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ReLiB REUSE & RECYCLING OF LITHIUM ION BATTERIES

RELIB: RECYCLING OF LITHIUM-ION BATTERIES

1st Four Month Review

3^{rd}- 4^{th} July 2018

PI: Paul Anderson, Allan Walton, Tony Hartwell, Simon Lambert, Rustam Stolkin, Marco Raugei, Robert Lee, Peter Wells

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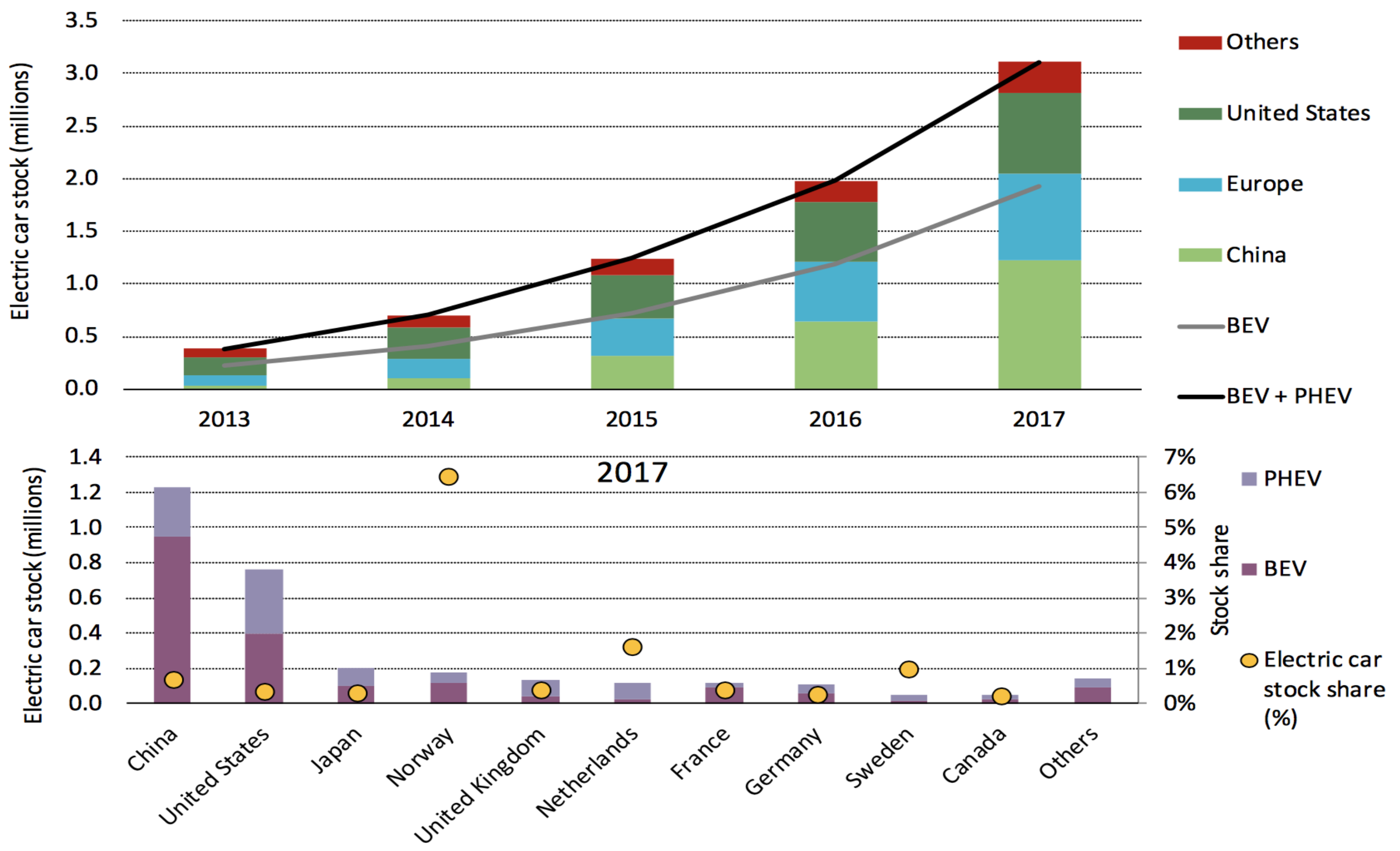
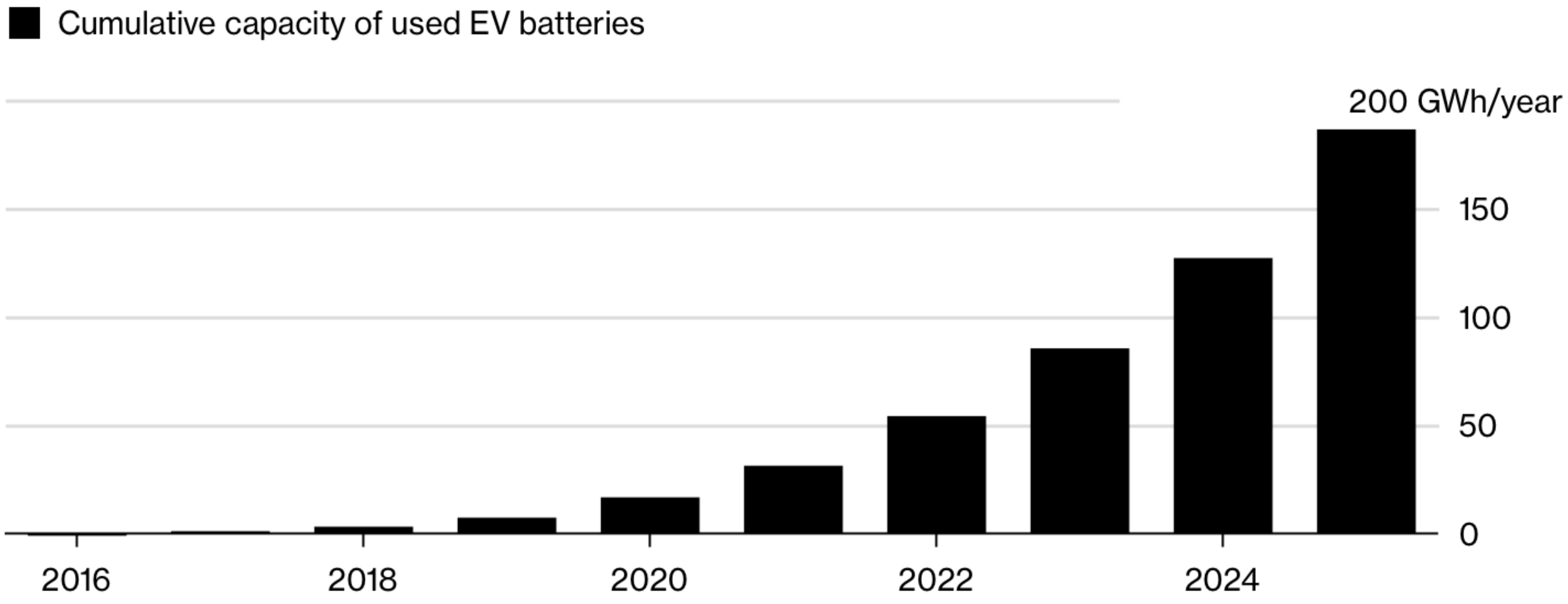
EVOLUTION OF GLOBAL ELECTRIC CAR STOCK (2013-17)

Figure 2.1 • Passenger electric car stock in major regions and the top-ten EVI countries



WHERE WILL 3 MILLION EV BATTERIES GO WHEN THEY RETIRE?



Source: Bloomberg NEF

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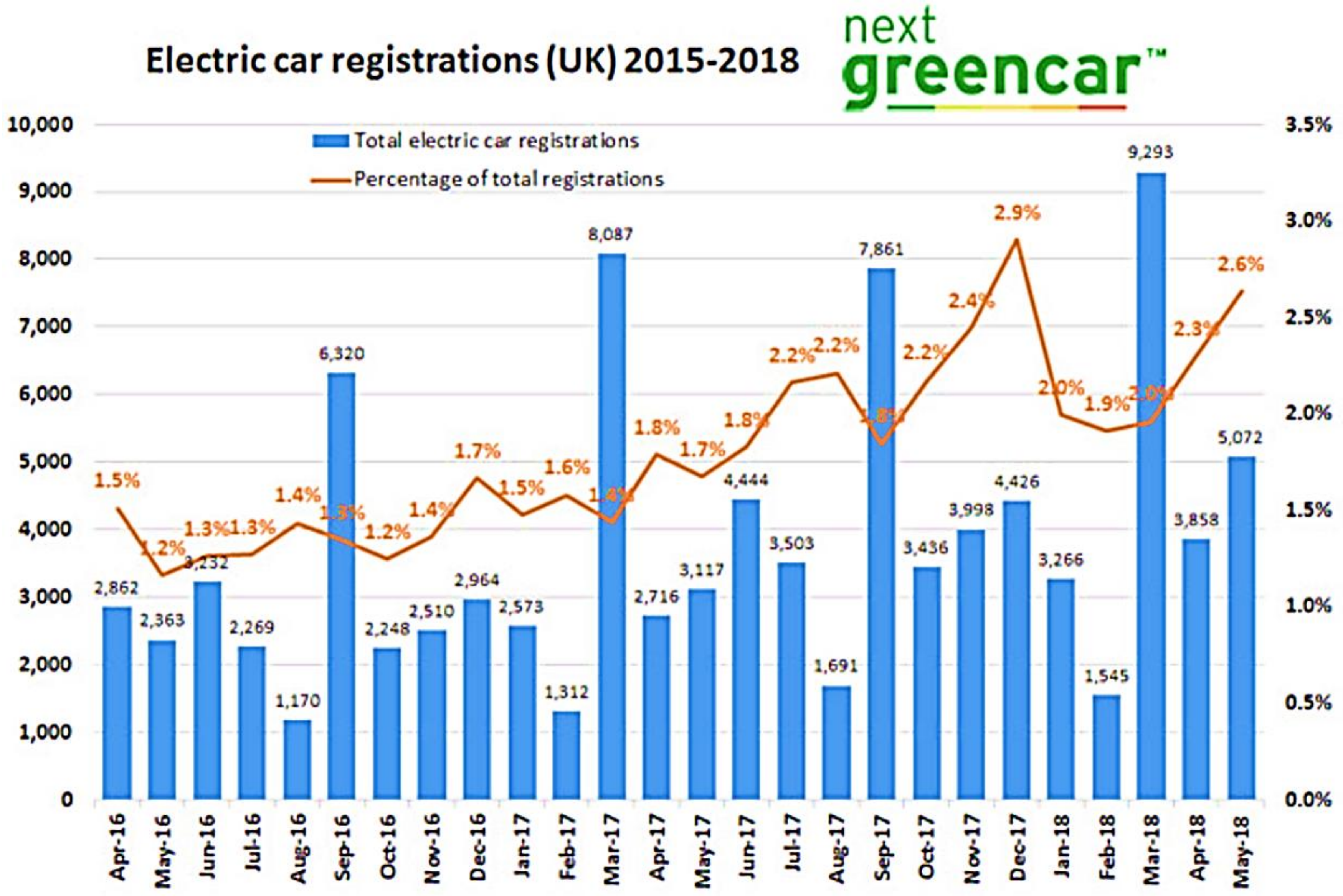
CURRENT TREND IN “ZERO EMISSION” VEHICLE SALES IN UK (EXCLUDES HYBRIDS)

Sales of “plug-in” vehicles reached 47,000 in 2017

Current fleet of EVs in the UK is 155,000 - BP expect this to grow to 12 million by 2040.



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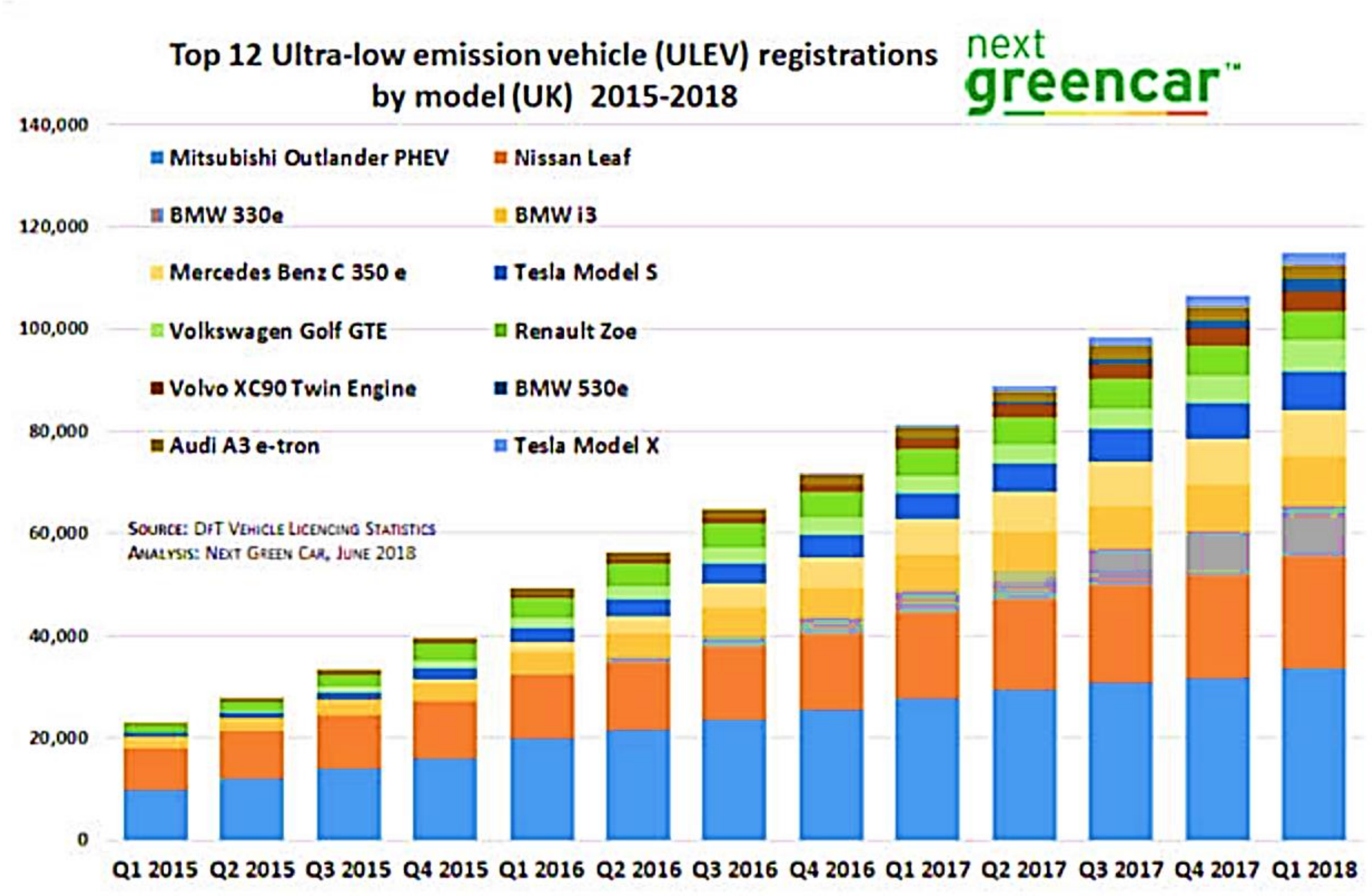
EV MODEL SOLD IN UK (2015 - 2018)

At present there are no facilities for recycling EV batteries in the UK- damaged EoL battery packs can NOT be exported.



Source: DfT Vehicle Licensing Statistics. Analysis Next Green Car, June 2018.

