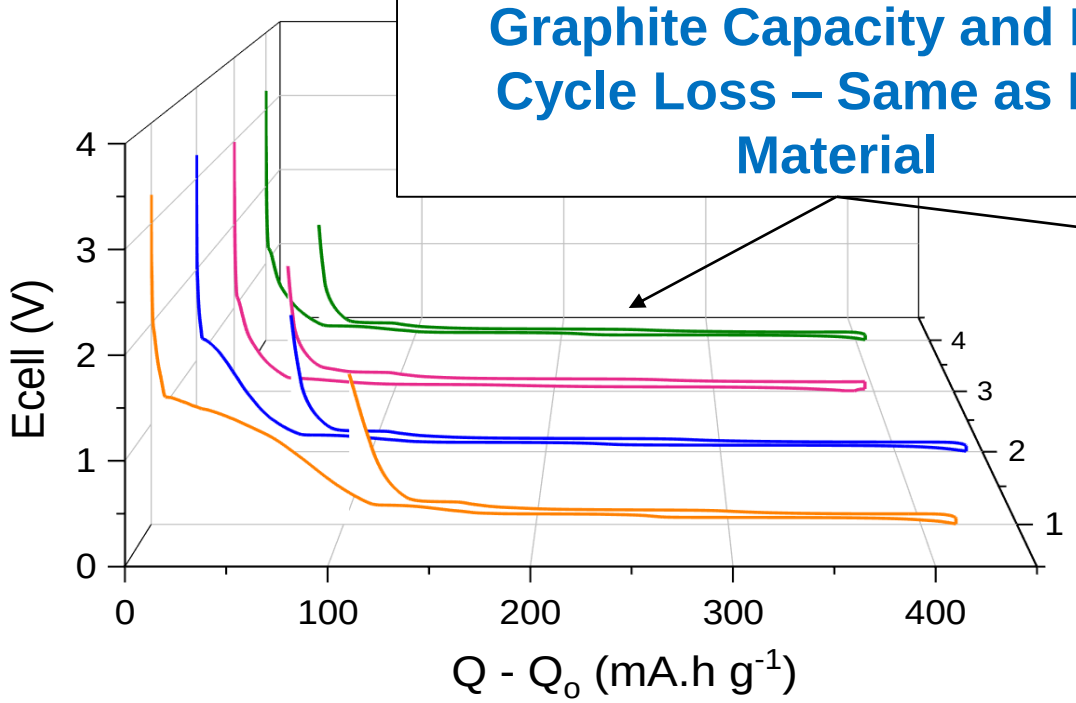
Graphite washed and processed in routes1-4

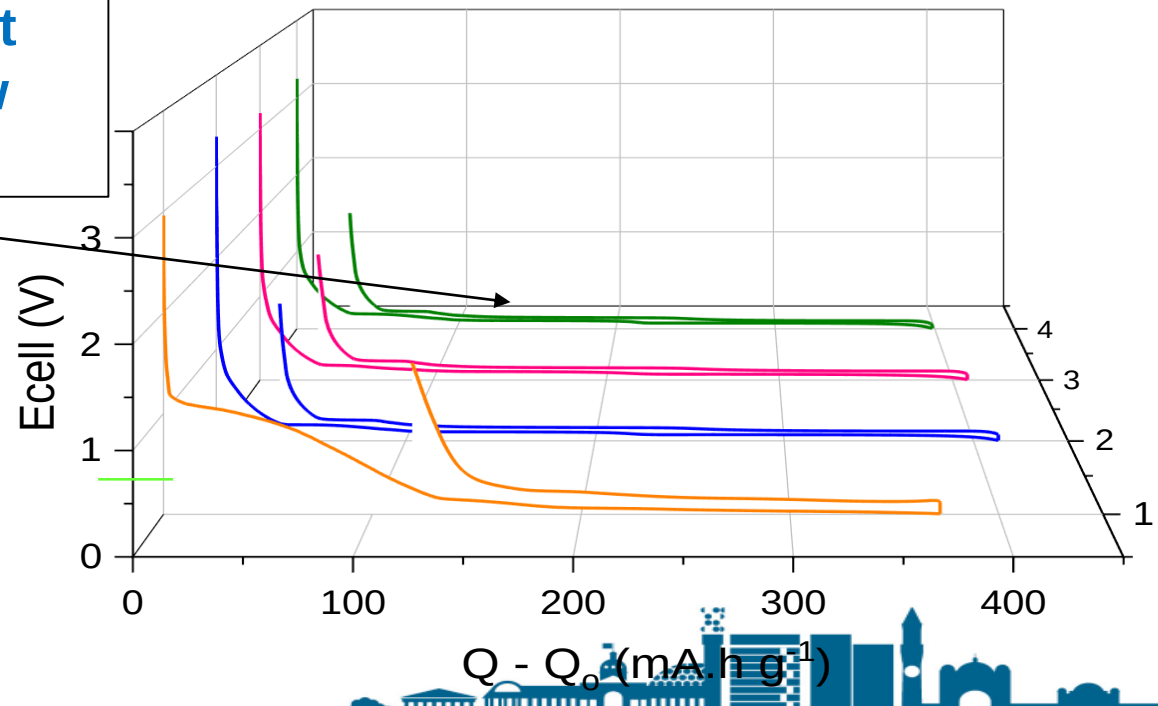




End of life

Graphite Capacity and First Cycle Loss – Same as New Material





Impact

The UK’s first demonstration of robotic battery disassembly and testing at the new energy innovation building that is being constructed at Tyseley Energy Park

Construction of mobile demonstrator to demonstrate applicability of ReLiB fast delamination technology initially to QC failed then shredded material with partners