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RELIB PROJECT

CHALLENGES FOR RECYCLING/RE-USE OF LITHIUM-ION BATTERIES

- Complex battery pack designs which require significant manual labour to disassemble (lack of design for recycle)
- Lack of efficient/accurate methods to determine state of health of packs, modules and cells
- Finely distributed elements
- Changing battery chemistries
- Lack of information on the location of elements in batteries at end of life
- Safety concerns over storage, transportation and disassembly
- At present <50% of materials can be recovered using conventional smelting.
- Lack of economic incentives
- Legislation around waste definitions, producer responsibility, permitting etc…

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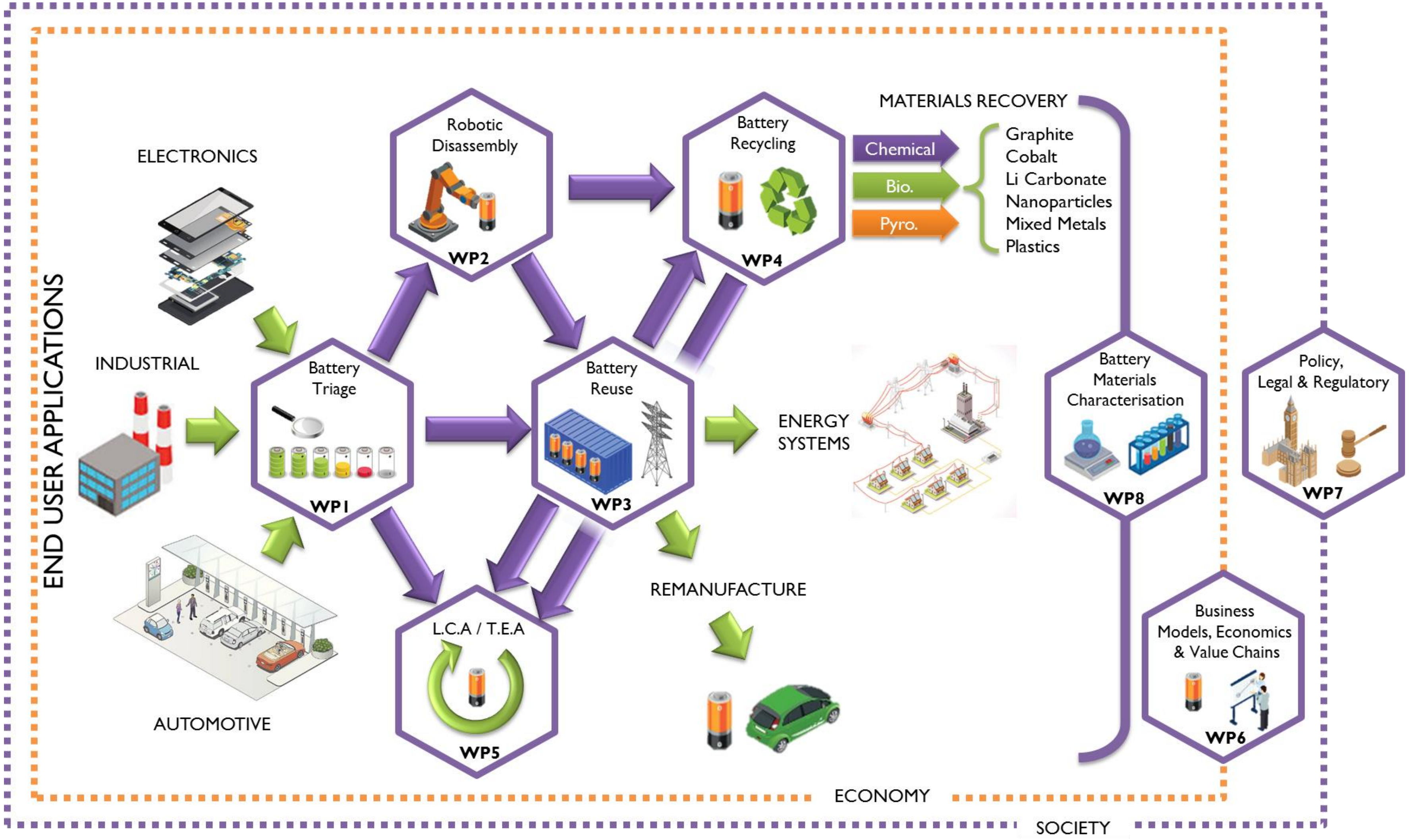
RELIB PROJECT STRUCTURE



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ReLiB - Work Packages

WP NO.	WORK PACKAGE TITLE	LEAD INSTITUTION
WP1	Battery Assessment	University of Newcastle
WP2	Gateway Testing & Robotic Disassembly	University of Birmingham
WP3	Re-use	University of Newcastle
WP4	Recycling	University of Birmingham & Newcastle
WP5	Life Cycle Assessment & Techno Economic Assessment	Oxford Brookes University
WP6	Business Models, Value Chains & Economic Analysis	Cardiff University
WP7	Legislation & Socio-economic Impacts	University of Birmingham
WP8	Materials Characterisation	University of Birmingham & Liverpool

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EXPECTED OUTCOMES

- New sensor arrays to autonomously identify components in packs
- AI controlled robotic systems for automated disassembly of battery packs, modules and cells to reduce cost
- New sensor arrays to determine state of health of battery modules for gate way testing
- *In-situ* testing of cells to determine state of degradation, morphology and location of elements in EoL cells
- Short loop recycling processes linked to physical sorting of battery fractions
- A combination of physical sorting processes, pyrometallurgy, chemical and biological leaching of alloys and elements
- Development of new products from the battery waste which can be used in a range of markets
- Techno economic and life cycle assessment to determine the viability of different process routes
- New governance structures to promote recycling of batteries
- Development of new business models

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WP1: BATTERY ASSESSMENT

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WP1: BATTERY ASSESSMENT

AIMS & PLANS

- **To build a database of battery packs in the first year including:**

  Visual map of while pack including;
  - ✓ Components- wiring looms, modules, bus bars, etc…
  - ✓ Mechanical fixtures, screws, bolts, etc…
  - ✓ Materials
  - ✓ Chemistries etc…
  - ✓ Mass & volume

- **Data will come in from WP2 (sensing) and WP8 (characterisation). The data will be used for:**
  - ✓ LCA studies (WP5)
  - ✓ Economics (WP6)
  - ✓ Sensor technologies (WP2)
  - ✓ Robotic sorting (WP2)

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WP1: BATTERY ASSESSMENT

KPIs

- (UoB) – Database set up to handle information from the partners (including for example analytical data, 3-D models of battery packs, results from separation trials etc…..) – **Month 4**

- (UoB) - 3-D models will be created for a range of battery packs and components from the visual mapping exercise – scans and sets of 3-D images of 3 full battery packs from different manufacturers will be stored in the database. – **Month 6**

- (UoB) – Annotated 3-D images showing components and materials used in each part of the battery packs - **Month 12**

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WP1: SOURCING BATTERIES

REAL 'END OF LIFE' VEHICLES

- No knowledge of life
- Realistic recycling/reuse situation

FIRST VEHICLE OBTAINED

- 2011 Nissan Leaf
- 40,000 miles - end of life or second life opportunity (see WP3)

INDUSTRIAL PARTNERS– AXION, ECO-BAT + OEMs, BMRA

- Sourcing packs & other material
- Removing packs from vehicles
- Transport and logistics

COMPLEXITY & VARIABILITY OF PACKS

Packs do not just contain batteries and vary significantly from between manufacturers and models

- Number and layout of cells/modules
- Busbars, wiring looms and electronics
- Protection (fuses & contactors etc)
- Mechanical fittings and fixing
- Cooling circuits and heat exchangers

The robot must be able to recognise these and crucially understand the system to be able to safely disassemble it – it needs to have intelligence

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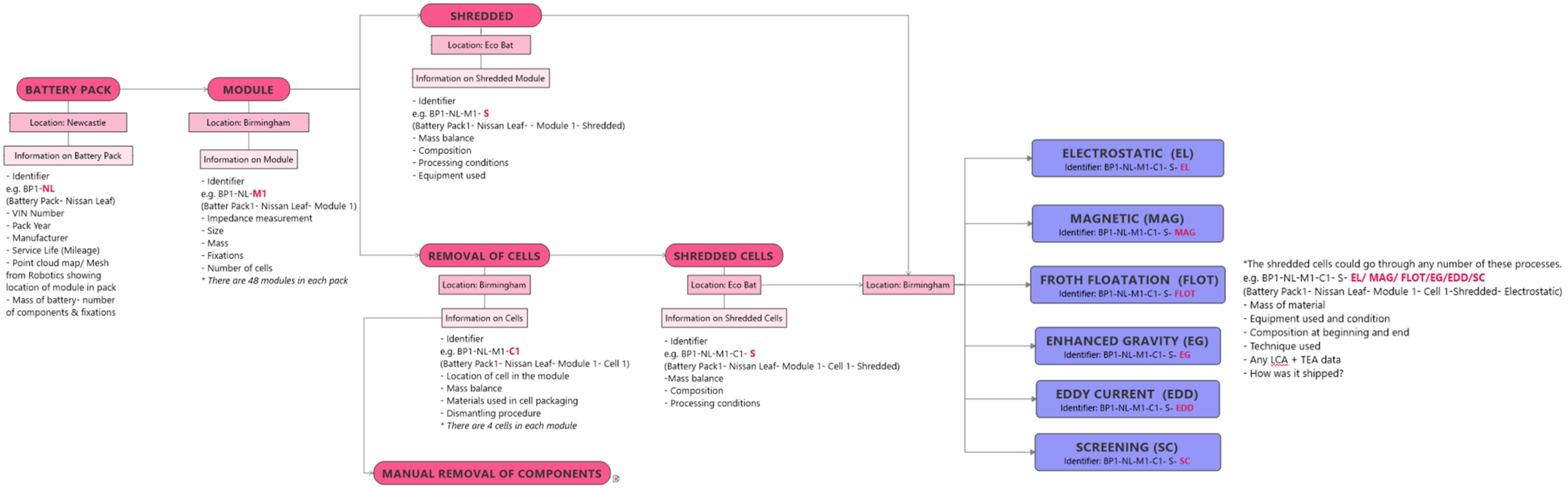
KPI1:TRACKING MATERIAL FLOW IN DATABASE



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KPI2: SAFE DISMANTLING BATTERY PACKS

- Dismantling of packs – create a workshop manual for a robot
- Component identification for AI training
- Mechanical and Electrical features
- In situ-characterisation & measurements – short-loop reuse

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SCANNING OF BATTERY PACKS

3D VISUALISATION OF BATTERY MODULE & DATA GATHERING

- Use advanced robotic vision methods to build detailed 3D models of batteries at all stages of disassembly – pack; module; cell; and ancillary parts such as wire-looms and structural components.
- Combination of off-the-shelf imaging devices, and also robot arms moving 3D cameras to different known viewpoints over the battery pack during different stages of disassembly.
- Advanced methods of matching and merging multiple point-cloud images to generate 3D models.
- Models used to project large number of synthetic views for training data of machine learning systems.

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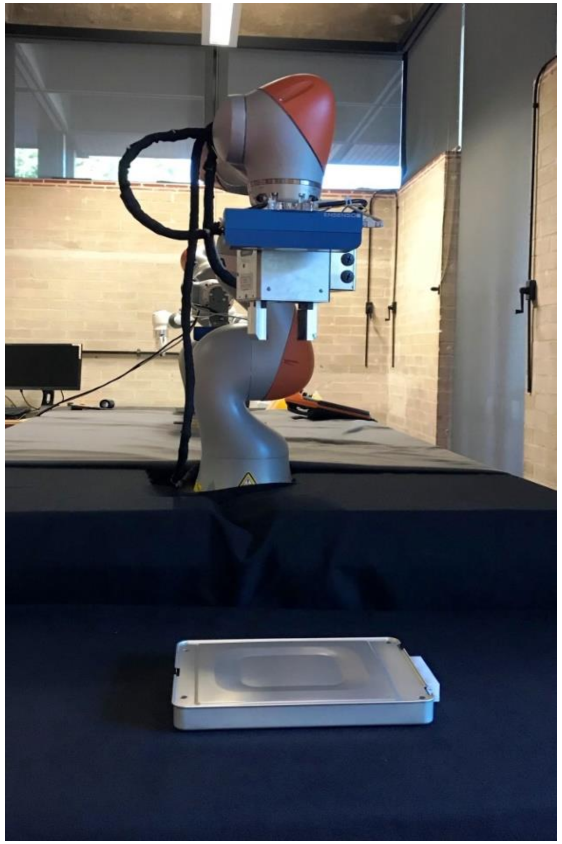
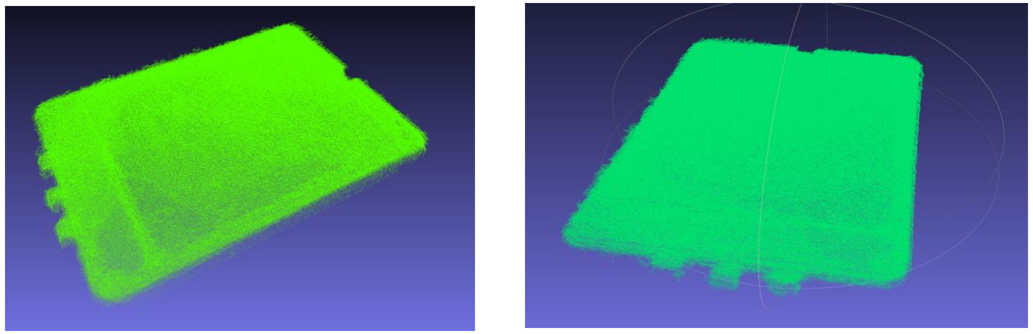
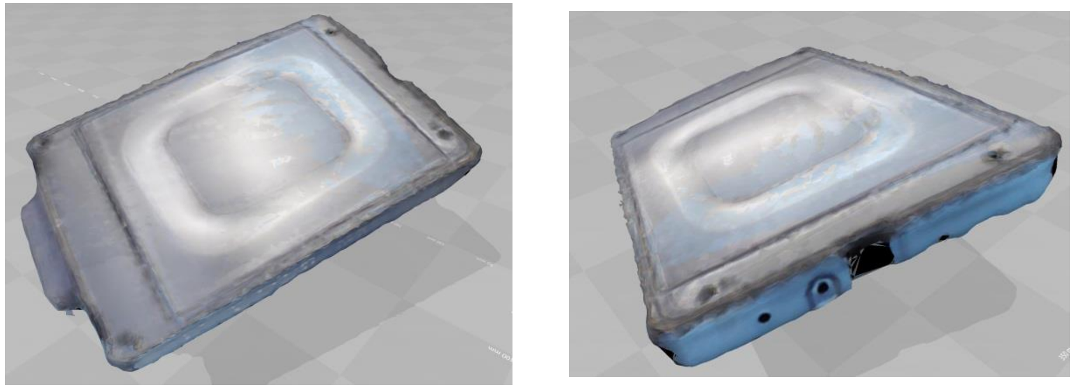
3D VISUALISATION OF BATTERY MODULE



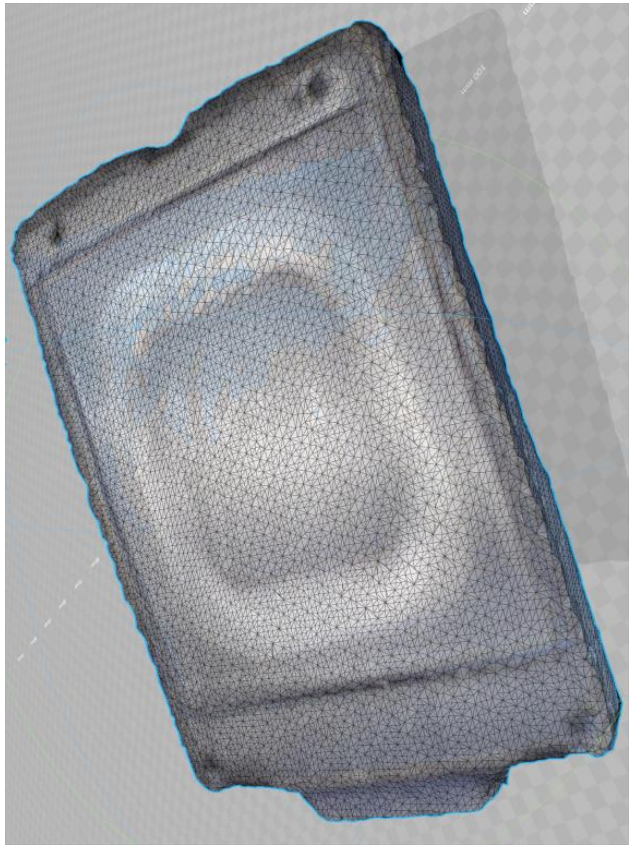
Module for scanning



Raw point-cloud images scanned from multiple views



Synthesized views from model



Mesh model combining views

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WP2: SENSING & SORTING

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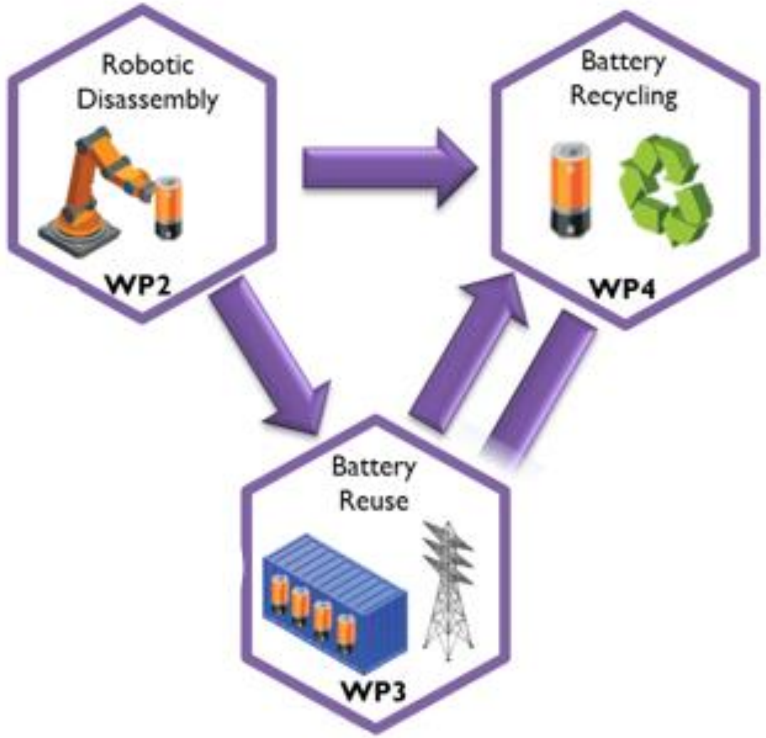
WP2: SENSING & SORTING

AIMS & PLANS

- **Generate tools for training AI robots**
  - ✓ Blanks of battery packs for safe robotic training
  - ✓ Automated sensor arrays and data processing for robotic NDT of in-situ batteries

- **Tools for implementation of decision matrices**
  - ✓ Point of reception inspection
  - ✓ Intelligent downstream routing of material/components

- **Robotic disassembly prototype facility**
  - ✓ Specification and design for y2-3 build and training



WP2: SENSING & SORTING

KPIs: GATEWAY TESTING AND SOURCING OF BATTERIES

- (NU) – A blank will be made of the Nissan Leaf battery pack (excluding the active material), which will be shipped to UoB for robotic disassembly trials in the robotics laboratory (photograph of pack for KPI) – **Month 8**

- (NU) - A sensor array will be built at NU to determine SOH and to gather data to compare to the characterisation data in WP8 – **Month 8**

- (UoB) - Robotic systems will be designed and the parts purchased in order to demonstrate that the battery pack lid can be removed, to present individual modules to the sensor array and to disassemble the modules (drawings of systems) - **Month 12**

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STATE OF THE ART FOR IN-LINE MEASUREMENT/ TESTING

VISUAL TECHNIQUES

- Automated sorting based on packaging (e.g. Optisort)

THERMAL IMAGING

- Primarily for safety

PASSIVE & ACTIVE ELECTRONIC & CHEMICAL TECHNIQUES

- Pack, module or cell level – different techniques
- Well established for production (eg cell aging, OCV…)
- Convertible to EoL

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WP3: RE-USE

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WP3: RE-USE

AIMS & PLANS

- **Collate and understand potential applications/ usages of second life batteries**
  - ✓ Techno-economic assessment of potential services
  - ✓ Suitability study – feedback to WP2

- **Asset management**
  - ✓ Reuse of existing BMS
  - ✓ SOH monitoring

- **Aging beyond 80% SOH**
  - ✓ Potential differences in degradation behaviour when used in second life
  - ✓ Lifetime prognosis
  - ✓ Frameworks for second life product guarantees

Fig. 2 : PCS and main transformers

Fig. 3 : Battery Arrays

WP3:RE-USE

KPIs

- (NU) - Database of proposed usages for second life batteries including technical challenges/proposed solutions established (data in database)- **Month 3**

- (NU) - Design of a test bed to demonstrate second life performance (diagram and report on equipment)- **Month 9**

- (NU) - Generic interface platform built for battery management systems (to link to major OEM platforms), (piece of equipment)- **Month 12**

- (NU) - A solution for safe, rapid pack discharge will be designed and modelled (report)- **Month 12**

WP4: RECYCLING

WP4: RECYCLING

AIMS & PLANS

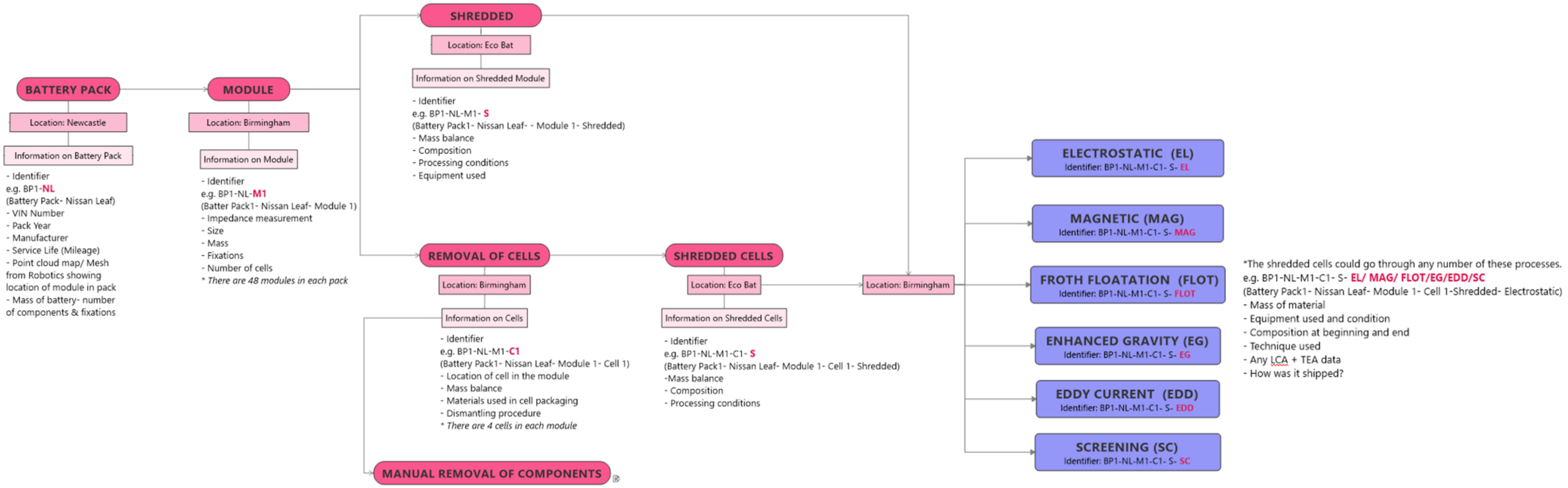
The aim of WP4 is to recover >90% of the elements from battery packs

- ✓ Physical processing and upgrading of battery materials (UoB + Ecobat)
- ✓ Pyrometallurgical extraction of metals (UoB + Tetronics)
- ✓ Biological extraction of elements (UoE + UoB)
- ✓ Chemical extraction of elements (UoL)

PROGRESS TO DATE

- ✓ Shredded pouch cell material has been produced
- ✓ Chemical analysis of screened size distributions of shredded battery undertaken
- ✓ Physical separation trials started using electrostatic separator, magnetic separator, froth flotation (Denver cell & Column cell)
- ✓ 1st report produced showing metallic separations
- ✓ Materials sent out to project partners

KPI1:TRACKING MATERIAL FLOW IN DATABASE



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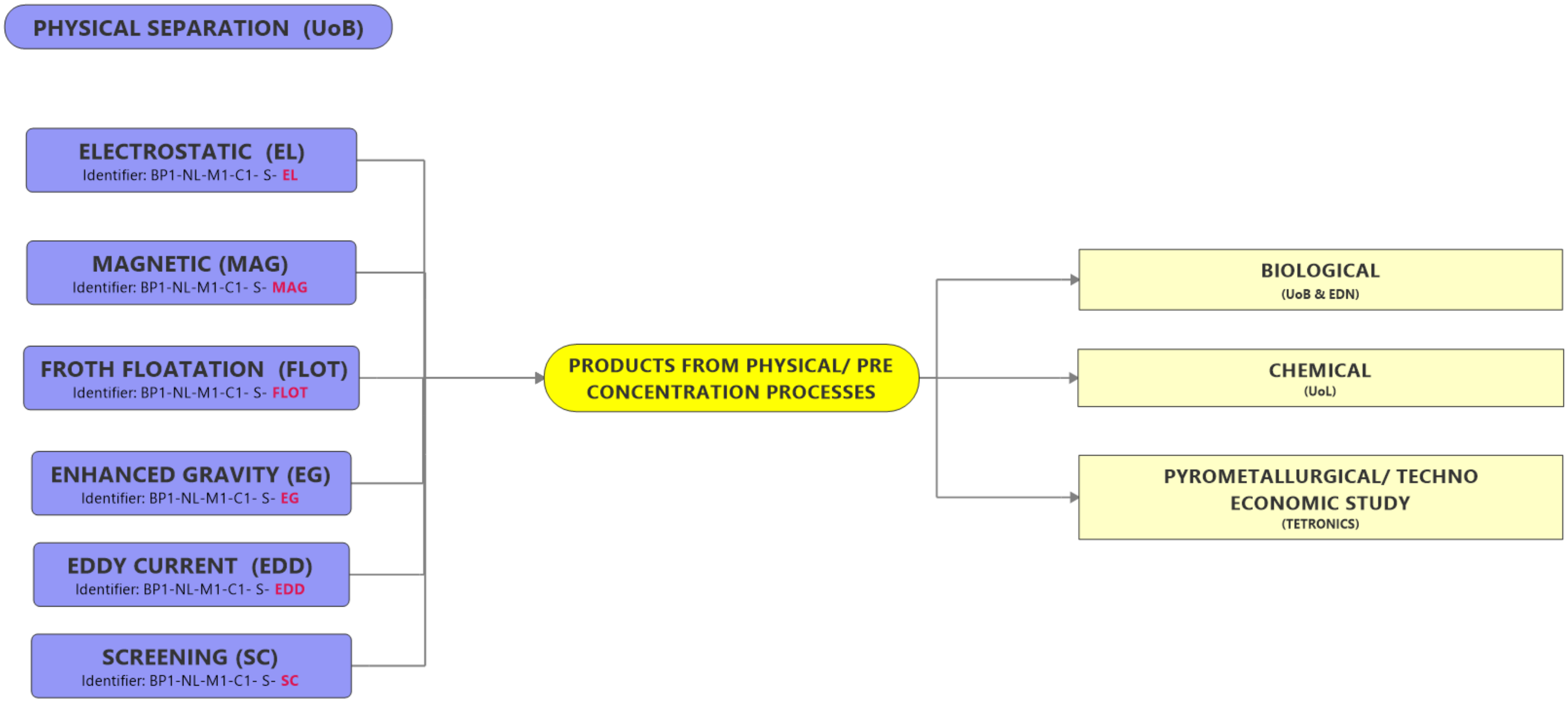
KPI1:TRACKING MATERIAL FLOW IN DATABASE



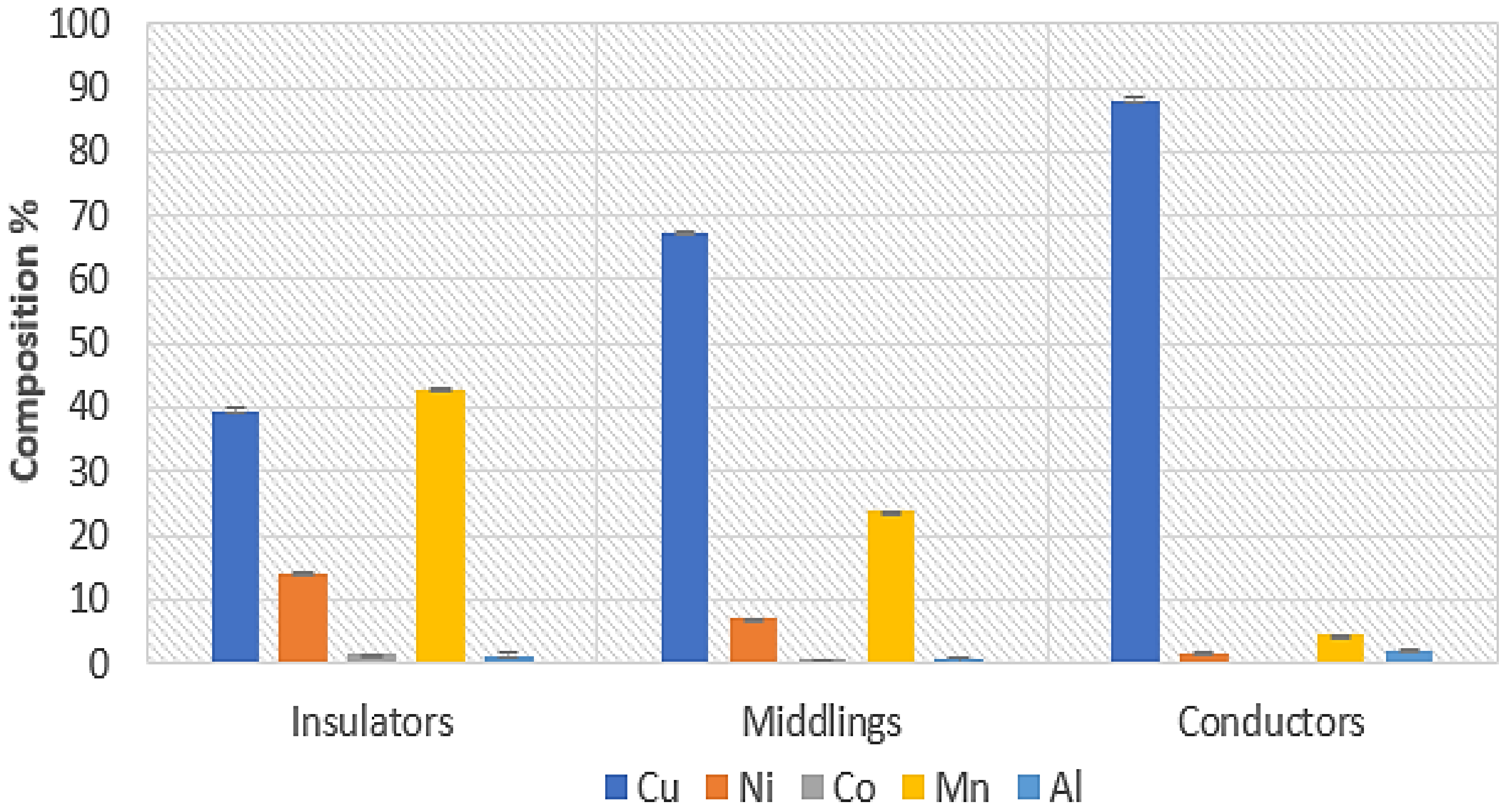
WP4: RECYCLING

KPIs

- (UoB) - Changes in battery materials during use will be mapped (particularly the cathode), and suggested routes for regeneration developed (report)-**Month 12**
- (UoB) - The thermodynamics of plasma recovery processing will be modelled giving optimised process conditions and operational costs for chosen lithium car battery chemistry (report)-**Month 9**
- (UoB) - shredding full cells will be undertaken (report and data produced for database). Physical separation trials started using electrostatic separator, eddy current and froth flotation. (Database of key metal recovery and grade for each process provided)-**Month 9**
- (UoB) - Shredded components will be supplied to co-workers (material) for characterization and downstream processing (kg quantities)-**Month 6**
- (UoB) – Bio –extraction of chosen elements (Co and Mn) from battery using organic acids generated by *A.Niger*. Database of recovery and grade produced- **Month 9**
- (UoB) - Bioprecipitation cell will be designed and built. Bioprecipitation trials for cobalt will be started. SEM images of cobalt and cell design drawings – **Month 12**
- (UoL) - Chemical dissolution will be modeled and a solvent selection program initiated for different scrap streams (report)- **Month 6**
- (UoL) - Laboratory scale trials for chemical separation will commence (test programme submitted and approved based on key element selection)-**Month 8**
- (UoL) - In situ TEM methods for novel biological and chemical recovery processes that can improve efficiency will be developed (report on equipment specification and technique potential)- **Month 12**

WP4: RECYCLING

ELECTROSTATIC SEPARATION OF SHREDDED BATTERY

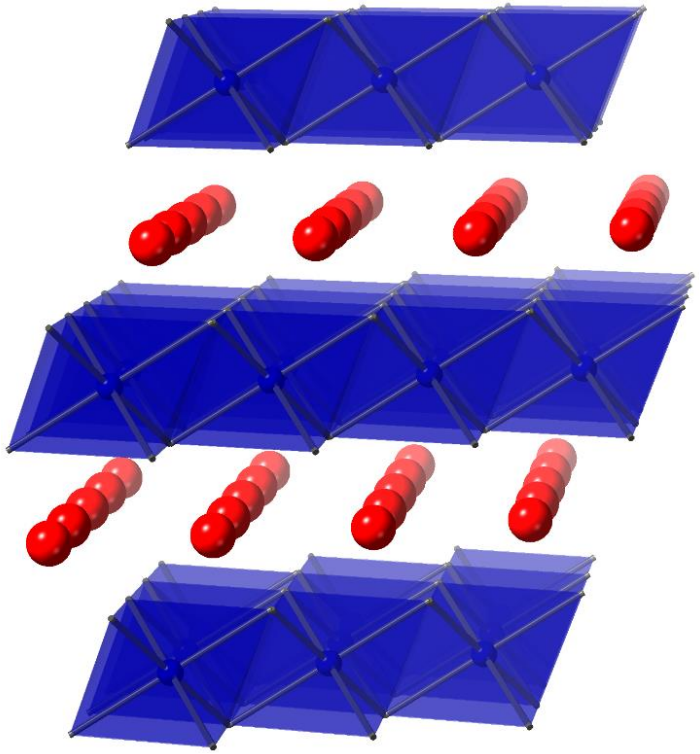


WP8: CHARACTERISATION

WP8: CHARACTERISATION

AIMS & PLANS

- ✓ characterize materials recovered from used batteries *via* different processing routes (WP4) to inform decisions about, and help fine tune, preferred extraction processes
- ✓ Cross reference with initial testing data to provide feedback to WP1&2
- ✓ Analyse active battery materials *in situ* with respect to morphology, chemical composition and phase information) simultaneously and with spatial resolution at different stages of life, (New, QA failed, Used)
- ✓ Develop recycling methodologies that target specific failure conditions (e.g. metal dissolution, lithium deficiency, fluorine contamination)



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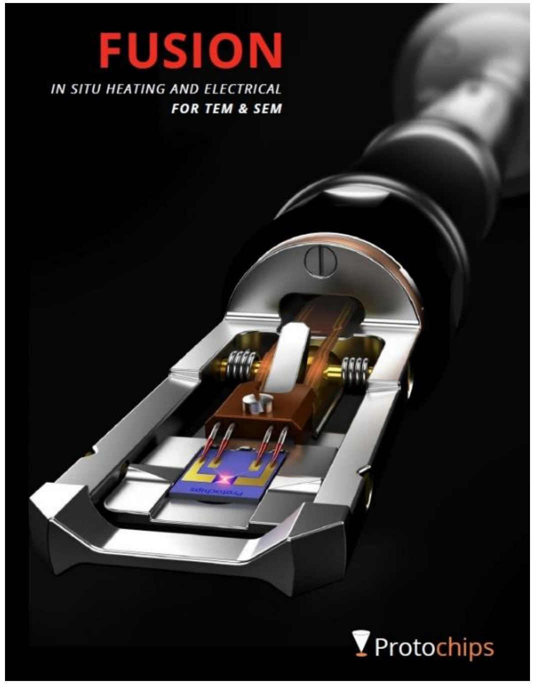
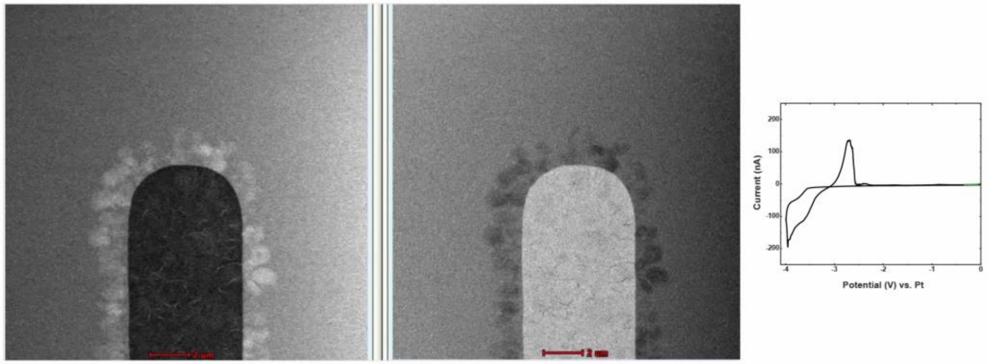
OPERANDO IMAGING OF CHEMICAL & BIOCHEMICAL METHODS FOR METAL EXTRACTION





- Observe the Dynamic Processes at Solid/Liquid Interfaces to Quantify the Rate/Amount of Metal Extraction
- Control parameters include temperature, chemical composition, surface area/facets, pH, concentration, biomolecular species

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WP5: LIFE CYCLE ANALYSIS

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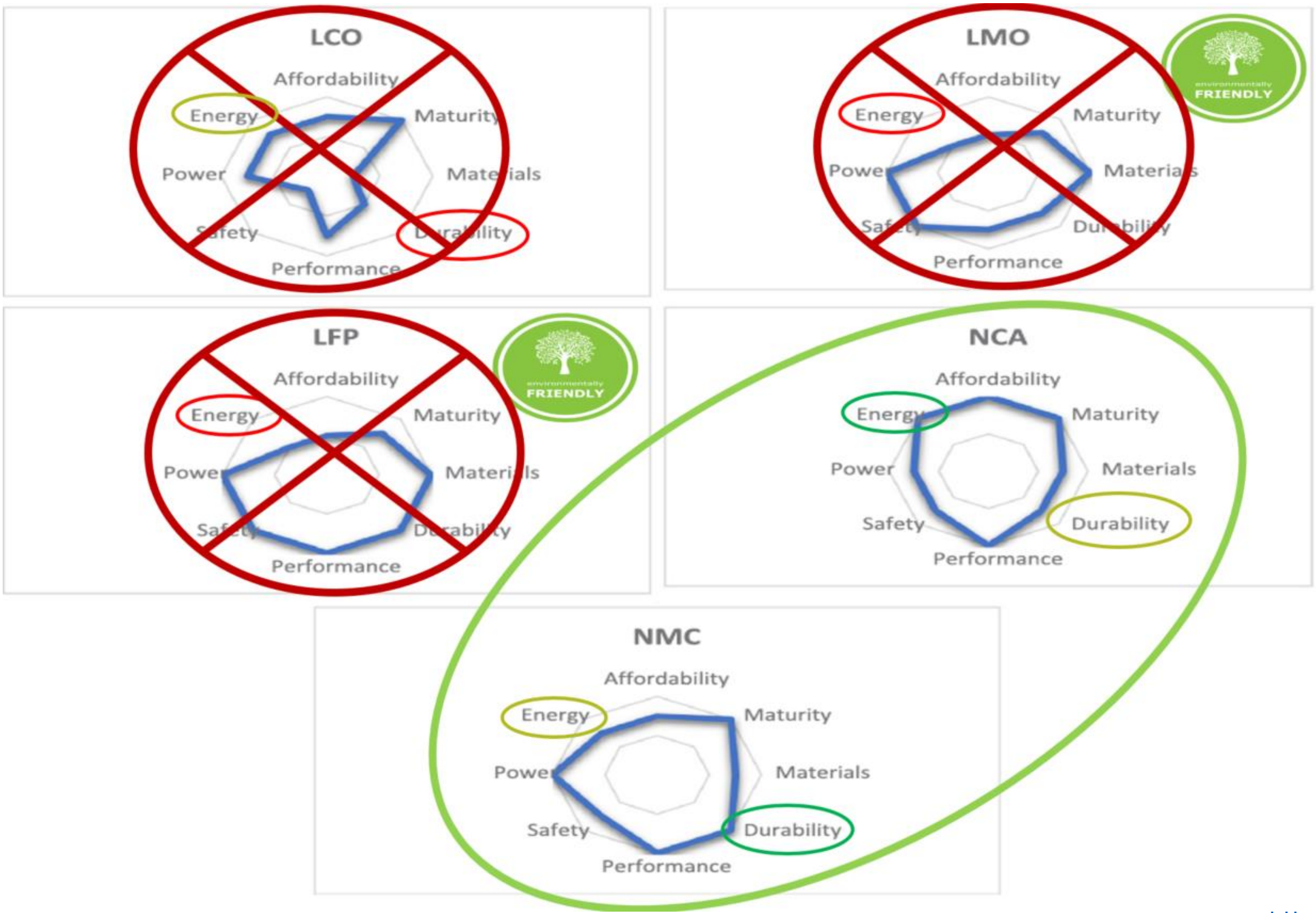
WP5: LCA & TEA

KPIs:

- (UBU) Boundary conditions set out for LCA analysis including functional units, materials to be analysed, comparisons to be made etc…… (report)- **Month 6**
- (UBU) - Data collected on primary production of Li and Co, Mn, Ni, etc. in conjunction with McGill University (report)- **Month 7**
- (UBU and UoB) - A literature survey will be performed to compile all of the LCA models and data on battery recycling in conjunction with Argonne National Laboratories (report)- **Month 4**
- (OBU + all partners) - Preliminary flow sheets will be mapped out for the processes developed in the project (diagrams)- **Month 12**

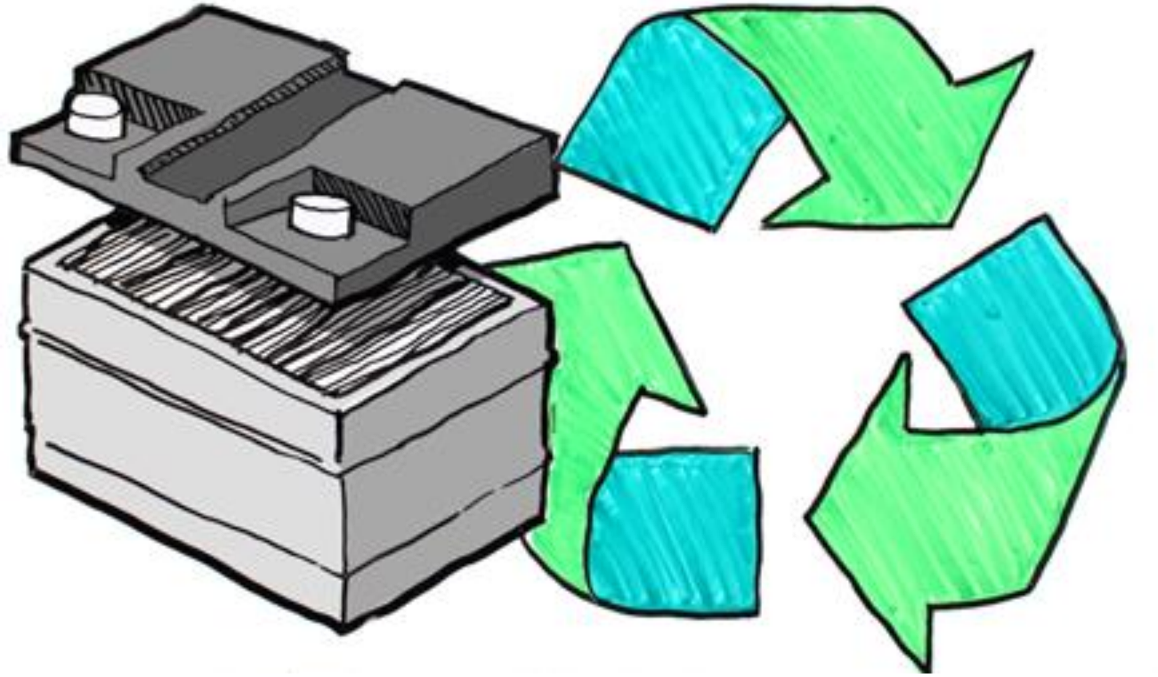
WP5: LIFE CYCLE ANALYSIS



Ref.: Zubi *et al.*, 2018
https://doi.org/10.1016/j.rser.2018.03.002

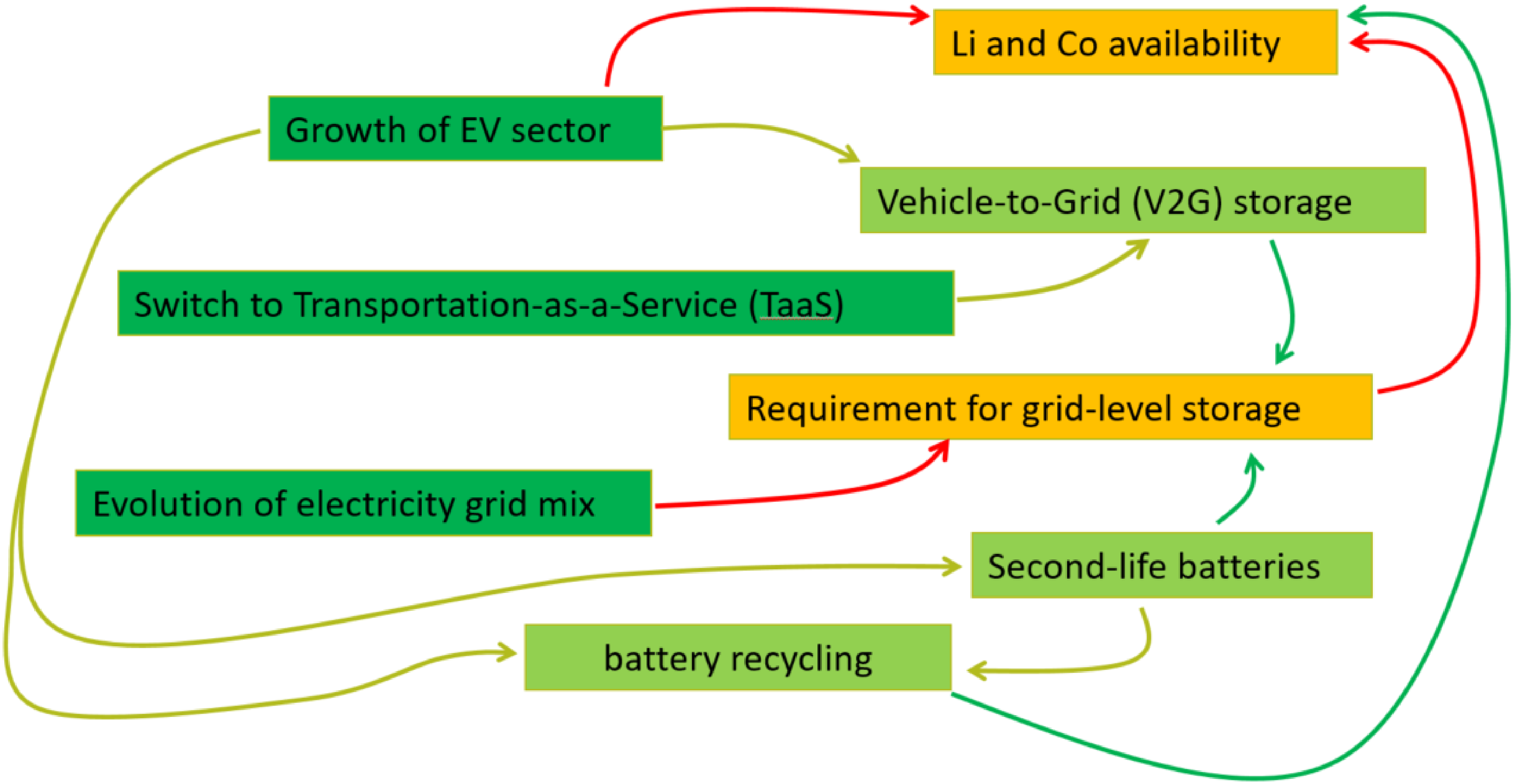
WHY RECYCLE?

- Lower cost vs. primary supply chain
- Reduced environmental impact vs. primary supply chain
- Li and Co availability constraints



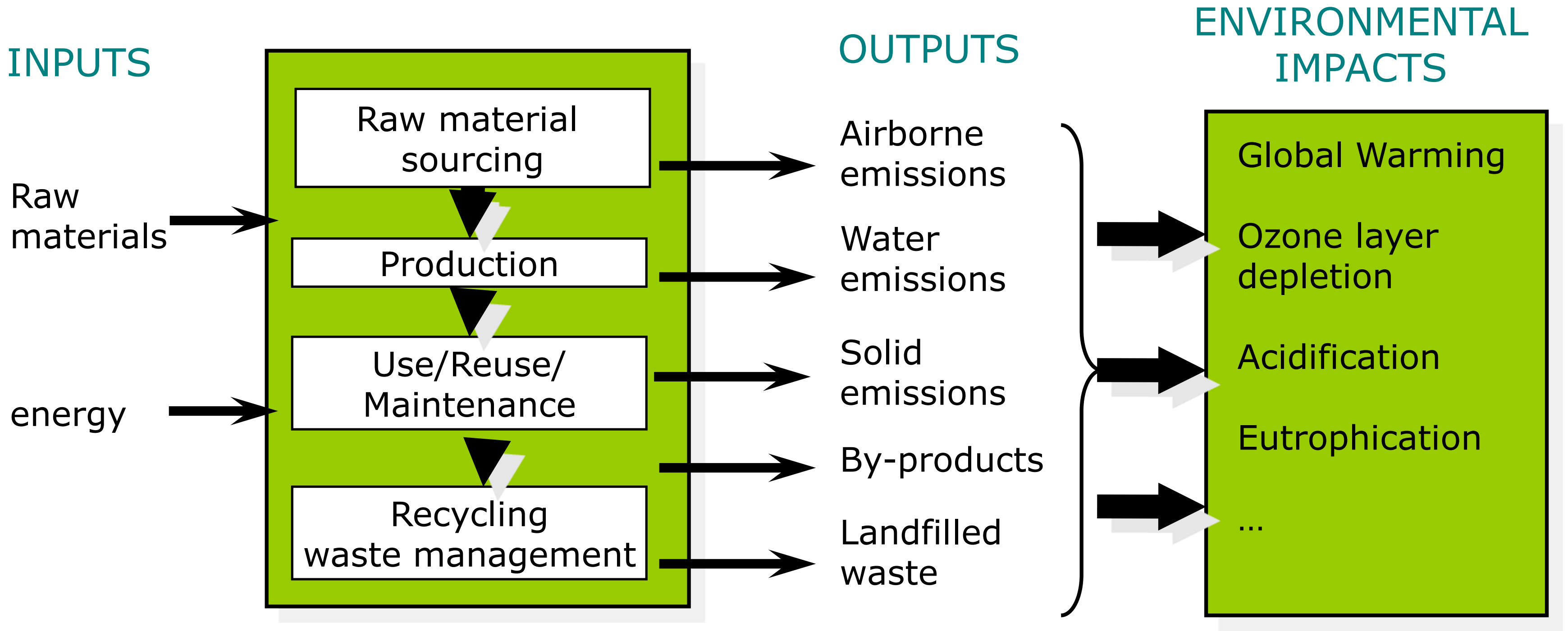
THE BIGGER PICTURE

- ✓ 3 Transitions under way
- ✓ 2 Associated challenges
- ✓ 3 Ways to address them



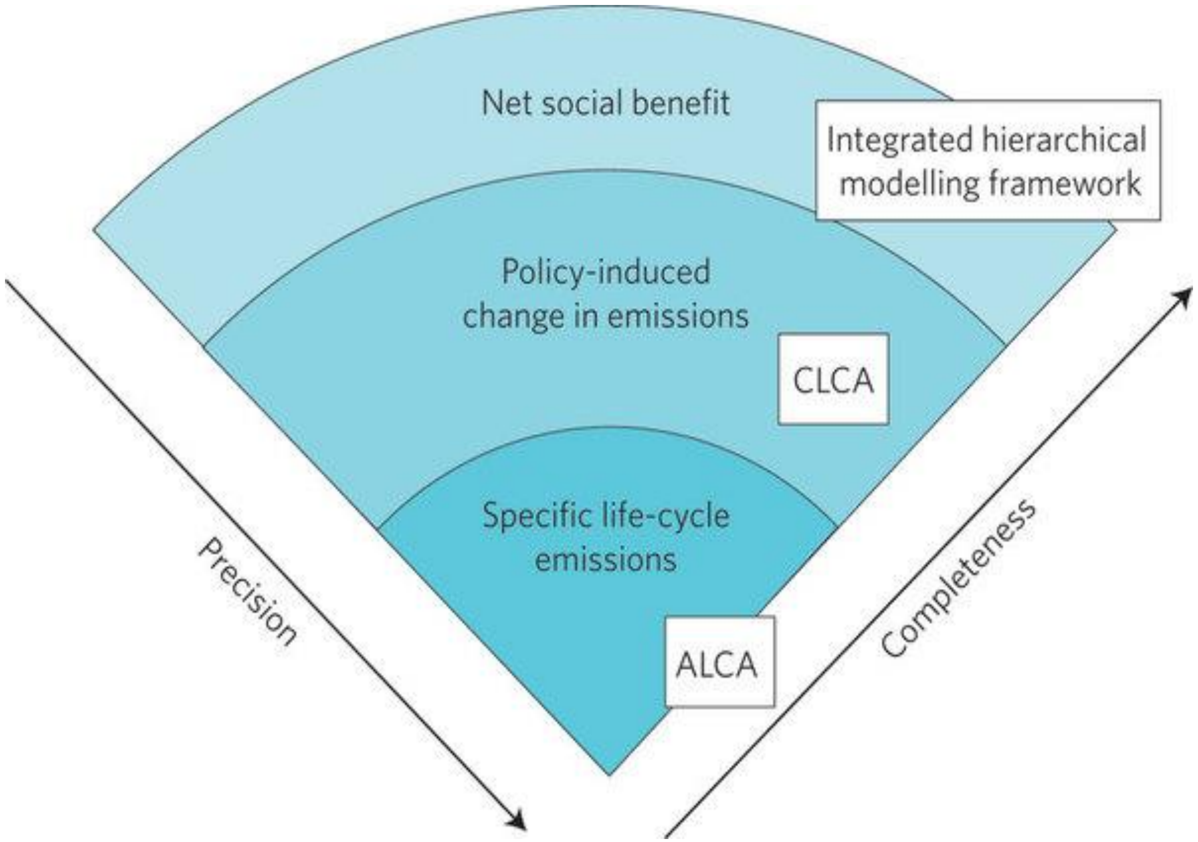
LIFE CYCLE ASSESSMENT

'Compilation and evaluation of the **inputs, outputs** and the potential **environmental impacts** of a product system throughout its life cycle'



LIFE CYCLE ASSESSMENT

- **Moves beyond end-of-pipe approaches**
- **Avoid impact shifting**
- **May be ‘attributional’ or ‘consequential’**



Ref.: Creutzig *et al.*, 2012
https://doi.org/10.1038/nclimate1416

LITERATURE REVIEW

DBs AND MODELS FOR LI-ION BATTERIES

a) Ecoinvent, 2018. **LMO battery model**, in: Life cycle inventory (LCI) database V3.4. https://www.ecoinvent.org/database/database.html

b) Thinkstep, 2018. **LFP battery model**, in: GaBi database extension XIV. http://gabi-documentation-2018.gabi-software.com/xml-data/processes/3c11aa30-1fec-4ee7-bce0-d36a892ef8ab.xml

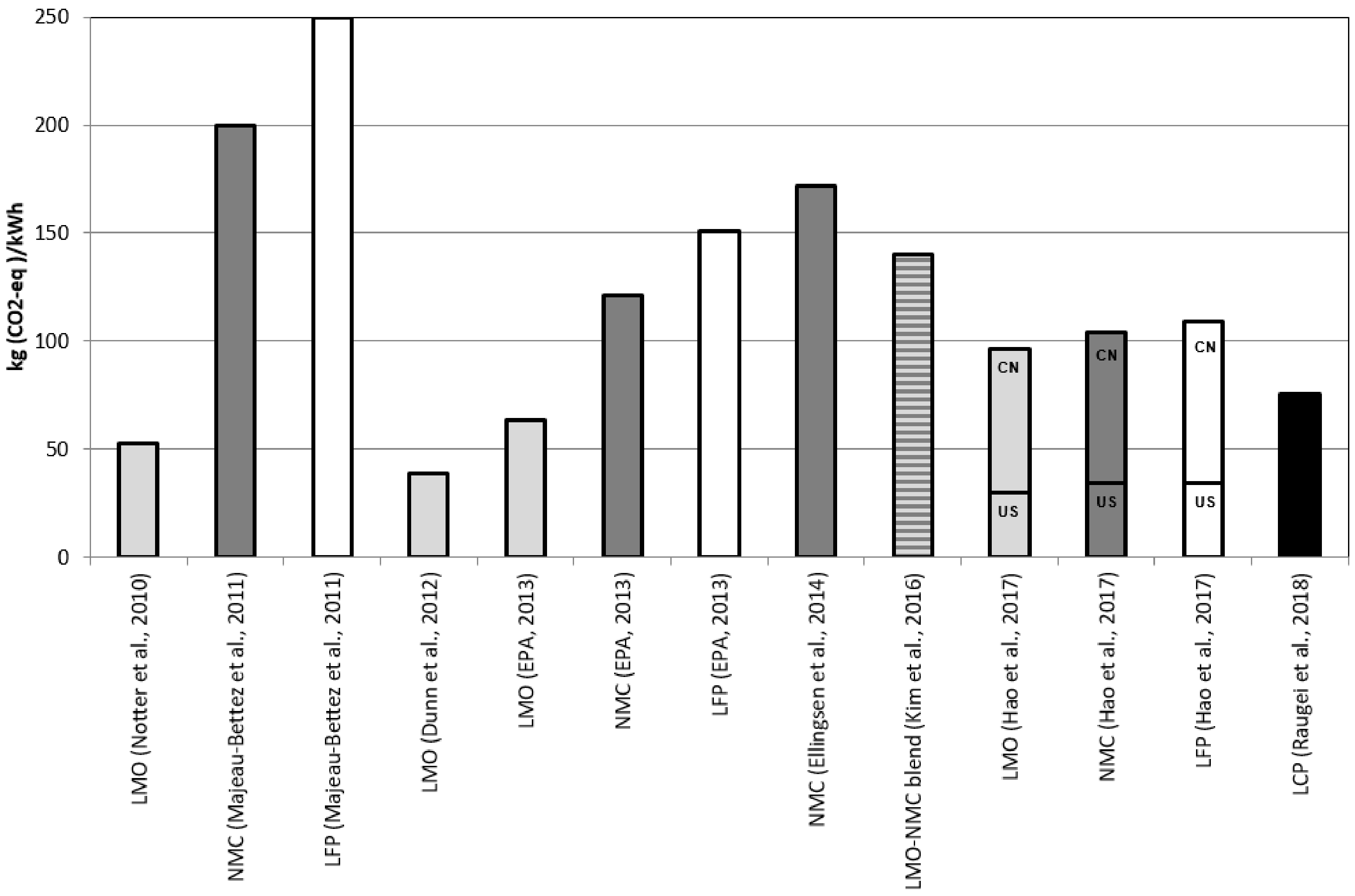
c) Argonne National Laboratory, 2015. **BatPaC**: A Lithium-Ion Battery Performance and Cost Model for Electric-Drive Vehicles. http://www.cse.anl.gov/batpac

d) Argonne National Laboratory, 2017. The Greenhouse gases, Regulated Emissions, and Energy use in Transportation (**GREET®**) Model. https://greet.es.anl.gov/

LITERATURE REVIEW

1. DBs and models for Li-ion batteries
2. LCAs of Li-ion battery packs for EVs (mostly cradle-to-gate)
3. Overview of EV battery recycling processes
4. LCAs of Li-ion battery recycling ← **very few studies in the literature!**

LITERATURE REVIEW



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WP6: ECONOMICS & VALUE CHAIN

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WP6: ECONOMICS & VALUE CHAIN

AIMS & PLANS

- WP6 is about business models, value chains, legal influence and economic analysis to understand the costs, revenues and business structures applied to the vehicle and battery value chain throughout the lifecycle.
- Input to WP1 is on the impact of vehicle/ battery ownership models (owned, leased, shared) on supply of ELVs

KPIs

- (CU)- Characterise the economic and business dimensions of the existing recycling value chain- **Month 4**
- (CU)- Determine in principle the impact of vehicle and battery ownership models on the supply of EOVs- **Month 7**
- (CU)- Define existing recycling business models- **Month 12**

WP6: ECONOMICS & VALUE CHAIN

EARLY RESULTS

- **Characterise the economic and business dimensions of the existing recycling value chain- Month 4**
  - ✓ ELV processing has an established structure and legal process
  - ✓ Approximately 1,300 ATFs and 40 shredders
  - ✓ 25% ASR
  - ✓ Unknown amount of leakage from the system
  - ✓ Unknown how far EVs will show same scrappage patterns as traditional cars
  - ✓ Unknown how far EVs will disrupt the economic viability of the system

WP7: LEGISLATION

WP7: LEGISLATION

AIMS & PLANS

- ✓ WP7 will investigate the regulatory framework for battery recycling in the UK, including the producer responsibility for recycling with regard to batteries sold on for re-use in WP3, automotive waste and battery legislation, and the classifications for waste material leading, for example, to issues around shipping and storage.

PROGRESS TO DATE

- ✓ Keynote presentation to Chartered Institution of Waste Management in March 2018.
- ✓ Given evidence to the Welsh Assembly on waste post Brexit.

WP7: LEGISLATION

KPIs:

- (UoB) - A 'Brexit' review to shape and influence which EU waste laws are retained law in the UK and to examine the effect on the UK of the forthcoming EU Circular Economy Package (report). **Month 9**

  Literature review completed and to be posted on the website.

- (UoB) - establishment of an advice hub for colleagues in other WPs and projects who need to negotiate legal, social or economic aspects of their research programmes (presentation of the hub to project partners at one of the 4 month meeting). **Month 9**

  Advice available, RA in position in September.

RELIB: PROJECT MANAGEMENT

Tony Hartwell

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RISKS, ISSUES & NEEDS

RISKS

- Safety issues associated with handling LiBs. Developing training materials and working with research and industrial practitioners.
- Recruitment & Retention of Key Staff

ISSUES

- Delays in recruitment could mean an underspend in year 1
- Striving to comply with Fast-Start ethic in University environment
- Availability & Quality of data on markets – addressing through links with businesses

NEEDS

- Permission to carry over funds from year 1
- Co-ordinate with other projects active in this area (Faraday Battery Challenge)

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STATUS OF HIRES

IN POST

Tony Hartwell	University of Birmingham	Project Lead
Amina Benyahia	University of Birmingham	Project Coordinator
Gavin Harper	University of Birmingham	Research Fellow
Alireza Rastegarpanah	University of Birmingham	PDRA- Robotics
Laura Driscoll	University of Birmingham	PDRA- Chemistry
Zubera Iqbal	University of Birmingham	PDRA-Chemical Engineering
Viet Nguyen	University of Birmingham	PDRA- Economics
Jackie Deans	University of Birmingham	Technician- Chemistry
Prodip Das	University of Newcastle	CoI (PDRA)
Musbahu Muhammad	University of Newcastle	PDRA
Mohamed Ahmeid	University of Newcastle	PDRA
Muez Shiref	University of Newcastle	PDRA
Pierrot Atidekou	University of Newcastle	PDRA
Technician	University of Newcastle	Existing Staff
Susan Earley	University of Newcastle	Administrator
Marco Raugei	Oxford Brookes University	PDRA
Houari Amari	University of Liverpool	PDRA
Virginia Echavarri-Bravo	University of Edinburgh	PDRA

OFFER MADE

Joyti Ahuja	University of Birmingham	PDRA (Law)
X	University of Newcastle	PDRA

RECRUITMENT UNDERWAY

Robotics Technician 1	University of Birmingham	Robotics Technician
Robotics PDRA	University of Birmingham	Robotics PDRA
Chemistry PDRA	University of Birmingham	Chemistry PDRA
PDRA	University of Newcastle	PDRA
PDRA	University of Newcastle	PDRA
PDRA	University of Newcastle	PDRA
PDRA	University of Newcastle	PDRA
PDRA	University of Leicester	PDRA
PDRA	Cardiff University	PDRA

UNIVERSITY OF BIRMINGHAM · Newcastle University · OXFORD BROOKES UNIVERSITY · THE UNIVERSITY of EDINBURGH · UNIVERSITY OF LIVERPOOL · CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD · UNIVERSITY OF LEICESTER · diamond

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EQUALITY & DIVERSITY

INCLUSION

(*e.g. Extract from University of Birmingham Equality Scheme 2016-2020*)

- We are inclusive of and address the needs of our diverse community
- Accessibility is a key component of all campus developments
- We have a zero tolerance culture in relation to discrimination and harassment
- We host a vibrant programme of activities to underpin our equalities agenda

SPECIFIC RELIB PROJECT DIVERSITY PLANNING

- In addition to complying with each partner University recruitment programme, the ReLiB team will work with the Faraday Institution team to encourage engagement in this sector through the development of training and outreach activities.

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STATE OF THE ART

- Database for proposed use of second life batteries complete
- Review of LCA for LiBs and recycling being completed
- Characterisation of the economic and business dimensions of recycling value chain established
- Review of state of the art LiBs recycling ongoing- attended recent meeting at NREL and monitoring developments in the EU, Japan and China (in communication with British Embassy in Japan for arrangements to visit Nissan/Sumitomo facility for remanufacturing EV battery packs)

TRAINING

- Initial Training for ReLiB and other FI projects on Battery Safety held yesterday
- Training on legal aspects is scheduled for the next FI Review.
- Working with industrial partners on training programmes for the removal of batteries from EV and subsequent management (storage, transportation and processing)

INDUSTRIAL ENGAGEMENT

- This is a **CRITICAL** aspect of this project
- Engagement with businesses across the value chain- visits to **five** businesses
- Visits to **two** sites with approved facilities for the handling of LiBs and they are interested in hosting on-site development work
- Commissioned one techno-economic study
- Looking to support UK businesses to fast-track deployment of systems to enhance the safety of their operations
- Currently focussing on companies engaged in handling batteries from EVs but have engagement from stakeholders across the supply chain and interest from many others
- Will have a stand at an exhibition for businesses engaged in the management of ELVs in July

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NETWORKING BETWEEN PARTNERS

- Collaboration agreement signed by the end of May 2018
- Monthly Newsletter issued to all ReLiB research partners
- Developing process for IP management/control
- Management Board established and monthly meetings scheduled.
- Discussions with ReLiB partners and other interested parties on the make-up and scope of Industrial and Strategic Advisory Boards
- At present we are developing processes for end-of-pipe management of LiBs, it would make sense to work with the developers of new battery materials, components and systems to incorporate end-of-life management considerations

BUSINESS ORGANISATIONS SUPPORTING BID

Organisation	Expertise
Axion	Circular Economy specialists - ELVs
Benchmark Mineral Intelligence	Mineral Market Data & Intelligence (Li, Co, etc)
British Metals Recycling Association	Association of UK Metal Recyclers
cap hpi	Automotive Data Specialists
Centrica	Energy & Services
Dulas Ltd	Renewable Energy Business
Eco-Bat & GP Batteries	UK Battery Recycler
Kuka Robotics UK	Global leader in Industrial Robots
Less Common Metals	Specialist alloy producer
Shield Investment Management	Technology VC
Tetronics	Resource Recovery Systems
Thatcham Research	Vehicle Safety

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YEAR 1 MILESTONES

		Year 1											
	Month	1	2	3	4	5	6	7	8	9	10	11	12
WP1	Battery Assessment		M1.1				M1.2						M1.3
WP 2	Gateway Testing and Autonomous Robotic Sorting							M2.3	M2.1	M2.2			M2.4
WP 3	Re-use			M3.1						M3.2			M3.3 M3.4
WP4	Recycling						M4.4 M4.7	M4.8		M4.2 M4.3 M4.5			M4.1 M4.6 M4.9
WP 5	Life Cycle Assessment and Techno-Economic Assessment		M5.3		M5.1					M5.2			M5.4
WP6	Business Models; Value Chains; Legal Influence and Economic Analysis				M6.1			M6.2					M6.3 M6.4
WP7	Legislation / Socio-Economic Impacts						M7.1			M7.2 M7.3			
WP8	Materials Characterisation								M8.1		M8.2		M8.3 M8.4

Milestone	Description
M1.1	Initial database set up
M1.2	3D models of battery packs and components
M1.3	Partial annotation of models from WP8
M2.1	Shipping of battery pack blanks
M2.2	3D vision scanning system set up at NU
M2.3	Sensor array built at NU
M2.4	Robotics systems designed and orders placed
M3.1	Database of proposed usages for second life batteries
M3.2	Test beds to demonstrate second life battery usage
M3.3	Building of generic interface plaform for OEM BMS
M3.4	Design and model of solution for safe, rapid pack discharge and injection
M4.1	Mapping changes in battery materials during use
M4.2	Thermodynamic modelling of plasma recovery process
M4.3	Shredding and physical separation trialand report
M4.4	Supply of shredded components to co-workers
M4.5	Biochemical recovery trials for lithium
M4.6	Initial bio precipitation trials for lithium
M4.7	Modelling and solvent selection program for chemical dissolution
M4.8	Start of laboratory scale test trials for chemical separation
M4.9	Development of in-situ TEM observation methods
M5.1	Boundary conditions for LCA
M5.2	Data collection on primary production of Li, Co, Mn, Ni
M5.3	Literature survey on LCA models and for battery recycling
M5.4	Preliminary flow sheets for battery recycling processes
M6.1	Characterise economic and business dimensions of recycling value chain
M6.2	Impact of vehicle and bettery ownership models on supply of EOVs
M6.3	Define existing recycling business models
M6.4	Techno-economic report on viability of plasma process
M7.1	Literature and legislative review of circular economy of batteries
M7.2	Brexit' review of EU waste laws and EU Circular Economy Package
M7.3	Establishment of advice hub
M8.1	Chemical composition of end-of-life battery materials assessed
M8.2	Cross reference M8.1 data with EIS data for WP2
M8.3	Benchmarking recovered materials to classify the quality of the process
M8.4	XRD, EDXD, XPDF benchmarking for use on real cells

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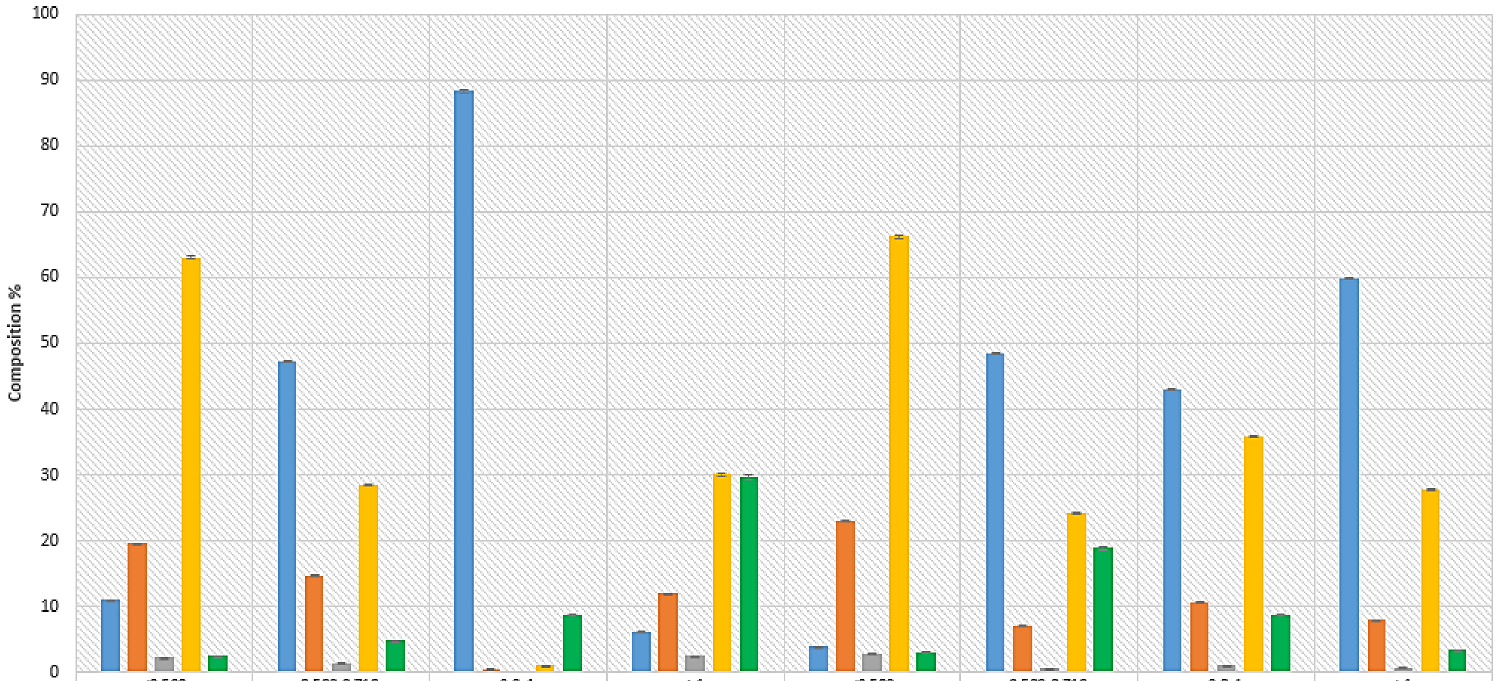
RELIB PROJECT STRUCTURE

Investigators	Role in the project
Neil Rowson	Minerals processing, physical sorting of waste
Paul Anderson	Characterisation
Peter Slater	Battery materials
Robert Lee	Legislation
Rustam Stolkin	Robotics
Tim Overton	Bioleaching
Phoebe Allan	Structural characterisation
Daniel Reed	Characterisation
Robert Elliott	Economics
Patricia Winfield	LCA, design for recycle
Allan Hutchinson	LCA
Nigel Browning	In situ electron microscopy
Karl Ryder	Chemical extraction of metals
Andrew Abbott	Chemical extraction of metals
Peter Wells	Supply chain economics
Louise Horsfall	Biological production of nano particles
Simon Lambert	WP1 leader, WP2, WP3 (electrical systems)
Neal Wade	Second life batteries
Oliver Heidrich	WP5 (LCA of recycling routes and re-use)
Paul Christensen	Sensing and degradation
Phillip Chater	Beamline scientist
Allan Walton	Sensing and sorting of waste

WP4: RECYCLING

DENVER CELL FLOTATION OF VARIOUS SHREDDED BATTERY SIZE RANGES

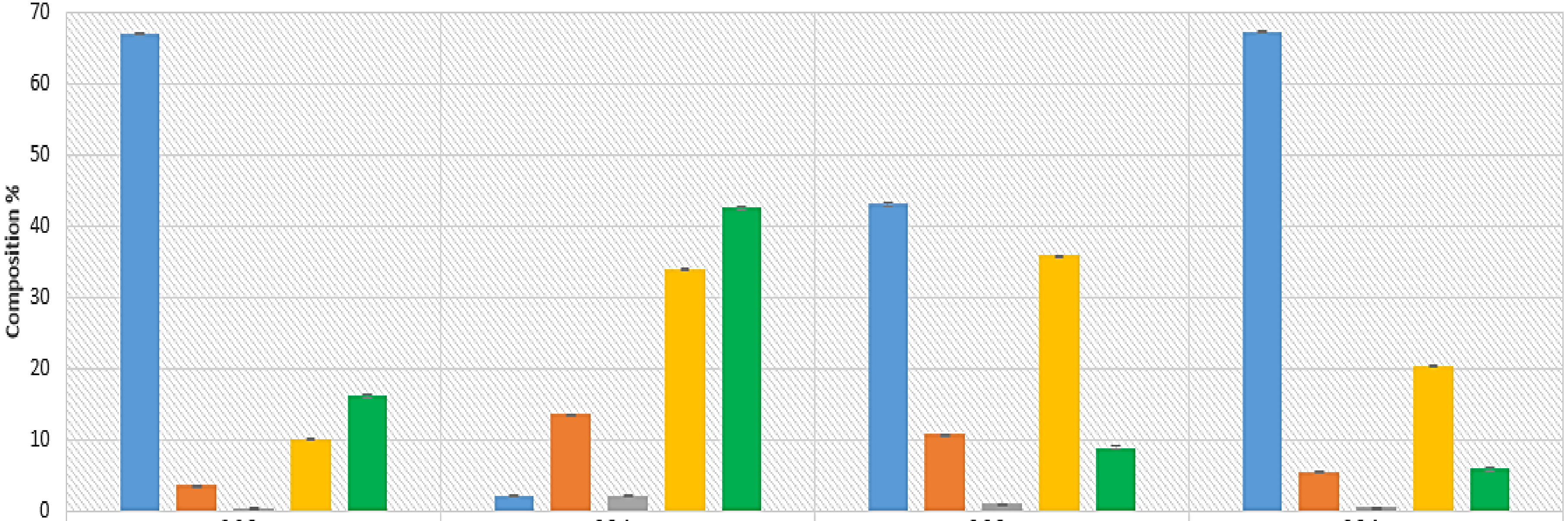


	<0.500	0.500-0.710	2.8-4	>4	<0.500	0.500-0.710	2.8-4	>4
Cu	11.106	47.329	88.327	6.16	3.908	48.43	43.069	59.869
Ni	19.589	14.738	0.527	11.994	23.13	7.121	10.688	7.953
Co	2.313	1.398	0.045	2.517	2.819	0.66	1.058	0.72
Mn	63.058	28.492	1.119	30.031	66.193	24.291	35.821	27.66
Al	2.517	4.883	8.742	29.641	3.051	18.886	8.86	3.416

Floats ← → | Particle Size Fractions (mm) | ← → Sinks

WP4: RECYCLING

COLUMN FLOTATION OF SIZED SHREDDED BATTERY



	Floats 2-2.8 mm	Floats 2.8-4 mm	Sinks 2-2.8 mm	Sinks 2.8-4 mm
Cu	66.991	2.061	43.069	67.208
Ni	3.572	13.511	10.688	5.493
Co	0.324	2.156	1.058	0.454
Mn	10.048	33.891	35.821	20.297
Al	16.107	42.472	8.86	5.898

Floats ⟵⟶ Sinks

Particle Size Fractions (mm)

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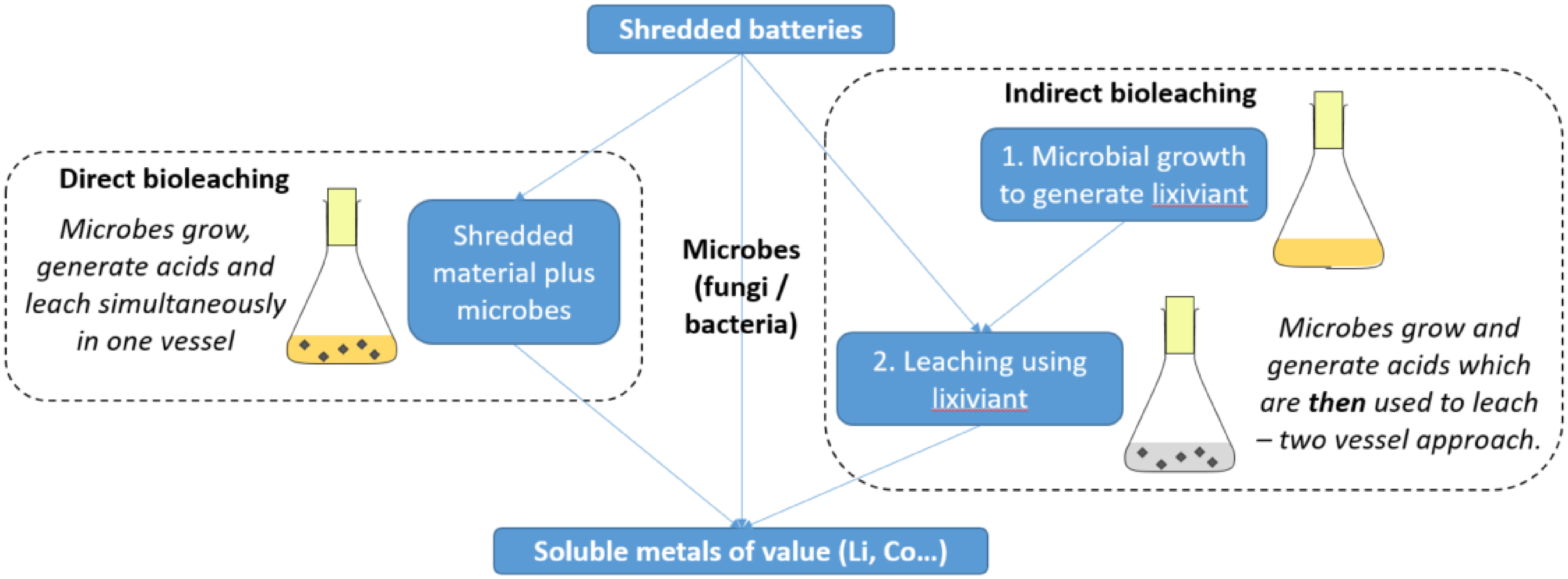
WP4: RECYCLING

BIOLEACHING



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WP4: RECYCLING

BIOLEACHING- PROGRESS TO DATE

- ✓ Review of state of the art
- ✓ Already commenced, methods identified from waste recycling and ore processing
- ✓ Assistance to come from Faraday summer placement undergraduate student

KEY EXPERIMENTAL QUESTIONS

- Choice of organism – *Aspergillus niger* will be tried first
- Is direct or indirect leaching best?
- What mixture of organic acids in the lixiviant are optimal for selective leaching?
- How can we control organic acid production to optimise lixiviant activity / selectivity?

WP2: advanced robotics for disassembly

Modelling and data gathering – linked to KPI2 with NU:

- Use advanced robotic vision methods to build detailed 3D models of batteries at all stages of disassembly – pack; module; cell; and ancillary parts such as wire-looms and structural components.
- Combination of off-the-shelf imaging devices, and also robot arms moving 3D cameras to different known viewpoints over the battery pack during different stages of disassembly.
- Advanced methods of matching and merging multiple point-cloud images to generate 3D models.
- Models used to project large number of synthetic views for training data of machine learning systems.

Autonomous robotic disassembly:

- Computer vision and machine learning for recognising large diversity of battery packs, including packs with various degrees of damage/deformation/appearance change.
- Vision systems for localising battery/parts with respect to robots.
- Vision guided robotic manipulation with advanced force-feedback control:
  - Unbolting
  - Cutting
  - Grasping
  - Manipulating

Robots should:

- Connect packs/modules/cells to electrical testing machinery at various stages.
- Remove outer casing of battery packs.
- Remove wiring looms.
- Extract individual modules.
- Cut open individual modules and disassemble at cell level.

Macro-scale/mechanical disassembly by robots upstream, will greatly facilitate materials separation downstream.

Our previous work that can be built on

Advanced robotics for nuclear waste handling:

- **Vision-based 3D reconstruction and recognition of complex, varied, mixed legacy nuclear waste materials.**
- **Vision-guided autonomous grasping and manipulation of diverse waste materials.**
- **Autonomous cutting of arbitrarily shaped waste**
- **Autonomous AI-controlled robotics in extremely high-consequence high-hazard environments.**

NCNR NATIONAL CENTRE FOR NUCLEAR ROBOTICS

RoMaNS ROBOTIC MANIPULATION FOR NUCLEAR SORT AND SEGREGATION

3-years collaboration with KUKA and its customers on advanced robotics for manufacturing:

- **Vision-based grasping of complex metallic (reflective) objects from random self-occluding heaps.**
- **Significant interaction with automotive industry.**

KUKA

Understanding conventional industrial robotics and what it doesn't do:

- **Examples of conventional robots in the manufacturing industry.**
- **These robots are not smart – cannot handle any uncertainty – rely on highly structured environments and simple repetitive motions.**
- **Why is disassembly harder than assembly?**

Slightly smarter industrial robotics:

- **Here the objects appear in uncertain positions and orientations – detected by a vision system.**
- **However the environment is still highly structured and the vision is simplistic:**
  - **Vision limited to detecting 2D blobs and orientation of long axis.**
  - **All parts are identical.**
  - **All parts on flat plane - no overlapping or occluded parts.**
  - **Parts are simple, and need only a single simple motion - grasping achieved with simple suction cups.**

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WP2: ADVANCED ROBOTICS FOR DISASSEMBLY

Novel advances in automation of materials recycling, however:

- Still relies on simple 2D vision of flat rectangles on a flat plane.
- Some limited sensor techniques
- Very small number of possible objects to be recognised.
- Only simple pre-programmed manipulative actions are required.

Robotic sorting of electronic waste to remove rare earth magnets – EU Remanence project

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Complexity of the battery challenge:

New vehicle pack (already complex)

vs. realities of waste recycling…

- Enormous variety of makes/models. These will continually change over time.
- Damaged, corroded, mixed, varied appearance and shape.
- Vehicle batteries already varied – number and variety will grow very rapidly and change continually.
- How to handle damaged/deformed batteries?

Current state-of-the-art for nuclear waste sorting

- 1970s-1980s technology…
- Painstaking joystick control by teams of expert operators

  but their average age is 55 years old…
- No autonomy.
- No telepresence or haptics.
- No compliance or force control.
- Limited visualisation.
- Limited situational awareness.
- Unlikely to succeed in societally acceptable time-scales…

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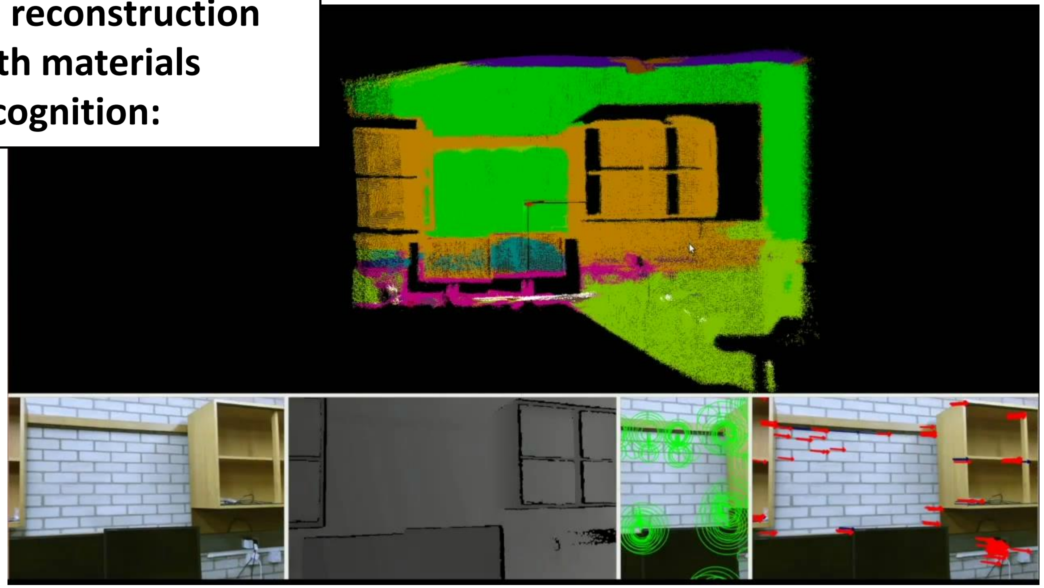
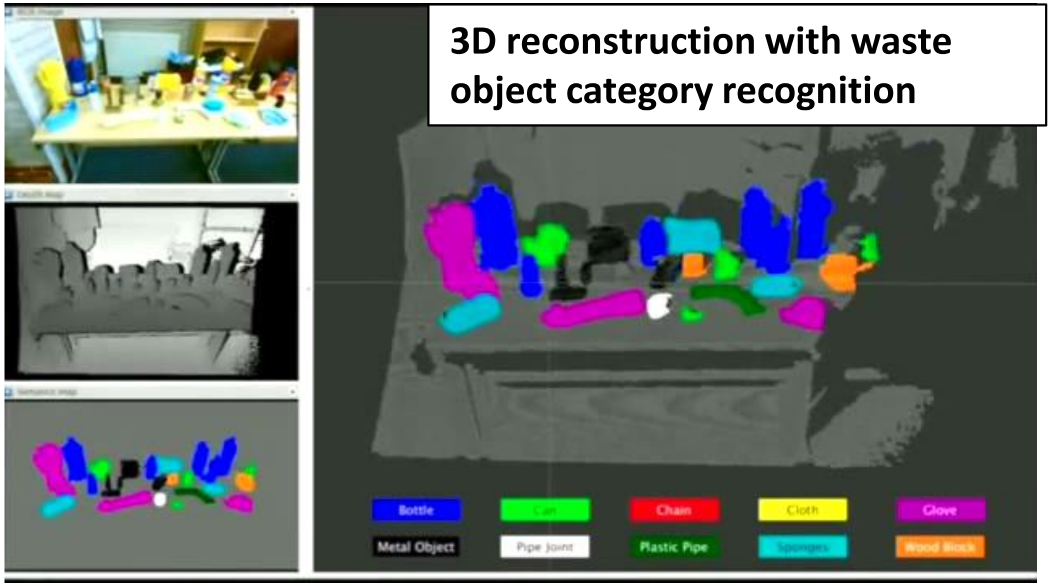
Our recent work in computer vision:

3D reconstruction with materials recognition:

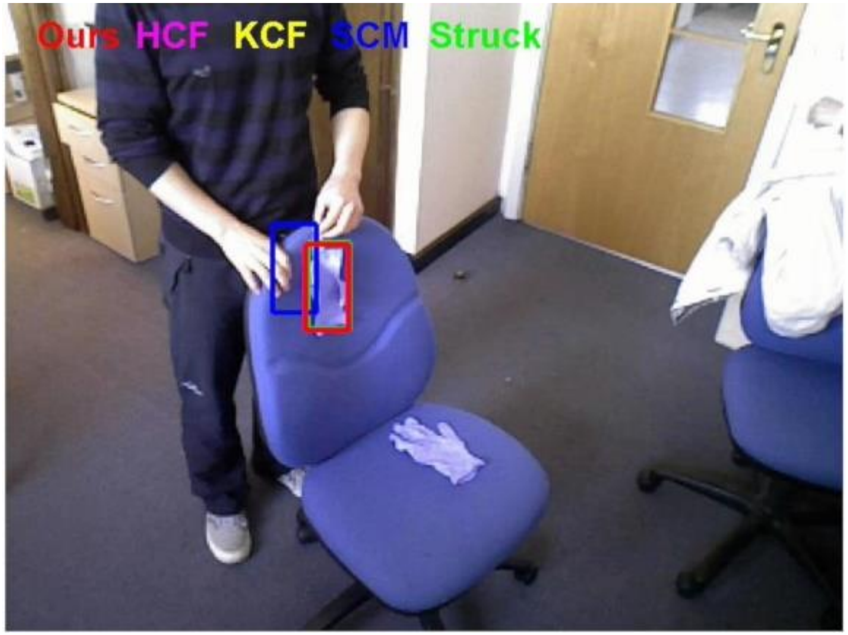


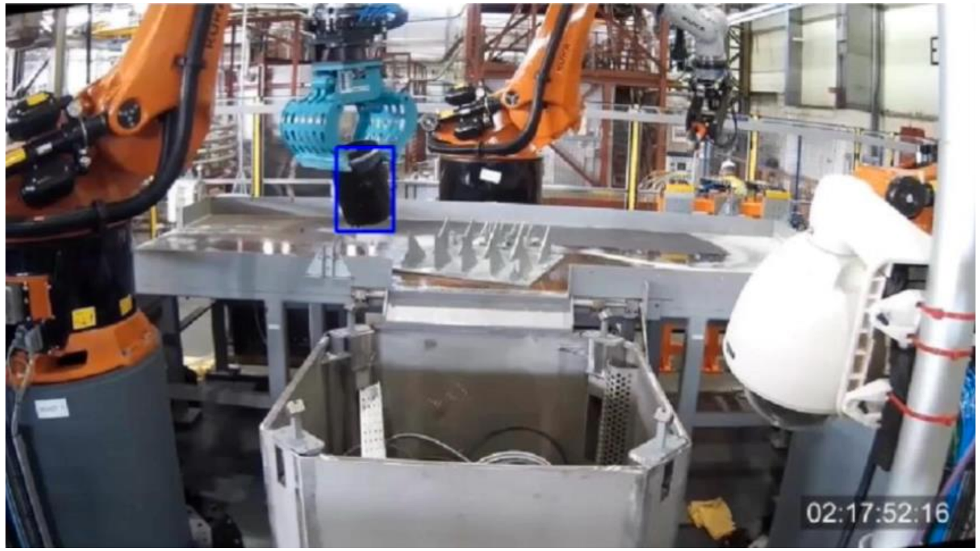
Pose-detection in cluttered heaps

3D reconstruction with waste object category recognition



Pose tracking and active/robotic vision:





Example of estimation of joint configuration
using our framework

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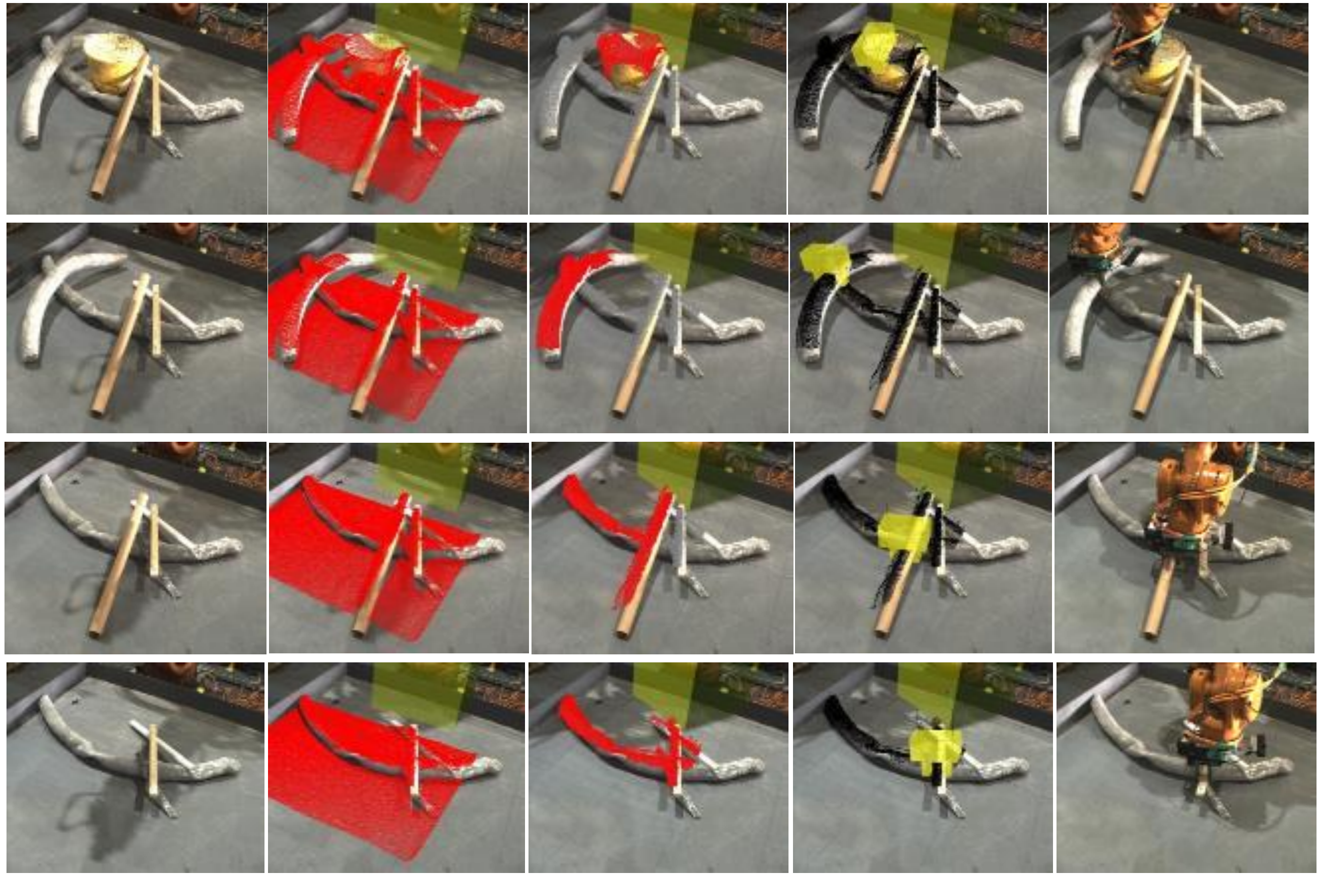
Autonomous vision-guided grasping:

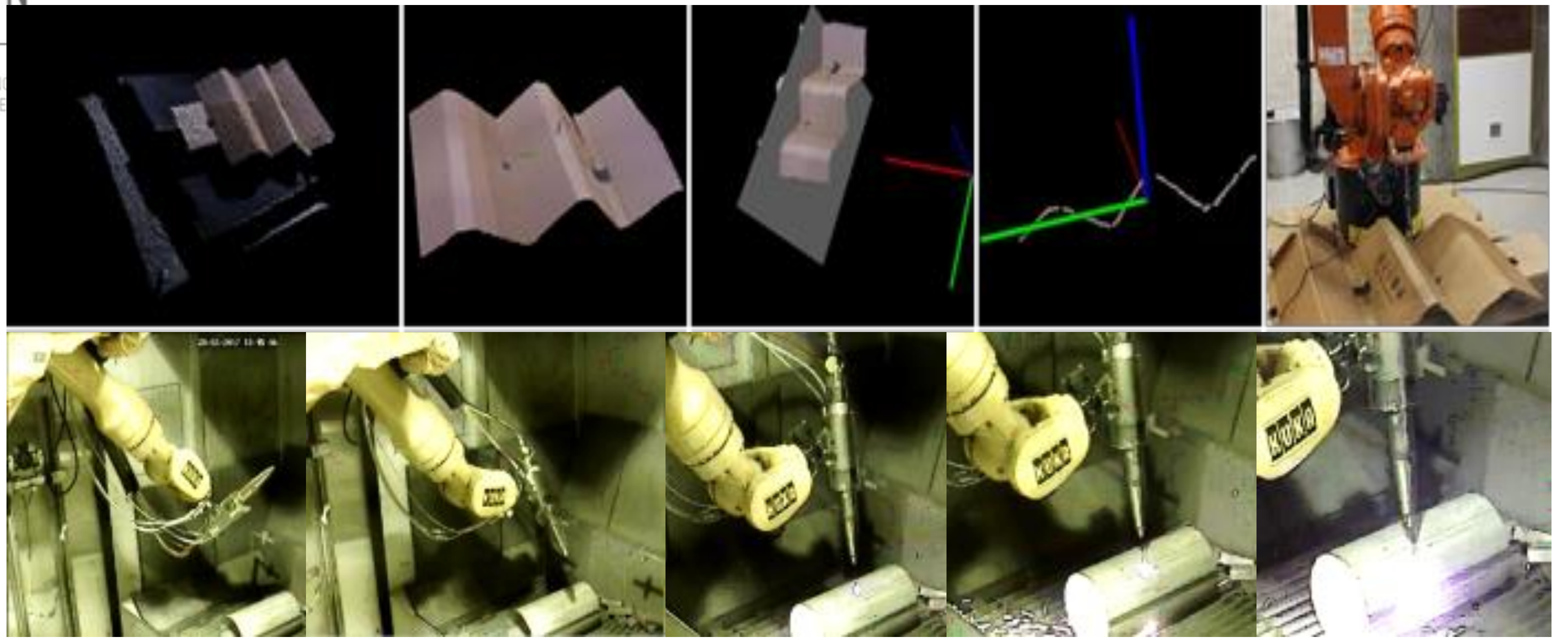


- **Autonomy in a risk-averse, conservative, high-consequence industry?**

- **Risk assessments…**
- **Nuclear safety regulations…**
- **Overcoming these challenges are also part of our intellectual achievement!**

RoMaNS augmented reality interface for semi-autonomous grasping (human-supervised autonomy), demonstrated on the RoMaNS industrial robot testbed, built at the NNL Workington nuclear industry site.
(a) Raw CCTV view of the scene, displayed to the human operator.
(b) Augmented view with projected point-cloud captured by the robot's wrist-mounted RGB-D camera.
(c) The autonomous agent segments salient objects/parts from the background. Non-background objects are denoted by grey points, while the autonomous agent uses red points to suggest the most easily graspable objects/parts in the scene (computed by a learned autonomous grasp planner).
(d) The agent suggests the best grasp (maximum likelihood grasp) to the human operator.
(e) After the human operator approves the simulated grasp, the real grasp is executed by the robot.

Autonomous vision-guided cutting:



Wrist-mounted camera captures object from multiple views, fuses images, segments from backlground to give 3D model of arbitrarily shaped object.

Simple interface (two mouse-clicks) defines a cutting plane. Cutting trajectory is automatically generated.

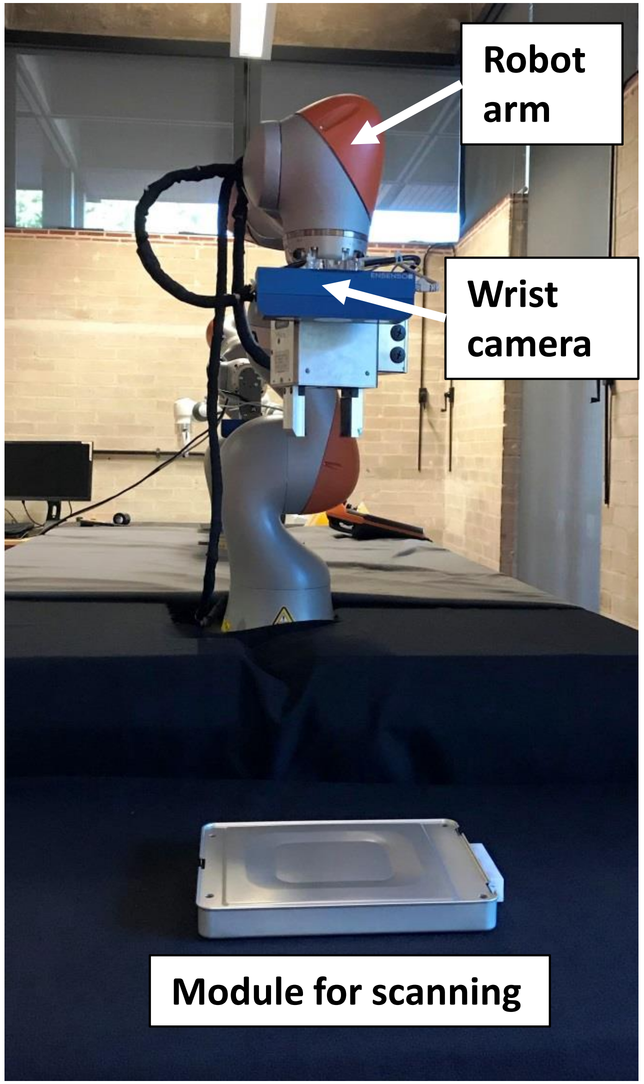
AI planner plans collision free trajectory of all arm joints to deliver laser along cutting path.

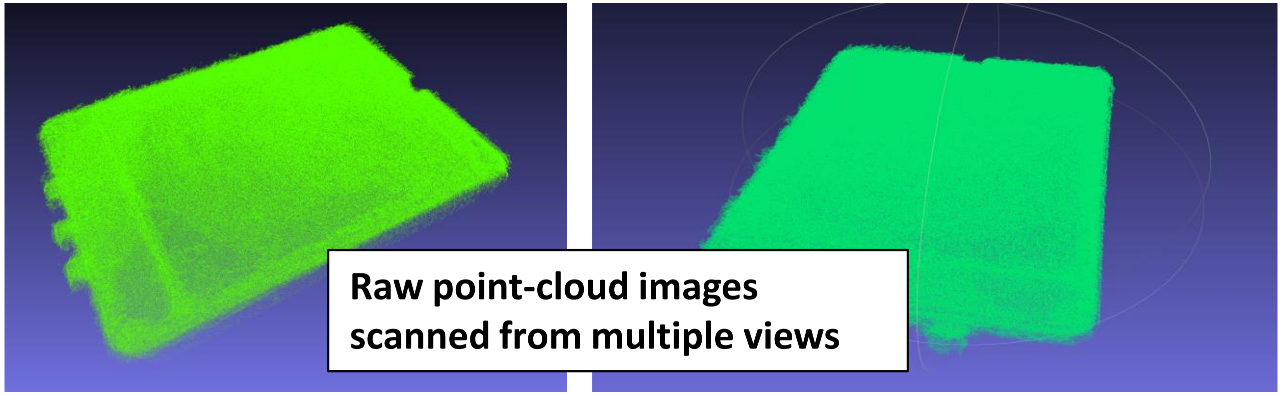
Above: in-lab demo using cardboard object with difficult surface shape.

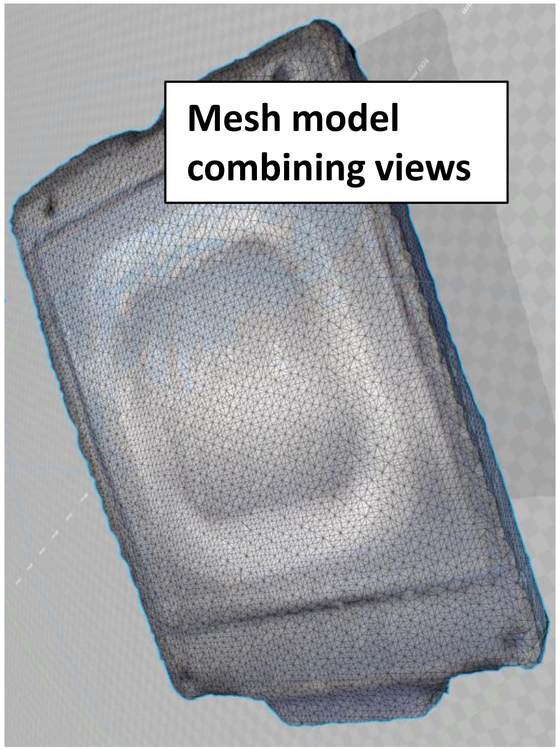
Bottom: <u>first ever autonomous robot (vision-guided AI-controlled) in history to be deployed in a radioactive environment</u> – vision-guided laser-cutting of contaminated steel in radioactive hot cell at NNL Preston nuclear site.

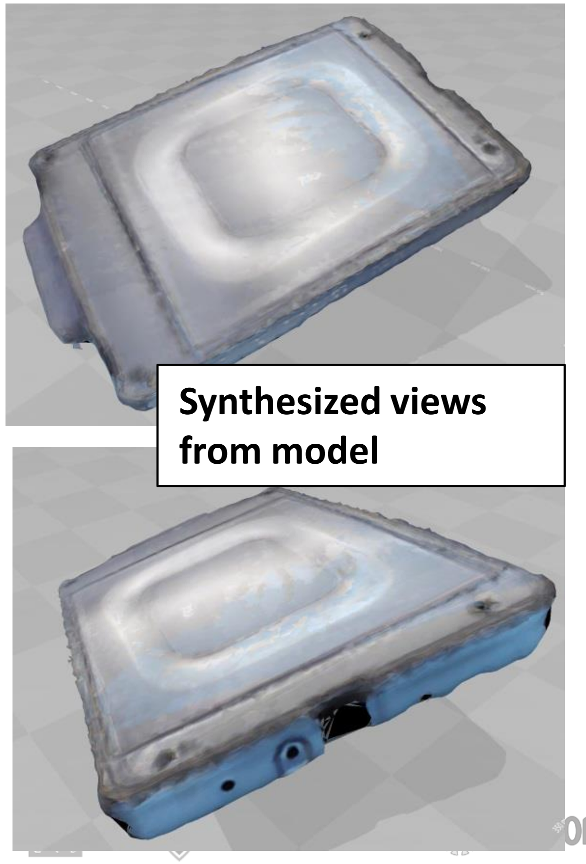
We have recently extended this work to smaller arm on a mobile manipulator robot, using contact cutting with a rotary tool. Advanced impedance control is needed to handle the contact forces. Video will be shown at next RANUF meeting!

Initial tests of robot-vision scanning for 3D modeling of battery modules:









WP2: next steps

3D modelling/data-fusion of batteries at multiple scales of disassembly

Vision and tactile-guided unbolting:

- **Design of socket-wrench end-effector tooling**
- **Visual detection and localisation of bolt heads**
- **Collision-free trajectory planning to bolt**
- **Visual guidance of robot onto bolt**
- **Peg-in-hole problem – combine passive and active compliance (force-torque feedback)**

Vision-guided contacting of module terminals:

- **Connect electrodes to module terminals for electrical testing**
- **Vision for detection and localisation of terminals**
- **Trajectory planning for collision-free motion to terminals**
- **End-effector mechanical design for connection tooling**